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Edited by Juan Blanco and Houshang Kheradmand

CLIMATE CHANGE – RESEARCH AND TECHNOLOGY FOR ADAPTATION AND MITIGATION

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Houshang Kheradmand

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Meet the editors

Dr. Blanco is a Research Associate at the University of British Columbia. His work is focused on the development and evaluation of ecological models to simulate the influences of management, climate and other ecological factors on tree growth. He is currently collaborating with research teams from Canada, USA, Spain, Cuba, and China in using ecological models to explore the effects of climate change, atmospheric pollution and alternative forest practices in natural and planted forest in boreal, temperate and tropical forests. His research has been applied in mining to optimize reclamation plans, in forestry to assess the potential for carbon sequestration and by government agencies to define local guidelines for long-term sustainable forest management. Among other topics related to forest ecology, Dr. Blanco has studied the influence of climate variations on tree growth and estimated the possible ecological consequences of climate change in forest ecosystems. He has also co-authored the first book dedicated exclusively to the use of hybrid ecological models in forest management, entitled "Forecasting Forest Futures" (Earthscan, London).

Dr. Kheradmand was born on March 1953 and received his masters in chemistry in 1980 and a doctorate in petro-chemistry in 1983 from ULP "Louis Pasteur University -Strasbourg", followed by a 2nd doctorate in polymer sciences in 1987 from Strasbourg Polymer Research Center. Since 1987 Dr. Kheradmand has worked in the European chemical industry with different responsibilities, such as Quality lab manager, R&D group leader, European product stewardship manager, European sustainable development manager, European Technology Awareness and Innovation Manager. He is Life Cycle thinking, Life Cycle Assessment and Sustainable Development expert.
He has an active participation in different European organizations such as CEFIC, CEPE, EPDLA - EPDLA Chairman, ERMA - Member of Executive Committee and Chairman of Technical Committee, French Ecolabel - Member of Paint Ecolabel technical committee, FFC (Fédération Française pour les sciences de la Chimie) - Member of FFC steering Committee and Member of ChDD ''Chimie pour un Développement Durable®' working groupe committee , IUPAC - Member of IYC 2011 launch ceremony organization team. Dr. Kheradmand has presented different topics in WW seminars and exhibitions.

Contents

Preface

Climate is a fundamental part of the world as we know it. The landscape and everything on it are determined by climate acting over long periods of time (Pittock 2005). Therefore, any change on climate will have effects sooner or later on the world around us. These changes have happened before in the past, and they will likely happen again in the future. Climate variability can be both natural or anthropogenic (Simard and Austin 2010). In either case, the change in the current climate will have impacts on the biogeophysical system of the Earth. As all human activities are built on this system, our society will be impacted as well. As a consequence, climate change is increasingly becoming one of the most important issues, generating discussions in economy, science, politics, etc. There is no discrepancy among scientists that climate change is real and it has the potential to change our environment (Oreskes and Conway 2010), but uncertainty exists about the magnitude and speed at which it will unfold (Moss et al. 2010). The most discussed effect of global warming is the increase of temperatures, although this increase will not be homogeneous through the seasons, with the winters expected to warm up significantly more than the summers. In addition, changes in precipitation are also expected that could lead to increase or decrease of rainfall, snowfall and other water-related events. Finally, a change in the frequency and intensity of storm events could be possible, although this is probably the most uncertain of the effects of global warming. These uncertainties highlight the need for more research on how global events have effects at regional and local scales, but they also indicated the need for the society at large to assume a risk-free approach to avoid the worse effects of climate change in our socio-economical and ecological systems (IPCC 2007).

Humans have been dealing with risk-related activities for a long time. For example, when buying a car or home insurance, the discussion is not about whether the adverse effects will happen or not, but on how to reduce its effects and recover from if they happen. In many countries having car insurance is compulsory to drive a car, even if only a small percentage of drivers suffer car accidents compared to the total number of cars. In addition, the most risky manoeuvres (i.e. excessive speed, not stopping on red light, etc.) are banned to reduce the risks of accidents. Similarly, developing policies and practices that reduce and minimize the risks and effects of climate change is needed, even if the worse situations will never happen. If not, we will be in the equivalent of driving without insurance and without respecting the signals. All policies and practices for economic, industrial and natural resource management need to be founded on sound scientific foundations. This volume offers an interdisciplinary view of the current issues related to climate change adaptation and mitigation, and provides a glimpse of the state-of-the-art research carried out around the world to inform scientists, policymakers and other stakeholders.

When planning how to reduce the threat of global warming and how to adapt to it, a very important piece of information is how intense the change will be. That implies estimating the trends of future concentrations of greenhouse gasses, and the potential future changes in temperature, precipitation, storm events and other climatic variables. These predictions are important not only to estimate the magnitude of the changes, but also to determine the uncertainty surrounding them. In the first section of this book different tools to estimate the future consequences of future climate change are presented. An important issue is to provide meaningful estimations of change at scales that can be used for management and policymaking. In the first two chapters of this section, Bartholy et al. and Jin et al. describe two methodologies to dynamically downscale climate projections applied in the Carpathian Basin and the USA, respectively. Then, Höök provides a critical review of the future scenarios of greenhouse gas emissions. Models are also needed to predict the cascade of effects caused by changes in climate. Lo et al. review the available ecophysiological models that can simulate the effects of climate on forests, whereas Eslamian et al. describe the statistical methodology to detect and model climate change effects in hydrology. Caselles et al. introduces a new algorithm to automatically generate land surface emissivity maps, and Rustamov et al. explain how space technology can be used to monitor the speed and extension of the changes caused by climate change. This section ends with the work by Nasurt, who describes the importance of taking aerosols into account when estimating the changes in the atmosphere, especially in arid regions.

One of the aspects of climate change that most coverage has received in the news is the reduction of greenhouse emissions. Reducing these emissions will slow down the speed of climate change and hopefully keep it under some levels considered as acceptable. However, the reduction in emissions will be achieved only if profound changes in our social, economic and industrials systems are achieved. The second section of this book explores some of the research done on this topic. Plugge et al. describe why a strong monitoring system is needed to reduce greenhouse gas emissions from deforestation. Zhou et al. discuss how a more accurate accountability of emissions related to international trade is needed. Kadar describes the links between power generation and greenhouse emissions, whereas Valero-Matas and Romay explore the feasibility of using alternative energy to reduce emission without reducing power generation. Wene reviews the importance of the process of technology learning in achieving a low-carbon economy, and Lhemann provides principles to create a greener urbanism.

Although all the efforts in reducing greenhouse emissions are worthwhile and need to be increased to avoid reaching potentially catastrophic concentrations of greenhouse gases in the atmosphere, the reality is that an increase in the global temperatures of some short is inevitable. Therefore, managers and policymakers should recognize this reality, and adapt the future policies that shape our socioeconomic systems to reduce the adverse effects to the minimum. The third and last section of this book introduces some experiences on this topic. Otelo et al. review different methods to achieve sustainable production of goods. Conner discusses the need to adapt infrastructures to climate change effects, whereas Mirza reviews the need to incorporate the effects of extreme weather events in the design of infrastructures. MsConnach et al. describe the impacts of climate change on the power industry and the steps being carried out for its adaptation. Sinnadurai examines how to incorporate climate change scenarios into the protection of natural areas, while Watson extends this topic by discussing how to plan for biological conservation under the threat of climate change. Agricultural systems will also need to be adapted to the new climatic reality. In the northern hemisphere, Puhakainen et al. describes the options for crop production in boreal areas, while in the south Nie discusses the use of perennial grasses to adapt Australian grazing systems to climate change. Campra presents a study case on how to use intensive greenhouse farming in the Mediterranean for adaptation and mitigation. The book ends with Hefferon's review on the innovations in the field of agricultural biotechnology to adapt future farming systems.

All things considered, these 24 chapters provide a good overview of the different research and technological efforts being carried out around the globe to reduce the emission of greenhouse gases and to adapt our socioeconomic and ecological systems to the inevitability of climate change. However, climate change adaptation and mitigation is not just a theoretical issue only important for scientists or technicians. These research and technological efforts are based on the observed and expected changes caused by the shifting climate in ecological and socioeconomic systems. The other two books of this series "Climate change – Geophysical Basis and Ecological Effects" and "Climate Change – Socioeconomic Effects" explore these topics in detail, and we encourage the reader to also consult them.

The Editors want to finish this preface acknowledging the collaboration and hard work of all the authors. We are also thankful to the Publishing Team of InTech for their continuous support and assistance during the creation of this book. Especial thanks are due to Ms Ana Pantar for inviting us to lead this exciting project, and to Ms Iva Lipovic for coordinating the different editorial tasks.

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Part 1

Predicting and Monitoring the Effects of Climate Change

1

Dynamical Downscaling of Projected 21st Century Climate for the Carpathian Basin

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1. Introduction

According to the Working Group I contributions (Solomon et al., 2007) to the Fourth Assessment Report of the Intergovermental Panel on Climate Change (IPCC), the key processes influencing the European climate include increased meridional transport of water vapour, modified atmospheric circulation, reduced winter snow cover (especially, in the northeastern regions), more frequent and more intense dry conditions of soil in summer in the Mediterranean and central European regions. Future projections of IPCC for Europe suggest that the annual mean temperature increase will likely to exceed the global warming rate in the 21st century. The largest increase is expected in winter in northern Europe (Benestad, 2005), and in summer in the Mediterranean area. Minimum temperatures in winter are very likely to increase more than the mean winter temperature in northern Europe (Hanssen-Bauer et al., 2005), while maximum temperatures in summer are likely to increase more than the mean summer temperature in southern and central Europe (Tebaldi et al., 2006). Concerning precipitation, the annual sum is very likely to increase in northern Europe (Hanssen-Bauer et al., 2005) and decrease in the Mediterranean area. On the other hand, in central Europe, which is located at the boundary of these large regions, precipitation is likely to increase in winter, while decrease in summer. In case of the summer drought events, the risk is likely to increase in central Europe and in the Mediterranean area due to projected decrease of summer precipitation and increase of spring evaporation (Pal et al., 2004; Christensen & Christensen, 2004). As a consequence of the European warming, the length of the snow season and the accumulated snow depth are very likely to decrease over the entire continent (Solomon et al., 2007).

Coarse spatial resolution of global climate models (GCMs) is inappropriate to describe regional climate processes; therefore, GCM outputs of typically 100-300 km may be misleading to compose regional climate change scenarios for the 21st century (Mearns et al., 2001). In order to determine better estimations of regional climate conditions, fine resolution regional climate models (RCMs) are widely used. RCMs are limited area models nested in GCMs, i.e., the initial and the boundary conditions of RCMs are provided by the GCM outputs (Giorgi, 1990). Due to computational constrains the domain of an RCM evidently does not cover the entire globe, and sometimes not even a continent. On the other hand, their horizontal resolution may be as fine as 5-10 km.

In Europe, the very first comprehensive and coordinated effort for providing RCM projections was the project PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects), which involved 21 European research institutes and universities (Christensen, 2005). The primary objectives of PRUDENCE were (i) to provide 50 km horizontal resolution climate change scenarios for Europe for 2071-2100 using dynamical downscaling methods with RCMs (compared to 1961-1990 as the reference period), and (ii) to explore the uncertainty in these projections considering the applied emission scenario (IPCC SRES A2 and B2), the boundary conditions (using HadAM3H, ECHAM4, and ARPEGE as the driving GCM), and the regional model (Christensen et al., 2007). Results of the project PRUDENCE are disseminated widely via Internet (http://prudence.dmi.dk), thus supporting socio-economic and policy related decisions.

In smaller regions such as the Carpathian Basin (located in Eastern/Central Europe), 50 km horizontal resolution may still not be appropriate to describe the meso-scale processes (e.g., cloud formation and convective precipitation). For this purpose on a national level several RCMs have been adapted with finer resolution (25 and 10 km). Here, results from two of the adapted RCMs for Hungary are analyzed, namely, models PRECIS and RegCM.

In this paper, first, data and models from PRUDENCE, PRECIS and RegCM are presented. Then, the regional climate change projections are summarized for the Carpathian Basin using the outputs of the available simulations. Results of the projected mean temperature and precipitation change by the end of the 21st century are discussed using composite maps. Furthermore, the simulated changes of the extreme climate indices following the guidelines suggested by one of the task groups of a joint WMO-CCl (World Meteorological Organization Commission for Climatology) – CLIVAR (a project of the World Climate Research Programme addressing Climate Variability and Predictability) Working Group formed in 1998 on climate change detection (Karl et al., 1999; Peterson et al., 2002) are also analyzed.

2. Data, models

The RCMs nested into GCM are used to improve the regional climate change scenarios for the European subregions. For analyzing the possible regional climate change in the Carpathian Basin, we analyzed PRUDENCE outputs, and have adapted the models PRECIS and RegCM at the Department of Meteorology, Eötvös Loránd University.

For assessing the future conditions, three emission scenarios are considered in this paper, namely, SRES A2, A1B, and B2 (Nakicenovic & Swart, 2000). According to the A2 global emission scenario, fertility patterns across regions converge very slowly resulting in continuously increasing world population. Economic development is primarily regionally oriented, per capita economic growth and technological changes are fragmented and slow. The projected CO_2 concentration may reach 850 ppm by the end of the 21st century (Nakicenovic & Swart, 2000), which is about triple of the pre-industrial concentration level (280 ppm). The global emission scenario B2 describes a world with intermediate population and economic growth, emphasizing local solutions to economic, social, and environmental sustainability. According to the B2 scenario, the projected CO_2 concentration is likely to exceed 600 ppm (Nakicenovic & Swart, 2000), which is somewhat larger than a double concentration level relative to the pre-industrial CO_2 conditions. A1B emission scenario estimates the CO_2 level reaching 717 ppm by 2100, which is an intermediate level considering all the three applied scenarios.

2.1 PRUDENCE outputs

16 experiments from the PRUDENCE simulations considered the IPCC SRES A2 emission scenario (Nakicenovic & Swart, 2000), while only 8 experiments used the B2 scenario (Table 1). Most of the PRUDENCE simulations (Déqué et al., 2005) used HadAM3H/HadCM3 (Gordon et al., 2000; Rowell, 2005) of the UK Met Office as the driving GCM. Only a few of them used ECHAM4 (Roeckner et al., 2006) or ARPEGE (Déqué et al., 1998). Simulated temperature and precipitation outputs were separated and downloaded (from the data server at http://prudence.dmi.dk) for the region covering the Carpathian Basin (45.25°-49.25°N, 13.75°-26.50°E).

Institute	RCM	Driving GCM	Scenario
Danish Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2, B2
Hadley Centre of the UK Met Office	HadRM3P	HadAM3H/HadCM3	A2, B2
ETH (Eidgenössische Technische Hochschule)	CHRM	HadAM3H/HadCM3	A2
GKSS (Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt)	CLM	HadAM3H/HadCM3	A2
Max Planck Institute	REMO	HadAM3H/HadCM3	A2
Swedish Meteorological and Hydrological Institute	RCAO	HadAM3H/HadCM3 ECHAM4/OPYC	A2, B2 B2
UCM (Universidad Complutense Madrid)	PROMES	HadAM3H/HadCM3	A2,B2
International Centre for Theoretical Physics	RegCM	HadAM3H/HadCM3	A2, B2
Norwegian Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2
KNMI (Koninklijk Nederlands Meteorologisch Institute)	RACMO	HadAM3H/HadCM3	A2
Météo-France	ARPEGE	HadAM3H/HadCM3 ARPEGE/OPA	A2, B2 B2

Table 1. List of the PRUDENCE RCMs used in this analysis

2.2 Model PRECIS

The model PRECIS is a high resolution limited area model (HadRM3P) with both atmospheric and land surface modules. The model was developed at the Hadley Climate Centre of the UK Met Office (Wilson et al., 2007), and it can be used over any part of the globe (e.g., Hudson and Jones, 2002, Rupa Kumar et al., 2006, Taylor et al., 2007, Akhtar et al., 2008). PRECIS is based on the atmospheric component of HadCM3 (Gordon et al., 2000) with substantial modifications to the model physics (Jones et al., 2004). The atmospheric component of PRECIS is a hydrostatic version of the full primitive equations, and it applies a regular latitude-longitude grid in the horizontal and a hybrid vertical coordinate. The horizontal resolution can be set to 0.44°×0.44° or 0.22°×0.22°, which gives a resolution of ~50 km or ~25 km, respectively, at the equator of the rotated grid (Jones et al., 2004). In our studies, we used 25 km horizontal resolution for modeling the Central European climate. Hence, the target region contains 123x96 grid points. There are 19 vertical levels in the model, the lowest at ~50 m and the highest at 0.5 hPa (Cullen, 1993) with terrain-following σ-coordinates (σ = pressure/surface pressure) used for the bottom four levels, pressure coordinates used for the top three levels, and a combination in between (Simmons and Burridge, 1981). The model equations are solved in spherical polar coordinates and the latitude-longitude grid is rotated so that the equator lies inside the region of interest in order to obtain quasi-uniform grid box area throughout the region. An Arakawa B grid (Arakawa and Lamb, 1977) is used for horizontal discretization to improve the accuracy of the split-explicit finite difference scheme. Due to its fine resolution, the model requires a time step of 5 minutes to maintain numerical stability (Jones et al., 2004).

In case of the control period (1961-1990), the initial and the lateral boundary conditions for the regional model are taken from (i) the ERA-40 reanalysis database (Uppala et al., 2005) using 1° horizontal resolution, compiled by the European Centre for Medium-range Weather Forecasts (ECMWF), and (ii) the HadCM3 ocean-atmosphere coupled GCM using ~150 km as a horizontal resolution. For the validation of the PRECIS results CRU TS 1.2 (Mitchell & Jones, 2005) datasets were used. According to the simulation outputs, PRECIS is able to sufficiently reconstruct the climate of the reference period in the Carpathian Basin (Bartholy et al., 2009a, 2009b). The temperature bias (i.e., difference between simulated and observed annual and seasonal mean temperature) is found mostly within (–1 °C; +1 °C) interval. The largest bias values are found in summer, when the average overestimation of PRECIS over Hungary is 2.2 °C.

Both spatial and temporal variability of precipitation is much larger than temperature variability. The spatially averaged precipitation is overestimated in the entire model domain, especially, in spring and winter (by 22% and 15%, respectively). The precipitation of the high-elevated regions is overestimated (by more than 30 mm in each season). The overestimation of the seasonal precipitation occurring in the plain regions is much less in spring than in the mountains (Bartholy et al., 2009c). On the other hand, the summer and autumn mean precipitation amounts are underestimated in the lowlands. The underestimation is larger in the southern subregions than in the northern part of the domain. Inside the area of Hungary the seasonal means are slightly underestimated (by less than 10% on average), except spring when it is overestimated by 35% on average. The spring bias values are significantly large in most of the gridpoints located inside the Hungarian borders.

Nevertheless, temperature and precipitation bias fields of the PRECIS simulations can be considered acceptable if compared to other European RCM simulations (Jacob et al., 2007, Bartholy et al., 2007). Therefore, model PRECIS can be used to estimate future climatic change of the Carpathian Basin. For the 2071-2100 future period, two experiments were completed (considering A2 and B2 global emission scenarios). Moreover, a transient model run for 1951-2100 have been accomplished using A1B scenario.

2.3 Model RegCM

Model RegCM is a 3-dimensional, σ-coordinate, primitive equation model, which was originally developed by Giorgi et al. (1993a, 1993b) and then modified, improved, and discussed by Giorgi & Mearns (1999) and Pal et al. (2000). The RegCM model (version 3.1) is available from the Abdus Salam International Centre for Theoretical Physics (ICTP). The dynamical core of the RegCM3 is fundamentally equivalent to the hydrostatic version of the NCAR/Pennsylvania State University mesoscale model MM5 (Grell et al., 1994). Surface processes are represented in the model using the Biosphere-Atmosphere Transfer Scheme, BATS (Dickinson et al., 1993). The non-local vertical diffusion scheme of Holtslag et al. (1990) is used to calculate the boundary layer physics. In addition, the physical parametrization is mostly based on the comprehensive radiative transfer package of the

NCAR Community Climate Model, CCM3 (Kiehl et al., 1996). The mass flux cumulus cloud scheme of Grell (1993) is used to represent the convective precipitation with two possible closures: Arakawa & Schubert (1974) and Fristch & Chappell (1980).

Model RegCM can use initial and lateral boundary conditions from global analysis dataset, the output of a GCM or the output of a previous RegCM simulation. In our experiments these driving datasets are compiled from the ECMWF ERA-40 reanalysis database (Uppala et al., 2005) using 1° horizontal resolution, and in case of scenario runs (for 3 time slices: 1961-1990, 2021-2050, and 2071-2100) the ECHAM5 GCM using 1.25° spatial resolution (Roeckner et al., 2006). The selected model domain covers Central/Eastern Europe centering at 47.5°N, 18.5°E and contains 120x100 grid points with 10 km grid spacing and 18 vertical levels. The target region is the Carpathian Basin with the 45.15°N, 13.35°E southwestern corner and 49.75°N, 23.55°E northeastern corner (Torma et al., 2008).

Validation of RegCM for the selected domain is discussed by Bartholy et al. (2009c) and Torma et al. (2011). Temperature is overestimated in winter (by 1.1 °C), and underestimated in the other seasons (by 0.3 °C, 0.2 °C, and 0.1 °C in spring, summer, and autumn, respectively). The largest bias values are identified in the high mountainous regions (Alps, southern part of the Carpathians). For Hungary, the seasonal bias values are +1.3 °C, –0.5 °C, –0.5 °C, and –0.2 °C for DJF, MAM, JJA, SON, respectively. The annual bias is less than 0.05 °C for the average of the Hungarian grid points. Precipitation is overestimated by 35% in winter, 25% in spring, 5% in summer, and 3% in autumn (on average for the whole domain). Persistent drying bias occurred in the southern part of the Alps. For Hungary, the seasonal bias values are acceptable and less than 23% (except in spring, when it is 29%). The annual bias is +16% for the Hungarian grid points on average.

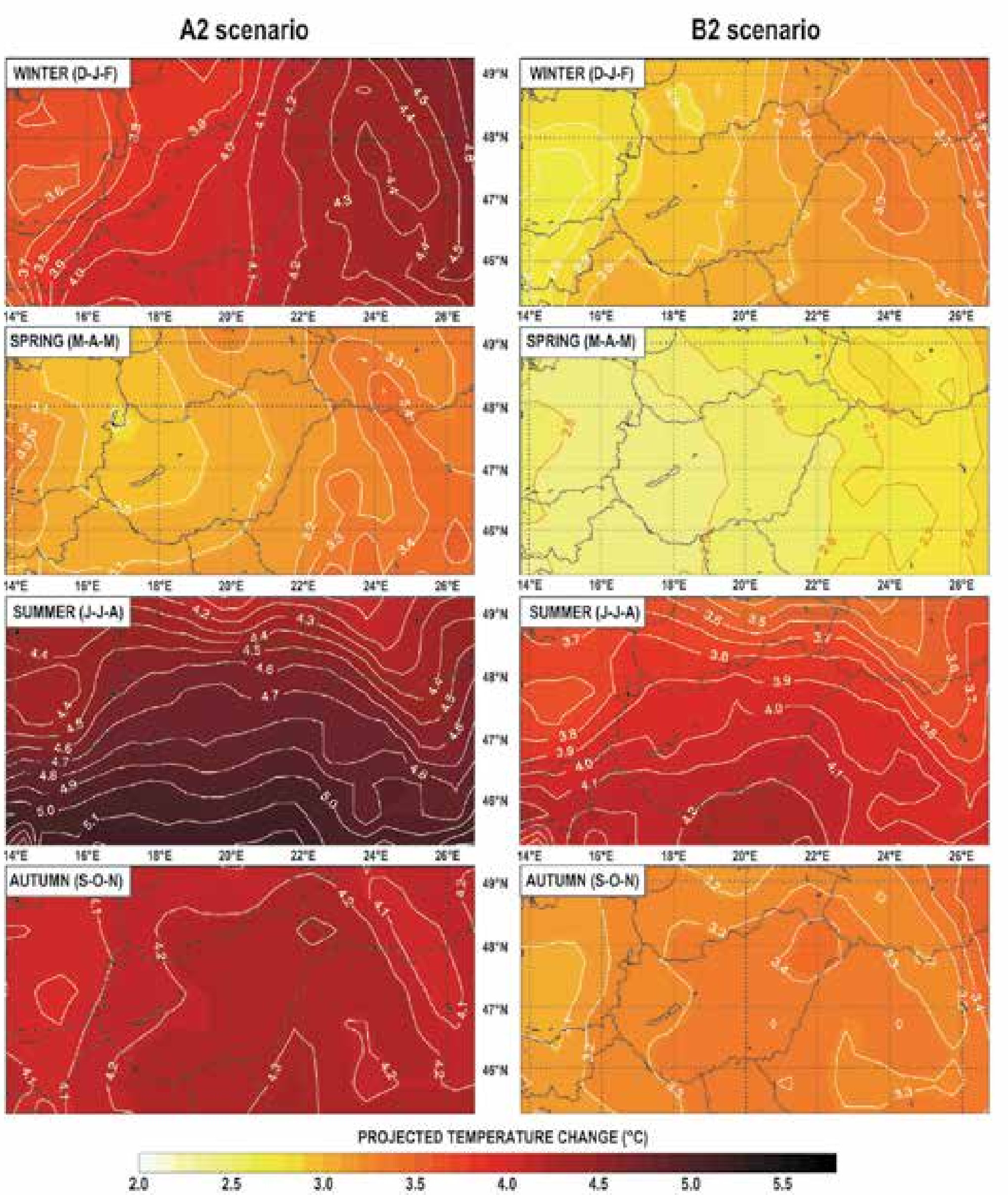
3. Projected changes of the mean climate

In order to estimate the future climatic conditions of the Carpathian Basin, composite maps of projected temperature and precipitation change are shown. Furthermore, seasonal spatial averages of projected climate change are summarized for all the grid points located in Hungary.

3.1 Temperature

The projected seasonal temperature changes for A2 and B2 scenarios are shown in Fig. 1 (left and right panel, respectively) using RCM outputs of the PRUDENCE database. Similarly to the global and the European climate change results, larger warming is estimated for A2 scenario in the Carpathian Basin than for B2 scenario. The largest temperature increase is likely to occur in summer for both scenarios, the interval of the projected increase for the Hungarian grid points is 4.5-5.1 °C (A2 scenario) and 3.7-4.2 °C (B2 scenario). The smallest seasonal increase is simulated in spring, when the projected temperature increase inside Hungary is 2.8-3.3 °C for A2 and 2.3-2.7 °C for B2 scenario.

In addition to the PRUDENCE results, PRECIS and RegCM simulations are also included in Table 2. Projected seasonal mean temperature increases by the late 21st century are calculated for the grid points located in Hungary, and can be compared. Overall, the largest and the smallest warmings are projected for summer and for spring, respectively.


A2 scenario

B2 scenario

WINTER (D-J-F)

SPRING (M-A-M)

SUMMER (J-J-A)

AUTUMN (S-O-N)

Fig. 1. Seasonal temperature change (°C) projected by 2071-2100 for the Carpathian Basin using the outputs of 16 and 8 PRUDENCE RCM simulations in case of A2 and B2 scenarios, respectively. (Reference period: 1961-1990)

Fig. 2 summarizes the projected mean seasonal warming for Hungary using the daily mean temperature simulations, as well, as the daily minimum and maximum temperature values. In general, the estimated warming by 2071-2100 is more than 2.4 °C and less than 5.1 °C for all seasons and for both scenarios.

RCM	Scenario	Winter	Spring	Summer	Autumn
PRUDENCE-composites	A2	4.0	3.1	4.8	4.2
PRECIS	A2	4.2	4.2	8.0	5.2
PRUDENCE-composites	B2	3.0	2.5	4.0	3.3
PRECIS	B2	3.2	3.1	6.0	3.9
PRECIS	A1B	4.2	3.7	6.7	5.0
RegCM	A1B	2.9	2.8	3.5	3.0

Table 2. Projected seasonal average warming (°C) for Hungary by 2071-2100 (reference period: 1961-1990)

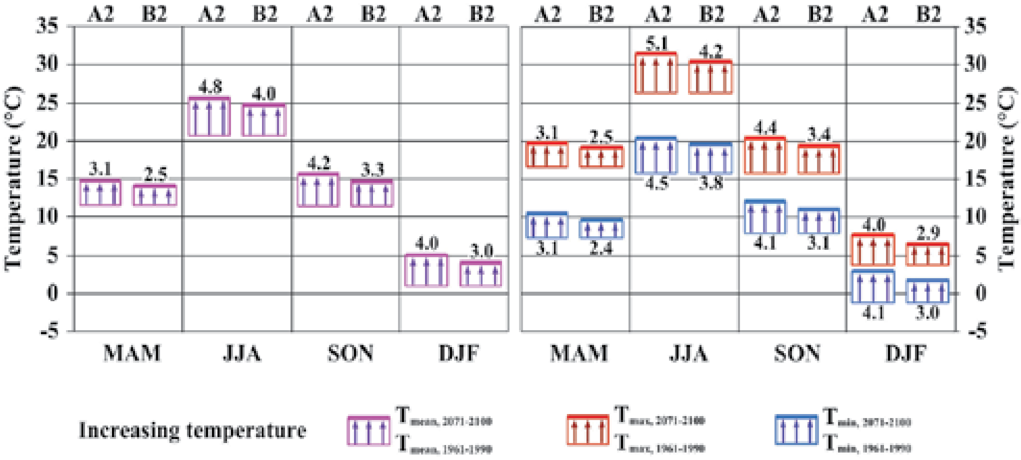


Fig. 2. Projected seasonal increase of daily mean, minimum and maximum temperature (°C) for Hungary using PRUDENCE outputs (temperature values of the reference period, 1961-1990, represent the seasonal mean temperature in Budapest on the basis of observations)

Projected temperature changes for the A2 scenario are larger than for the B2 scenarios in case of all the three temperature parameters. The smallest difference is estimated in spring (0.6-0.7 °C), and the largest in winter (1.0-1.1 °C). The largest daily mean temperature increase is projected in summer, 4.8 °C (A2) and 4.0 °C (B2), and the smallest in spring (3.1 °C for A2 and 2.5 °C for B2 scenario). Estimated increase of the daily maximum temperature exceeds that of the daily minimum temperature by about 0.1-0.6 °C (the largest is in summer). The only exception is in winter when the seasonal average daily minimum temperature is projected to increase by 4.1 °C (considering the A2 scenario) and 3.0 °C (considering the B2 scenario) – both of them are 0.1 °C larger than what is projected for the daily maximum temperature increase. The seasonal standard deviation fields (Bartholy et al., 2007) suggest that the largest uncertainty of the estimated temperature change occurs in summer for both emission scenarios.

3.2 Precipitation

Similarly to temperature projections, composites of mean seasonal precipitation change and standard deviations are mapped for both A2 and B2 scenarios for the 2071-2100 period. Fig. 3 presents the projected seasonal precipitation change for A2 and B2 scenarios (left and right panel, respectively) for the Carpathian Basin. The annual precipitation sum is not expected to change significantly in this region (Bartholy et al., 2003), but it is not valid for seasonal precipitation. According to the results shown in Fig. 3, summer precipitation is very likely to decrease in Hungary by 24-33% (A2 scenario) and 10-20% (B2 scenario). Winter precipitation in Hungary is likely to increase considerably by 23-37% and 20-27% using A2 and B2 scenarios, respectively. Moreover, slight decrease of autumn and slight increase of spring precipitation are also projected, however, neither of them is significant. Based on the seasonal standard deviation values (Bartholy et al., 2007), the largest uncertainty of precipitation change is estimated in summer, especially, in case of A2 scenario (when the standard deviation of the RCM results exceeds 20%).

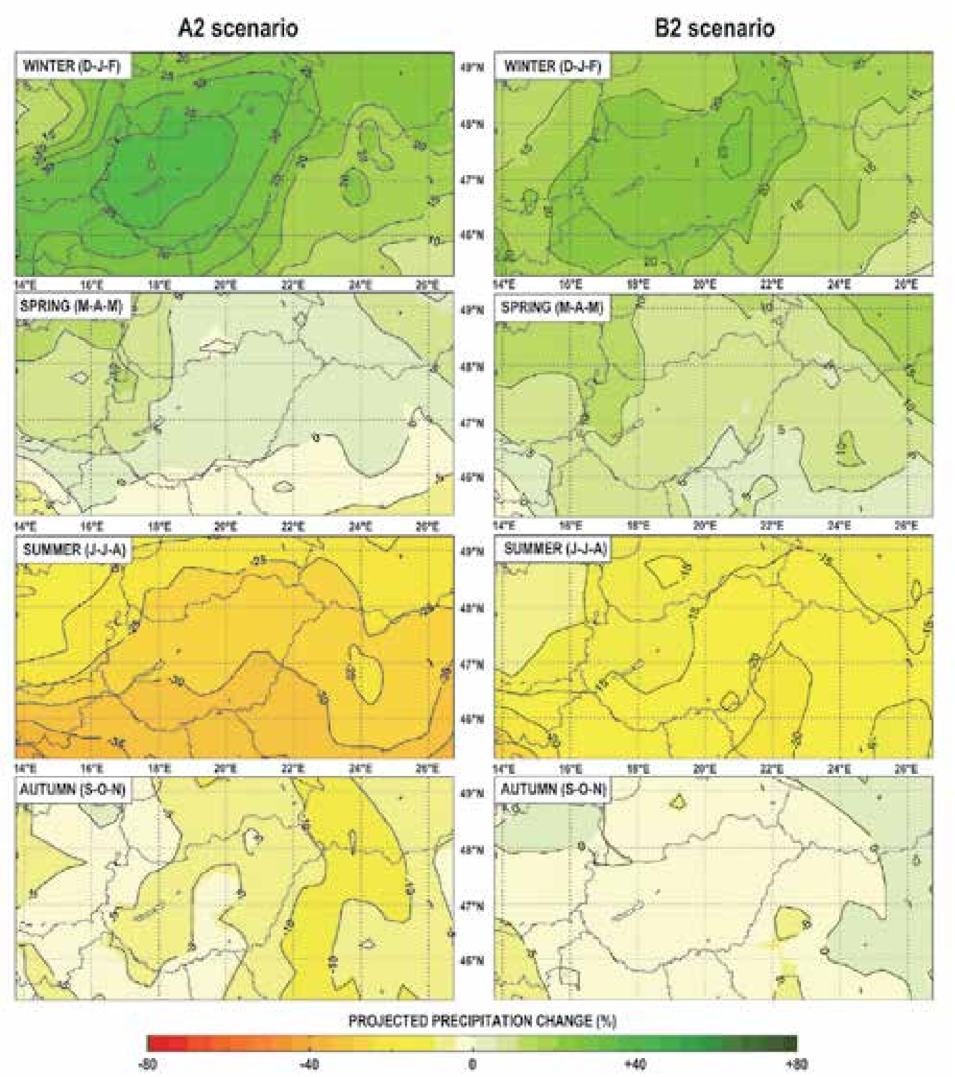


Fig. 3. Seasonal precipitation change (%) projected by 2071-2100 for the Carpathian Basin using the outputs of 16 and 8 PRUDENCE RCM simulations in case of A2 and B2 scenarios, respectively. (Reference period: 1961-1990)

Estimated seasonal mean precipitation changes by 2071-2100 on the basis of PRUDENCE results are compared to PRECIS and RegCM simulations in Table 3. The average percentage of precipitation changes are determined considering the grid points located in Hungary. Overall, different sources agree on the summer drying tendencies. Increase of precipitation in winter is also very likely in the future. Projected changes for spring and autumn are smaller than projections for the solstice seasons. Moreover, different RCMs often estimate changes to opposite direction, which highlights the large uncertainty associated to these precipitation projections.

RCM	Scenario	Winter	Spring	Summer	Autumn
PRUDENCE-composites	A2	+32	+5	-29	-7
PRECIS	A2	+14	-13	-58	-8
PRUDENCE-composites	B2	+24	+8	-15	-3
PRECIS	B2	-6	-8	-43	-18
PRECIS	A1B	+34	+5	-33	-4
RegCM	A1B	+8	-5	-18	+5

Table 3. Projected seasonal average precipitation change (%) for Hungary by 2071-2100 (reference period: 1961-1990)

The projected seasonal change of precipitation for Hungary in case of A2 and B2 scenarios are summarized in Fig. 4. Green and yellow arrows indicate increase and decrease of precipitation, respectively. According to the 1961-1990 reference period, the wettest season was summer, less precipitation was observed in spring, less in autumn, and the driest season was winter. If the projections are realized then the annual distribution of precipitation will be totally restructured, namely, the wettest seasons will be winter and spring (in this order) in cases of both A2 and B2 scenarios. The driest season will be summer in case of A2 scenario, while autumn in case of B2 scenario.

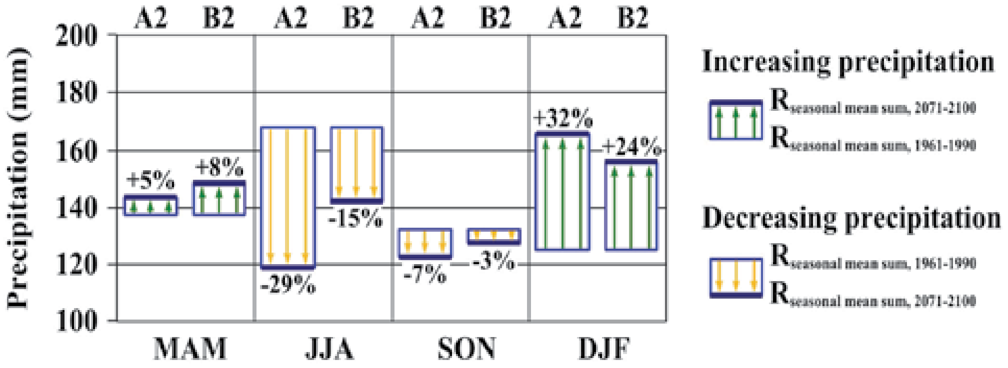


Fig. 4. Projected seasonal change of mean precipitation (mm) for Hungary using PRUDENCE outputs (increasing or decreasing precipitation is also indicated in %). Precipitation values of the reference period, 1961-1990, represent the seasonal mean precipitation amount in Budapest on the basis of observations.

On the base of the projections, the annual difference between the seasonal precipitation amounts is projected to decrease significantly (by half) in case of B2 scenario, which implies more similar seasonal amounts. The precipitation difference is not projected to change in case of A2 scenario, nevertheless, the wettest and the driest seasons will be completely changed.

4. Extremes

Regional analysis of the detected trend of different extreme climate indices for the Carpathian Basin is discussed by Bartholy & Pongrácz (2005, 2006, 2007) where the list and the definition of the indices can be found also. In this paper, the projected future trends of extreme climate indices are analyzed in the Carpathian Basin using daily temperature and precipitation outputs of four different PRUDENCE RCMs run by (i) the Danish Meteorological Institute (DMI), (ii) the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, (iii) the Royal Meteorological Institute of the Netherlands (Koninklijk Nederlands Meteorologisch Institute, KNMI), and (iv) the Swiss Federal Institute of Technology Zurich (Eidgenössische Technische Hochschule Zürich, ETHZ). For all of these simulations the boundary conditions were provided by the HadAM3H/HadCM3 (Table 1). DMI used the HIRHAM4 RCM (Christensen et al., 1996), which has been developed jointly by DMI and the Max-Planck Institute in Hamburg. ICTP used the regional climate model RegCM (Giorgi et al., 1999), which was already described in details in section 2.3. KNMI used the RACMO2 (Lenderink et al., 2003), which combines dynamical core of the HIRLAM Numerical Weather Prediction System with the physical parameterization of the European Centre for Medium-range Weather Forecasting used for the ERA-40 re-analysis project. ETHZ used the Climate High Resolution Model (CHRM) RCM described by Vidale et al. (2003). Model performances of the four selected RCMs are analyzed by Jacob et al. (2007) using the simulations of the reference period 1961-1990. Besides the A2 scenario experiments, DMI and ICTP accomplished further experiments using the B2 emission scenario. In addition to these scenarios, A1B is also considered in our analysis: the same climate indices have been determined using the RegCM simulations driven by ECHAM5 GCM (Roeckner et al., 2006).

The simulated trends of the extreme temperature indices are compared in Fig. 5 using the daily temperature outputs of the regional climate modeling experiments (both for the 1961-1990 and the 2071-2100 periods) of four different RCMs. The annual values of the indices are calculated as a spatial average of all the grid points located in Hungary, and then, the projected change is determined. According to the results, negative extremes are estimated to decrease while positive extremes tend to increase significantly. Both imply regional warming in the Carpathian Basin. The largest increase due to this warming trend can be estimated in case of extremely hot days (Tx35GE), hot nights (Tn20GT), hot days (Tx30GE) by more than 100%. In general, the simulated changes are the largest in case of the most pessimistic A2 emission scenario, for instance, the ratio to the changes estimated for the most optimistic B2 is about 1:3. The simulated warming trends of all the temperature indices are completely consistent with the detected trend in the 1961-2001 period (Bartholy & Pongrácz, 2006, 2007).

Table 4 summarizes the projected future trends of the extreme precipitation indices determined using the climate simulations of selected RCMs (i.e., HIRHAM4, RegCM, RACMO2, and CHRM) for the 1961-1990 and the 2071-2100 periods. Estimated changes of annual precipitation indices are generally consistent with the detected trends in the last quarter of the 20th century (Bartholy & Pongrácz, 2005, 2007). However, the projected regional increase or decrease is usually small (not exceeding 20% in absolute value), except

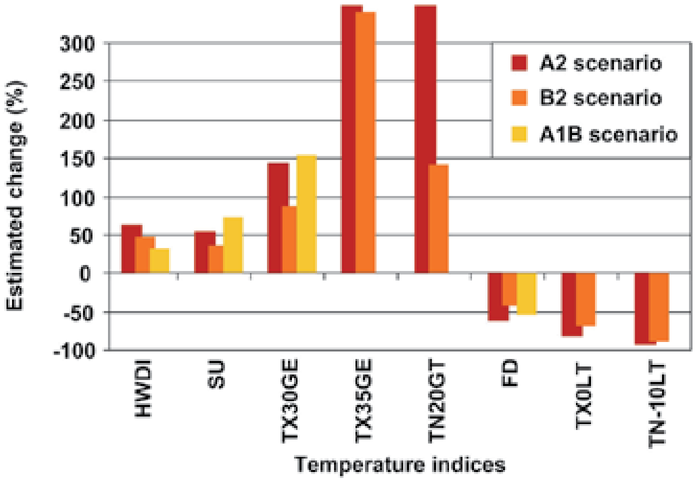


Fig. 5. Projected change of the extreme temperature indices by 2071-2100 based on the daily outputs of the regional climate models HIRHAM, RegCM, RACMO, and CHRM. Reference period: 1961-1990. HWDI is the heat wave duration index defined as for at least 5 consecutive days $T_{max} = T_{max,N} + 5$ °C, where $T_{max,N}$ indicates the mean T_{max} for the baseperiod 1961-1990. SU is the annual number of summer days defined as annual occurrences of $T_{max} \geq 25$ °C. TX30GE is the annual number of hot days defined as annual occurrences of $T_{max} \geq 30$ °C. TX35GE is the annual number of extreme hot days defined as annual occurrences of $T_{max} \geq 35$ °C. TN20GT is the annual number of hot nights defined as annual occurrences of $T_{min} \geq 20$ °C. FD is the annual number of frost days defined as annual occurrences of $T_{min} < 0$ °C. TX0LT is the annual number of winter days defined as annual occurrences of $T_{max} < 0$ °C. TN-10LT is the annual number of severe cold days defined as annual occurrences of $T_{min} < -10$ °C.

Precipitation index	A2			B2			A1B		
	year	January	July	year	January	July	year	January	July
Rx1 (R_{max})	+17%	+29%	–2%	+13%	+23%	–5%	+14%	+13%	+4%
Rx5 ($R_{max,\ 5\ days}$)	+10%	+26%	–11%	+11%	+17%	–11%	+10%	+10%	–5%
SDII (R_{year}/RR1)	+10%	+16%	+13%	+7%	+12%	+1%	+12%	+13%	+10%
RR20 ($R_{day} \geq 20$ mm)	+60%	+233%	+66%	+68%	+212%	–24%	+49%	+69%	+36%
RR10 ($R_{day} \geq 10$ mm)	+14%	+95%	–11%	+20%	+58%	–14%	+22%	+32%	+20%
RR1 ($R_{day} \geq 1$ mm)	–10%	+19%	–31%	–2%	+6%	–19%	–13%	–5%	–25%

Table 4. Projected change of extreme precipitation indices (2071-2100) based on the daily outputs of the regional model HIRHAM, RegCM, RACMO, and CHRM (reference period: 1961-1990). In case of A1B scenario, only RegCM outputs are considered. Rx1 and Rx5 are the largest 1-day and 5-day precipitation totals, respectively. SDII is the simple daily intensity index defined as the ratio of the total precipitation sum and the total number of precipitation days exceeding 1 mm. RR20, RR10, and RR1 are the numbers of precipitation days exceeding 20 mm, 10 mm, and 1 mm, respectively.

of RR20, the number of very heavy precipitation days. Much larger positive and negative changes are projected in January and in July, respectively, on the base of the RCM simulations. These results suggest that the climate tends to be wetter in winter in the Carpathian Basin. The summer precipitation is likely to become less frequent and overall drier but more intense by the end of the 21st century, which is highlighted by the positive estimated changes of SDII (by +13%, +1%, and +10% in case of A2, B2, and A1B scenarios, respectively).

5. Estimated trends of empirical distributions of monthly climate anomalies

Besides the projected future trends of mean values and extreme indices, distributions and empirical probabilities are also analyzed for the period 2071-2100 (compared to 1961-1990, as a reference period) using fine resolution RCM (i.e., PRECIS and RegCM) simulations.

Fig. 6 compares the seasonal projections of monthly anomalies exceeding 4 °C to the observed datasets. In the past, such large monthly anomalies occurred extremely rarely, only in the winter months when the temperature variability is the largest during the year. For the future all simulations project significant increase in the occurrences of these largely warm conditions relative to the past climate.

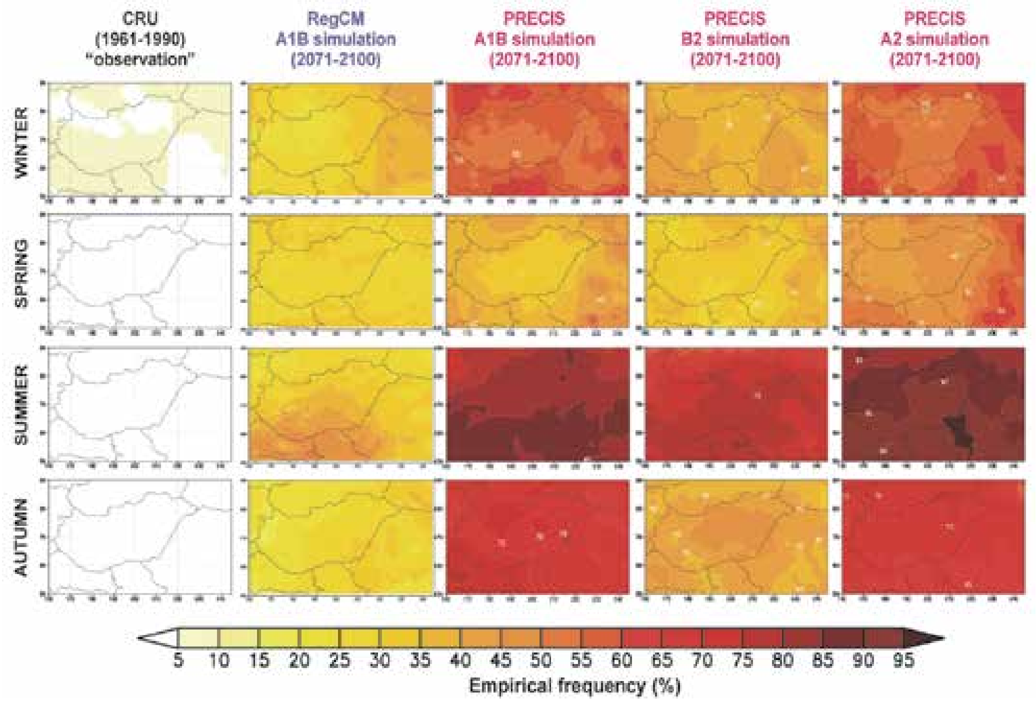


Fig. 6. Projected occurrence of monthly temperature anomalies exceeding +4 °C relative to the 1961-1990 mean values in the four seasons.

Overall, PRECIS simulations suggest larger increase than RegCM simulations, which is in good agreement with the projected mean annual and seasonal warming of the RCMs. In case of all the regional scenarios, summer frequency increase is the largest. PRECIS simulations suggest that the empirical frequency of at least 4 °C monthly temperature anomalies in Hungary exceeds 70%, 80%, and 85%, for B2, A1B, and A2 scenario, respectively.

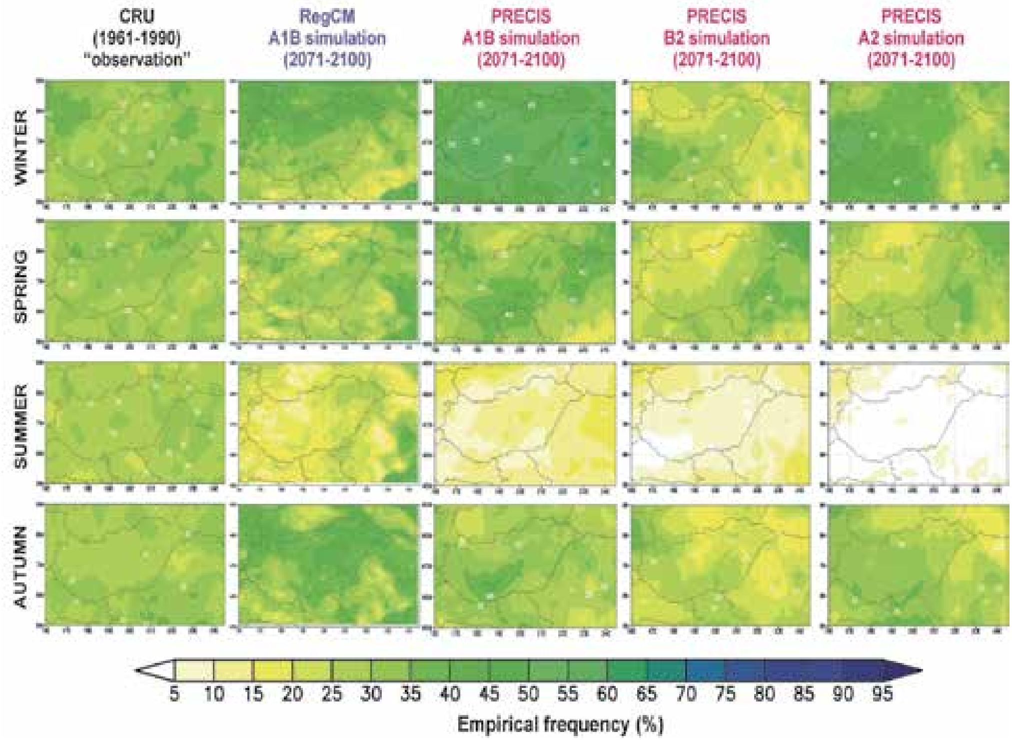


Fig. 7. Projected occurrence of wet monthly precipitation anomalies exceeding +20% relative to the 1961-1990 mean values in the four seasons.

Figs. 7 and 8 compare the seasonal occurrences of monthly precipitation anomalies exceeding +20% (implying wetter than normal climatic conditions) and –20% (implying drier than normal climatic conditions), respectively, to the CRU observations.

Since precipitation has a large variability both in time and space, projected changes in most of the seasons are not significant. Nevertheless, wetter conditions in summer tend to decrease by the end of the 21st century in case of all regional scenarios. In the past, 1961-1990, wet anomalies (shown in Fig. 7) occurred in 25-30% of all the summer months in Hungary. According to the RCM simulations this occurrence will likely to decrease considerably. PRECIS simulations project larger decrease by 2071-2100 than RegCM simulations. RegCM outputs suggest that the empirical frequency is likely to become 10-20% in the western part of the country, whereas 25-30% in the eastern regions. PRECIS simulations suggest that the occurrence frequencies of at least 20% monthly precipitation anomalies in Hungary is not likely to exceed 10%, 15%, and 5%, for B2, A1B, and A2 scenario, respectively.

In the meanwhile, dry climatic conditions (shown in Fig. 8) in summer are likely to occur more often in the future (on the basis of the observations, empirical frequency of monthly precipitation anomalies exceeding –20% is 30-40%). Again, PRECIS simulations suggest larger increase than RegCM simulations. According to the PRECIS outputs, the projected occurrence frequency is likely to at least double by 2071-2100 relative to 1961-1990. Maps on both Fig. 7 and Fig. 8 agree on the future summer drying of the Carpathian Basin, which is also supported by the projected mean precipitation changes (analyzed in section 3.2). In the other seasons, projected occurrence frequency is not likely to change significantly.

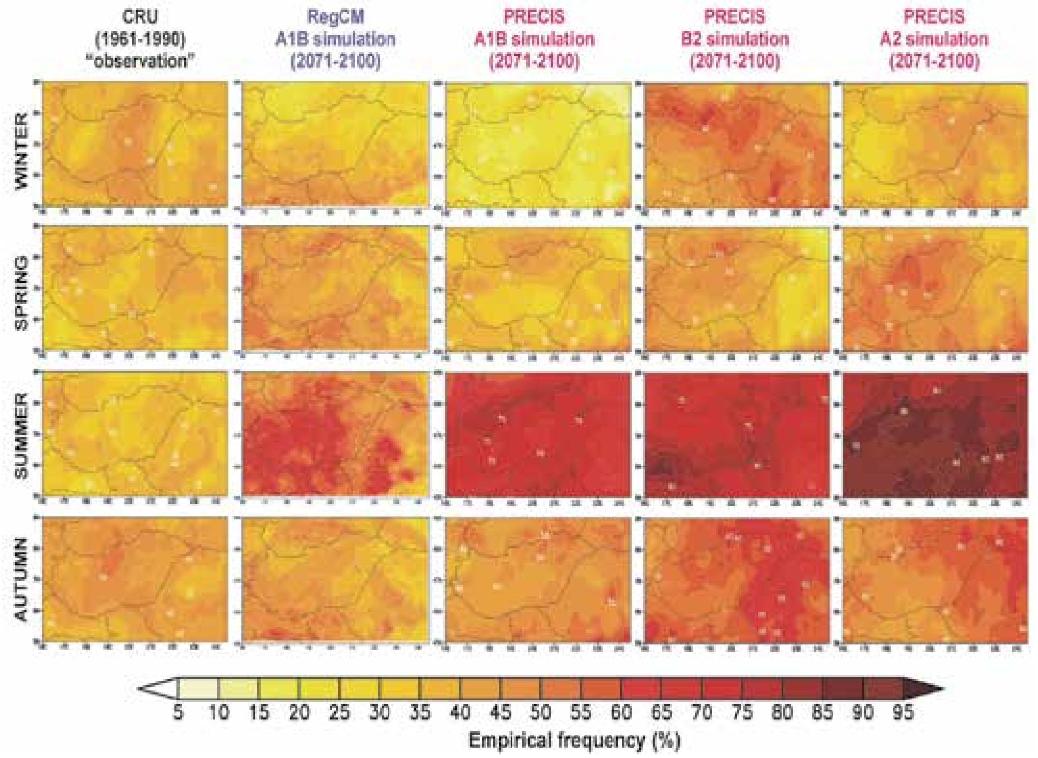


Fig. 8. Projected occurrence of dry monthly precipitation anomalies exceeding –20% relative to the 1961-1990 mean values in the four seasons.

6. Conclusion

Regional climate change trends in the Carpathian Basin (and especially in Hungary) have been assessed in this paper. For this purpose RCM model simulations from PRUDENCE (19 experiments with 50 km horizontal resolution), PRECIS (3 experiments with 25 km horizontal resolution), and RegCM (1 experiment with 10 km horizontal resolution) have been used. Regional consequences of three different emission scenarios have been evaluated, namely, SRES A2, A1B, and B2.

On the basis of the results presented in this paper the following conclusions can be drawn.

1. In the future, the largest mean temperature increase in the Carpathian Basin is likely to occur in summer (3.7-5.1 °C relative to the 1961-1990 reference period). The smallest seasonal increase is simulated in spring (2.7-3.3 °C).
2. The largest warming is estimated for A2 scenario, which is the most pessimistic global emission scenario among the three analyzed here.

3. Opposite changes are projected for seasonal precipitation in the Carpathian Basin. The summer precipitation is very likely to decrease by about 10-33%, whereas winter precipitation tends to increase considerably by 20-37%.
4. In the 1961-1990 reference period, the wettest season was summer, less precipitation was observed in spring and autumn (in this order), and the driest season was winter. RCM simulations projects that the annual distribution of precipitation may be totally restructured resulting in winter/summer becoming the wettest/driest season, which is the opposite of recent climatic conditions.
5. RCM simulations project that the negative temperature extreme indices are likely to decrease in the future, whereas the positive temperature extreme indices tend to increase significantly. Both imply regional warming in the Carpathian Basin.
6. Analysis of precipitation indices suggests that the climate in the Carpathian Basin tends to be wetter in winter. The summer precipitation is likely to become less frequent and overall drier but more intense by the end of the 21st century.
7. The seasonal occurrences of monthly temperature anomalies exceeding +4 °C are projected to increase significantly, the largest changes are estimated in summer (the seasonal occurrences are likely to exceed 70% by 2071-2100).
8. Future summer drying of the Carpathian Basin is very likely. Occurrences of summer monthly precipitation anomalies exceeding +20% (implying wetter than normal climatic conditions) are projected to decrease by 2071-2100 relative to 1961-1990, whereas occurrences of summer monthly precipitation anomalies exceeding –20% (implying drier than normal climatic conditions) are projected to increase.

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2

An Improved Dynamical Downscaling for the Western United States

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1. Introduction

A quantitative assessment of climate change impacts on water management depends heavily on the knowledge of basic climate variables, such as precipitation and temperature, and how they might change over time. The approach of dynamical downscaling – nesting regional climate models (RCMs) within general circulation models (GCMs) – has shown promise in producing climate information at scales useful to e.g. water managers (Leung et al. 2006). Organized efforts such as the European project PRUDENCE (Christensen et al. 2007) and the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009) have demonstrated the value of dynamical downscaling on regional climate projections. However, a significant degree of uncertainty in regional downscaling still exists. The uncertainties are more so in mountainous and drought-prone regions such as the western United States (U.S.) (Lo et al. 2008), as this region of the U.S. is projected to experience significant warming and precipitation reduction that portend a drying climate scenario (IPCC 2007). Hence, an assessment of climate projection uncertainties is paramount.

The western U.S. relies both economically and socially on the development of winter mountain snowpack and the timely release of its retained water (Gleick and Chalecki 1999). Decreasing and early melting of the snowpack across the western U.S. have occurred during the past century (Cayan et al. 2001; Pierce et al. 2008) and are expected to continue due to a warming climate (McCabe and Wolock 1999; Leung et al. 2004). RCMs are envisaged to be a crucial tool to simulate future projections at finer scales. However, a recent analysis on change in snow property (Gillies et al. 2011) have noted that most NARCCAP models tend to produce persistent cold biases in the surface over the western U.S., thus leading to an overestimation of the snowfall and the snow depth. Analyzing several mesoscale forecast models, Coniglio et al. (2010) have observed similar cold biases in daily minimum temperature, which are attributable to the models' inability to break down the morning inversion layer quickly enough. Such cold biases are most serious in the interior West. While temperature biases alone may be corrected by statistical methods, these documented cold biases in RCMs can and do alter the climate projections; this is because the amount of available water in the atmosphere is also a function of evapotranspiration, which changes exponentially with temperature variations (Nash and Gleick 1993). Moreover, the impacts of such temperature biases on many derived variables (such as snow) cannot be statistically corrected in the downscaling.

Precipitation simulation has been a challenge in the western U.S. as well. A study by Wang et al. (2009) (hereafter WGTG) examined the precipitation seasonal and interannual variabilities simulated by six RCMs that participated in NARCCAP (models described in Figure 1). The results of WGTG indicated that all the models driven by reanalysis data persistently overestimated the winter precipitation amounts but underestimated summer precipitation amounts. Such biases, which are consistent with those found in other simulations over the western U.S. (Leung et al. 2004; Caldwell et al. 2009; Qian et al. 2010), result in a severe distortion of the seasonal cycle, particularly over regions that are further inland (cf. areas B, C, & D in Figure 1). For instance, the distinct semi-annual variation of the Wasatch Range (area B) was simulated as a winter-dominant annual cycle by all models, while the dry spring and wet summer in the Colorado Rockies (area C) were portrayed erroneously as wet spring and dry summer in 3 out of 6 models. Among these common biases, the monsoon rainfall (area D) was severely underestimated by 5 models resulting in an incorrect winter-predominant precipitation regime. WGTG further showed that the overprediction in the winter precipitation leads to a "false association" with the El Niño-Southern Oscillation (ENSO) while in reality, the ENSO-precipitation correlation is quite low in this region (e.g., Dettinger et al. 1998). What is more, recent observational studies (e.g., Anderson et al. 2010) point out that the summer precipitation in southwest U.S. has increased over the past half century and is associated with a broader coverage through enhanced monsoon rainfall. However, such an observation contradicts the projected decrease in summer precipitation over the same region by the IPCC (2007). Given the ubiquitous RCM biases in the monsoon rainfall – as is evident in Figure 1 – the reliability of climate projections downscaled from RCMs remains highly uncertain.

The challenge in regional downscaling is further exemplified by the projected changes in winter precipitation over the western U.S. (Figure 2) simulated by two NARCCAP models: the Canadian RCM (left) and the UC-Santa Cruz RCM3 (right), both of which are downscaled from the Canadian GCM Version 3. Despite apparent agreement in precipitation changes at higher latitudes, the downscaled results for the subtropics and monsoon affected regions are noticeably different between the two models, particularly in the Southwest. In this region, the CRCM simulated an overall increase in winter precipitation, while the RCM3 simulated much less of an increase and even has some areas experiencing a decrease. Since these projections were forced by the same GCM boundary conditions, their discrepancies pose a concern regarding the extent to which climate change scenario is representative. Such discrepancies are compounded further when it comes to the evaluation of RCMs downscaled output. Conventional detection and attribution methods (e.g., Hegerl et al. 2006) are generically developed from signal processing and so, require a large number of simulations to generate ensemble means; this requires a significant capacity in computing resources. At present, few operational institutions are capable of this level of computation and data storage. Thus, a more efficient performance measure is needed to evaluate simulation discrepancies as has been revealed in Figures 1 and 2.

While ongoing efforts continue to improve the physics schemes in RCMs, a different set of challenge lies in the inherent biases of the GCM forcing data. That is, even if an RCM can produce a realistic regional climate when driven by observations, any biases in the parent

GCM will inevitably distort the downscaled climate (e.g., Lo et al. 2008). An example from our recent in-house study shows just such an effect (Figure 3): the reanalysis-driven simulation of the Weather Research and Forecasting (WRF) model produced a realistic temperature downscaling over the western U.S. (Figures 3a and 3b); however, temperature downscaled from a GCM revealed widespread cold biases (Figure 3c). Similar temperature biases were also reported by Caldwell et al. (2009).

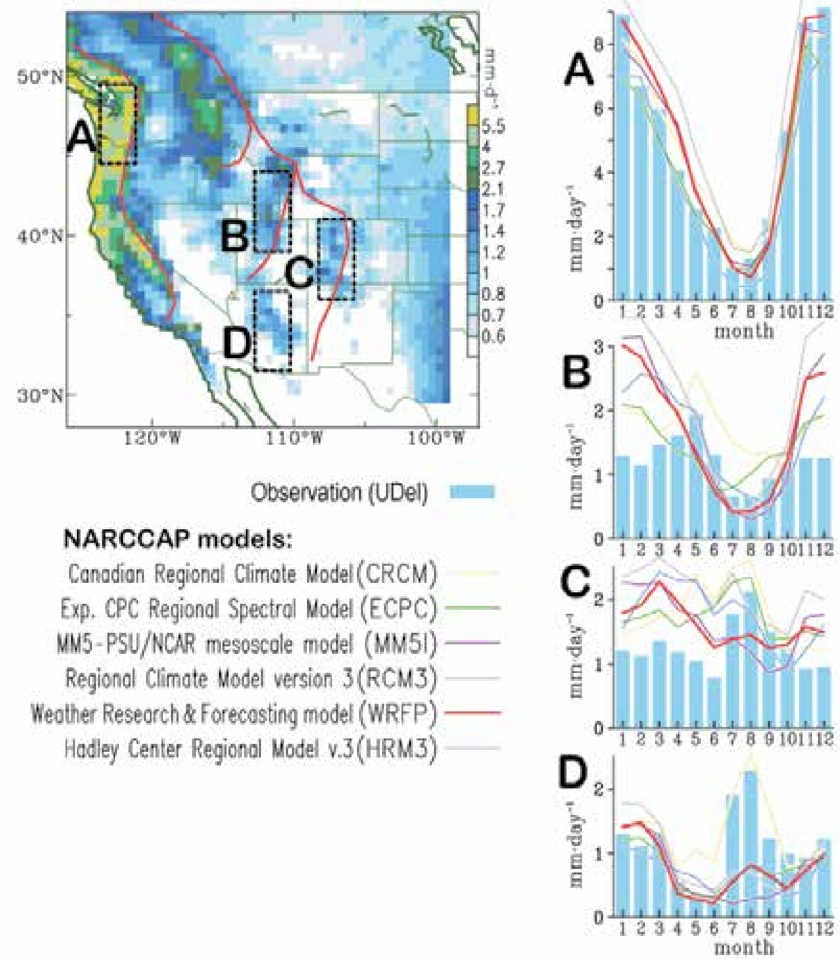

Fig. 1. Cold season (Nov-May) precipitation distribution and monthly observed (bar) and simulated (lines) precipitation at four designated areas. Modified from Wang et al. (2009).

These results strongly suggest that realistic regional downscaling is only achievable with a calibrated RCM driven by an un-biased GCM forcing. In this chapter, we propose an economic and efficient method to reduce uncertainties in climate projections, with a specific focus on the western U.S. Model settings and data sources necessary for developing this method are introduced in Section 2. Simulation design is outlined in Section 3. Results and discussions are presented in Section 4. A summary and some conclusions are given in Section 5.

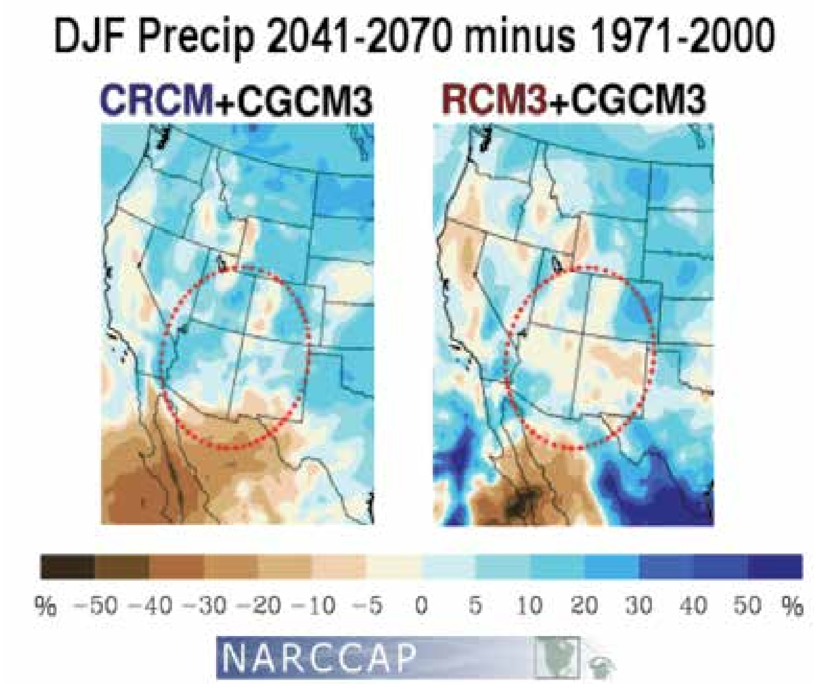

Fig. 2. Difference of winter precipitation in percentage between periods of 2041-2070 and 1971-2000 downscaled from CGCM3 by CRCM (left) and RCM3 (right) of the NARCCAP. The Southwest region with large discrepancy is circled.

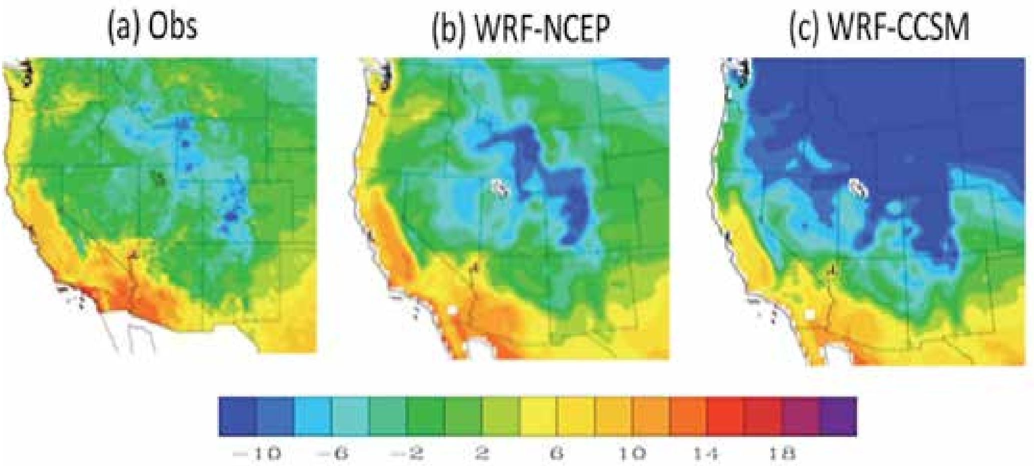

Fig. 3. Surface temperature (°C) in December 1999 from a) PRISM (Parameter-elevation Regressions on Independent Slopes Model) data (4 km), b) coupled WRF-CLM simulations driven by the National Centers for Environmental Prediction reanalysis data I (NCEP-1) (30 km), and c) WRF-CLM simulations driven by CCSM (30 km).

2. Model and data sources

We used the latest version WRF model (version 3.2) for the dynamical downscaling. Figure 4 shows the simulation domain centered over the western U.S. but also covering adjacent areas including the Pacific. We decided upon a 30 km resolution to better account for the complex terrain of the region, but at the same time comparable to the 50 km resolution of NARCCAP. The WRF model was configured with 28 vertical sigma layers from the surface to the 50 hPa level. In addition, the WRF model was coupled to the Community Land Model version 3.5 (CLM), hereafter WRF-CLM. The CLM was designed to describe snow, soil, and vegetation processes for global and regional applications (Bonan et al. 2002; Jin et al. 2010a, b); this latest version includes a 5-layer snow scheme, a 10-layer soil scheme, and a single layer vegetation scheme. The vegetation involves solar radiation reflected and absorbed by the canopy as well as its transfer within the canopy (Sellers 1985). Up to 10 sub-grids per model grid are included in CLM to represent sub-grid heterogeneity of the land surface. The surface is classified into 24 land categories, including different types of vegetation, bare soil, oceans, lakes, wetlands, and glaciers. The soil layer is divided into 19 categories defined as percentages of sand and clay.

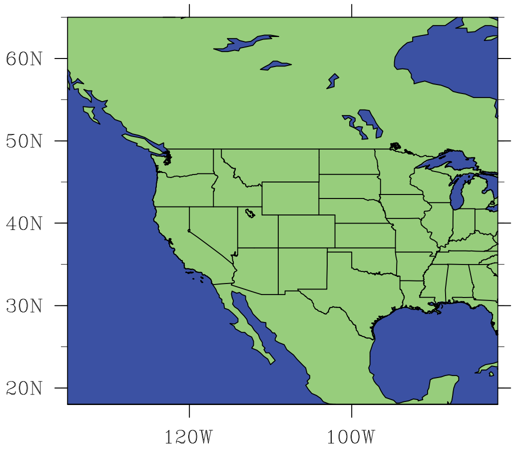

Fig. 4. Proposed simulation domains for the WRF model at 30 km resolution.

Reanalysis to drive the WRF model was obtained from the National Centers for Environmental Prediction-Department of Energy Global Reanalysis II (NCEP-2; Kanamitsu et al. 2002) available 1979-present. The GCM to drive the WRF model is the Community Climate System Model (CCSM) used in the IPCC Fourth Assessment Report. Other observational data sets used in this study included monthly $0.5^{o} \times 0.5^{o}$ gridded precipitation and temperature (Legates and Willmott 1990), the North American Regional Reanalysis at a 32-km resolution (NARR; Mesinger et al. 2006), and 4-km precipitation and temperature data from the PRISM.

For downscaling evaluations, we used the NARCCAP output. NARCCAP's six RCMs (including WRF) were driven by NCEP-2 reanalysis and a set of atmosphere-ocean general circulation models (AOGCMs) over a domain that covers the continental U.S. and much of Canada. The AOGCMs (including CCSM) were forced with the A2 Emissions Scenario which has cumulative CO_2 concentrations projected to be around 575 ppm by the middle of the 21st century. Reanalysis-forced simulations were also produced for the period 1979-2004; those simulations were analyzed by WGTG. For climate downscaling, the RCMs are nested in the AOGCMs for the historical period 1971-2000 and for a future period 2041-2070. All the RCMs were run at a spatial resolution of 50 km. For details about NARCCAP see Mearns et al. (2009) and their website at http://www.narccap.ucar.edu/.

3. Simulation framework

To assess the range of projection uncertainties in regional downscaling, we conducted (1) a physics-calibrated RCM that was forced by (2) a set of bias-corrected GCM data, (3) to produce a set of calibrated/corrected downscaling data, and (4) to evaluate this data set with control simulations as well as the NARCCAP output. These approaches are illustrated schematically in (Figure 5) and are detailed further.

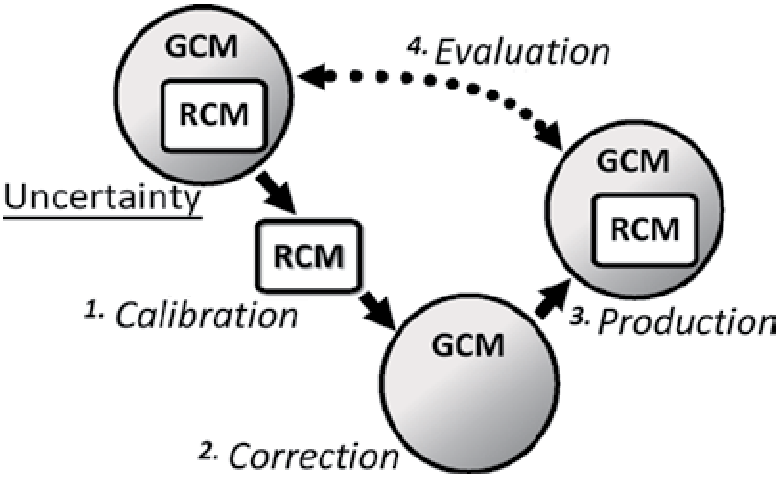

Fig. 5. Schematic illustration of the simulation framework.

(1) WRF model calibration and validation

Winter precipitation is primarily a large-scale process linked more closely to cloud microphysics than cumulus convection (Grubišić et al. 2005; Yuan et al. 2008), while summer monsoonal precipitation is mainly a cumulus convection process and is sensitive to the microphysics involved (e.g., Yang et al. 2009). Consequently, treatments to suppress any excessive winter precipitation often results in loss of summer precipitation; likewise, methods to increase summer convective rainfall can easily enhance the already overestimated winter precipitation. With this challenge in mind, we calibrated the WRF model by first obtaining the best microphysics scheme for winter and second, tested the cumulus convective schemes for summer but retaining the selected microphysics scheme in winter. The purpose was to correct the biases in seasonal precipitation in order to simulate an accurate annual cycle.

(2) CCSM output bias correction

In order to reduce the impact of GCM biases on regional downscaling, any GCM forcing data can be "corrected" prior to being used to drive any dynamic downscaling. The goal here is to have the CCSM output to approximate the reanalysis data so that the calibrated WRF-CLM can achieve consistent performance when driven by the CCSM. An initial step for a bias correction was to apply statistical downscaling techniques on the CCSM forcing data. Statistical downscaling generally consists of (a) the development of statistical relationships between observed climate variables and large-scale predictors, and (b) the application of such relationships to the GCM output (Wilby et al. 1998). Here, we modified the technique somewhat by developing a regression model for each variable between the CCSM and the reanalysis towards eliminating their climatological differences. This type of analysis generates a set of "climatologically viable" CCSM data to force WRF-CLM.

(3) Downscaling for the western U.S.

Using the calibrated WRF-CLM forced by corrected CCSM boundary conditions, we produced regional climate simulations for the western U.S. Three sets of data were generated: (a) those driven by reanalyses, b) those driven by the original CCSM, and (c) those driven by the climatologically corrected CCSM. These three sets of simulations were evaluated against each other and with observations. A comparison with NARCCAP outputs ensue to provide an uncertainty assessment.

4. Results

4.1 WRF-CLM calibration and validation

Through Fourier analysis, WGTG decomposed the seasonality of western US precipitation into an annual cycle (1st harmonic) and a semiannual cycle (2nd harmonic). These annual and semiannual precipitation cycles were subjected to Empirical Orthogonal Function (EOF) analysis, obtaining two leading modes for each cycle. In the annual cycle, EOF1 and EOF2 represent a winter-summer seesaw and a spring-fall oscillation, respectively. The winter-summer seesaw depicts a precipitation pattern divided by the Rocky Mountains, reflecting the seasonal march of upper-level winds interacting with the orography. The spring-fall oscillation and the semiannual cycle both reveal an oscillating dipole between the northwest and the southwest; the latter cycles are particularly sensitive to convective precipitation. Figure 6 shows the results from the NARCCAP simulations depicting the combined spring-fall and EOF1-semiannual modes (left) of precipitation in Colorado (area C in Figure 1), in comparison to the EOF2-semiannual mode (right). It is apparent in Figure 6 that most models produced a distorted seasonal cycle due to an overly strong spring-fall oscillation and an out-of-phase semiannual cycle; the WRF model was among them.

Winter precipitation overprediction over terrain has been a common deficiency within many Bulk Microphysical Parameterization schemes (BMPS), because most BMPS treat snow and graupel as two separate categories without partial riming within the cloud; correcting this error would help improve the amounts of cloud water and reduce the surface precipitation over windward slopes (Colle and Lin 2010). We have found through various experiments that cumulus parameterization schemes (CPSs) have very little impact on winter precipitation amounts in the western US. Thus, we focused on the microphysics coupled with the WRF model and selected one that is most effective in reducing the overprediction of precipitation. After obtaining the optimal microphysics scheme for winter precipitation it was used for sensitivity testing of CPSs for summer precipitation. By experimenting with the full combination of BMPS and CPSs available in WRF-CLM, we selected the Morrison 2-moment BMP (Thompson et al. 2008) that reduces the most of the overprediction bias. We also found that the Grell-Devenyi ensemble CPS – a multi-closure, multi-parameter, ensemble method (Grell and Devenyi 2002) – most accurately reflected the summer precipitation in the Southwest monsoon region. The inclusion of CLM also improves the precipitation simulation in the western U.S., as has been shown in Jin et al. (2010a, 2010b).

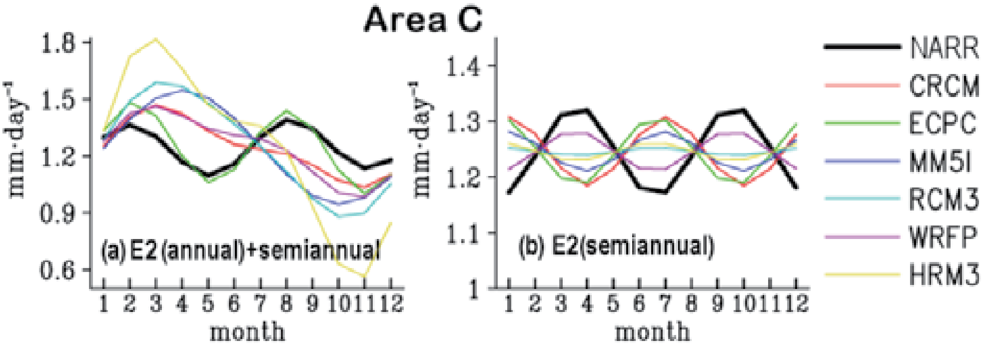

Fig. 6. Precipitation reconstructions in area C (Fig. 2) from the combined spring-fall mode and the first semiannual mode (left) and second semiannual mode. Modified from Wang et al. (2009).

To illustrate the calibration effectiveness, we present the result in 2008. The control run was forced by the NCEP-2 with the same physics packages as the NARCCAP WRF, denoted as WRF(Ctrl). Figure 7 shows the monthly precipitation of WRF(Ctrl) over the Wasatch Range (area B in Figure 1) and northern Arizona (area D). Compared to the observations (blue histograms), precipitation biases similar to those in Figure 1 still prevail – overestimation in cold-season amounts and underestimation in warm-season amounts. Next we applied the calibration, denoted as WRF(Exp). Except for the optimal BMPS and CPS settings and the coupling with CLM, the rest of model parameters (e.g., land surface physics and boundary layer schemes) remained the same as in WRF(Ctrl). As shown in Figure 7 (red lines), precipitation in WRF(Exp) already reveals a marked improvement towards a more accurate seasonal variability where reduced winter precipitation and the enhanced summer (monsoon) rainfall are more adequately simulated. A further improvement is revealed in the summer daily precipitation events. As shown in Figure 8 (left) across 37°N, pronounced diurnal rainfall episodes occurred during 4-12 August 2008. However, the diurnal rainfall signal is very weak in WRF (Ctrl) resulting in less than a half of the observed amounts falling over the terrain (middle). But this is remedied by WRF(Exp) substantially increases the diurnal rainfall leading to a more realistic seasonal distribution (right). The precipitation frequency is also enhanced.

4.2 Forcing data correction and WRF simulations for the western U.S.

In previous analysis (Figure 3), we saw that WRF-CLM could produce reasonably accurate simulations if forced with the reanalysis data. However, when the model is forced with CCSM data it generated unrealistic simulations that were obviously biased. To reduce the bias, which in this case was inherited from the CCSM, we developed a set of statistical functions between the forcing variables in CCSM and NCEP-2. These statistical functions covered various timescales including a diurnal range (6 hr data), season and annual cycles, and climate mean state. The training period for the statistical functions is 1979-1999. The statistical functions followed those used in Dettinger et al. (2004) and Miller et al. (2008). The point to note is that the differences between CCSM and NCEP-2 are minimized based upon bilinear regression parameters that were derived during their training period.As an example, Figure 9 shows the regression-corrected CCSM annual temperature and precipitation in the southwestern U.S. (42^oN 114.3^oW, 32^oN 102^oW) versus the original simulation. The original CCSM appears to overestimate the trends in both temperature and precipitation. However, the statistically corrected temperature and precipitation time series are in good agreement with the PRISM data during the historical period (1895-1999), a result we consider to enhance the reliability of future projections (2000-2099), which are being generated for further studies. We then applied this regression-based correction method to all variables in the CCSM used to force WRF-CLM. These variables included air temperature, moisture, geopotential height, wind, and sea surface temperature, all of which were updated at a 6-hour frequency.

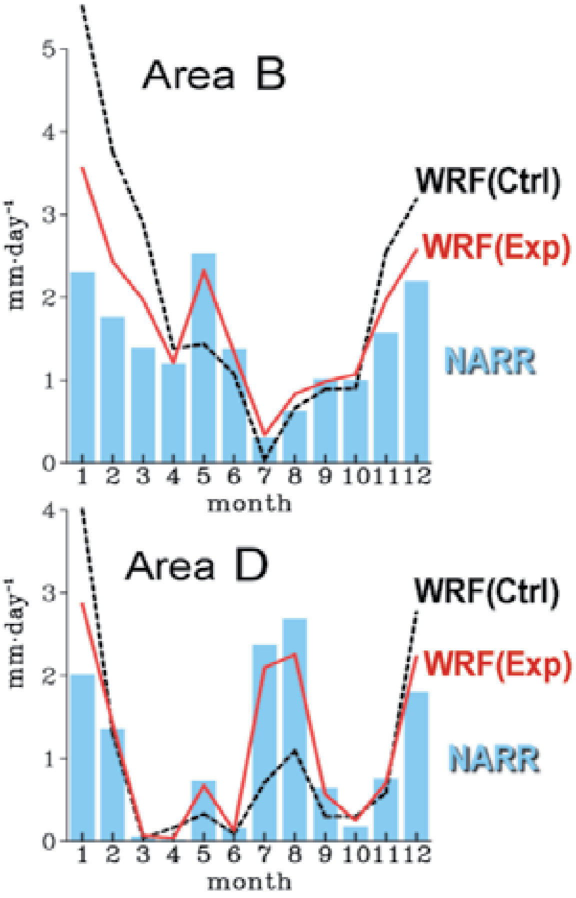

Fig. 7. Monthly precipitation of 2008 in areas B and D from the observation (bars), WRF(Ctrl) (black dashed line), and WRF(Exp) (red solid line). The observation here uses the North American Regional Reanalysis (NARR).

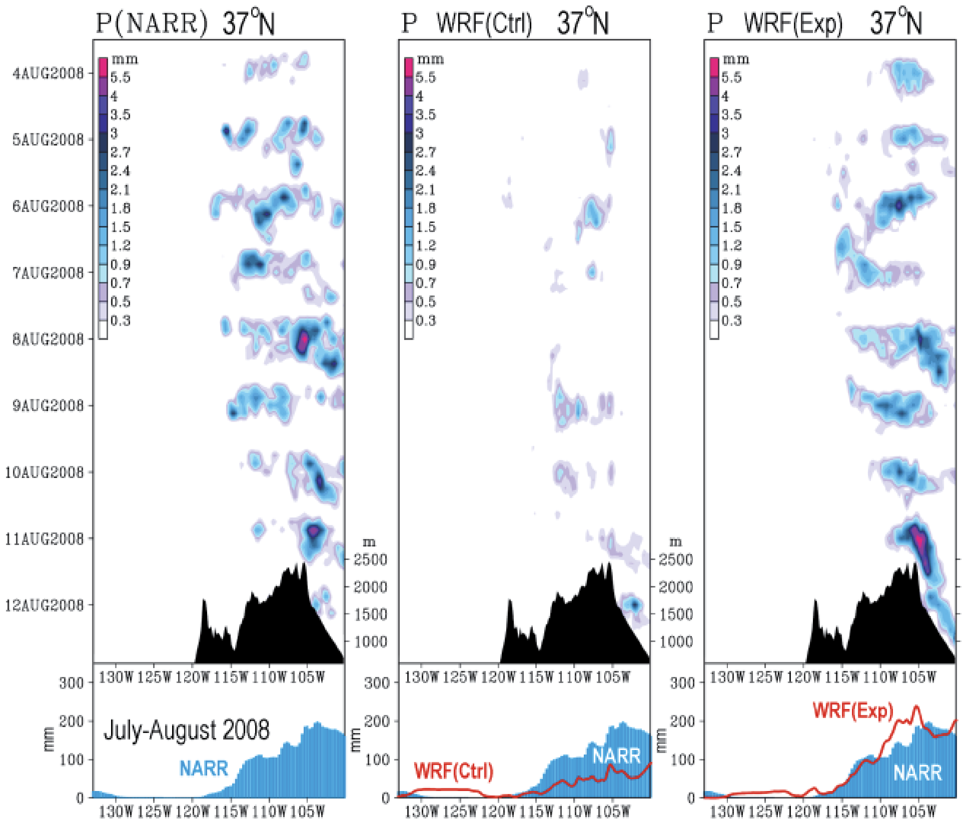

Fig. 8. Longitude-time cross sections of precipitation averaged at 37-40°N from 3 August to 12 August 2008 with the July-August accumulation (bottom), derived from the NARR (left), WRF(Ctrl) (middle), and WRF(Exp) (right). Terrain is illustrated as black shadings.

Figure 10 shows the winter (December-February) precipitation for the western U.S. averaged over the period 1989-1999, including two sets of gridded observations: PRISM (Figure 10a) and the University of Delaware data (Figure 10b). Note that even these observations exhibit some apparent differences, especially at high elevations over mountain ranges along the Rockies. Nevertheless, the WRF simulation forced with the NCEP-2 data (Figure 10c) is in good agreement with both observation data sets, with an average bias of 26 mm/month over the entire simulation domain compared to PRISM. However, when the same WRF-CLM is forced with the original CCSM output, the model severely overestimates the precipitation and the domain-wide averaged bias doubles to 59 mm/month. This difference clearly demonstrates the inherited biases from the CCSM forcing data – biases that are difficult to diagnose. After correcting the CCSM forcing data through the aforesaid statistical functions, the result (Figure 10e) exhibits a marked improvement – the domain-averaged bias was reduced to 31 mm/month.

4.3 Long-term trend in the Western U.S.

The reanalysis-driven calibration simulation for the period 1979-2004 (in line with NARCCAP) is promising in the context of the provision of useful assessments for projection

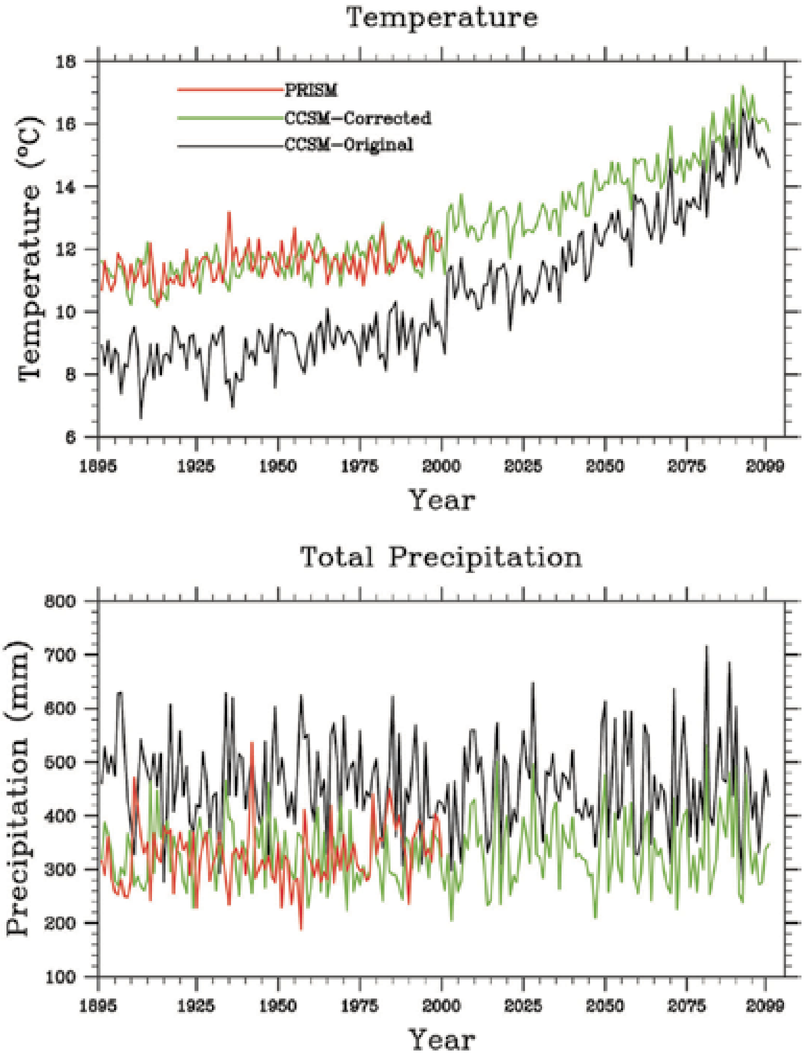

Fig. 9. CCSM projections of annual temperature (left) and precipitation (right) over the southwestern U.S. The black line is for the original CCSM projections, the green line is for statistically-corrected CCSM projections, and the red line is for PRSIM data. In this project we will use a similar method to correct the CCSM forcing data for WRF-CLM.

uncertainties. Figure 11 shows the linear trends in precipitation over the central western U.S. (Areas B and C in Figure 1) simulated from the six reanalysis-driven NARCCAP models. Except for the Hadley Center RCM (HRM3), none of the models capture the observed downtrend in precipitation. After the calibration process as described in Section 4.1 was applied, WRF-CLM simulated a much more realistic precipitation trend. It is therefore reasonable to expect that, by evaluating climate projections made from the calibrated/corrected downscaling against the original and existing (i.e. NARCCAP) ones, the uncertainty range of the climate projections can be quantified. We may also be able to address the challenge outlined in Figure 2, that is, to identify a representative projection with physically based assessment and with higher confidence.

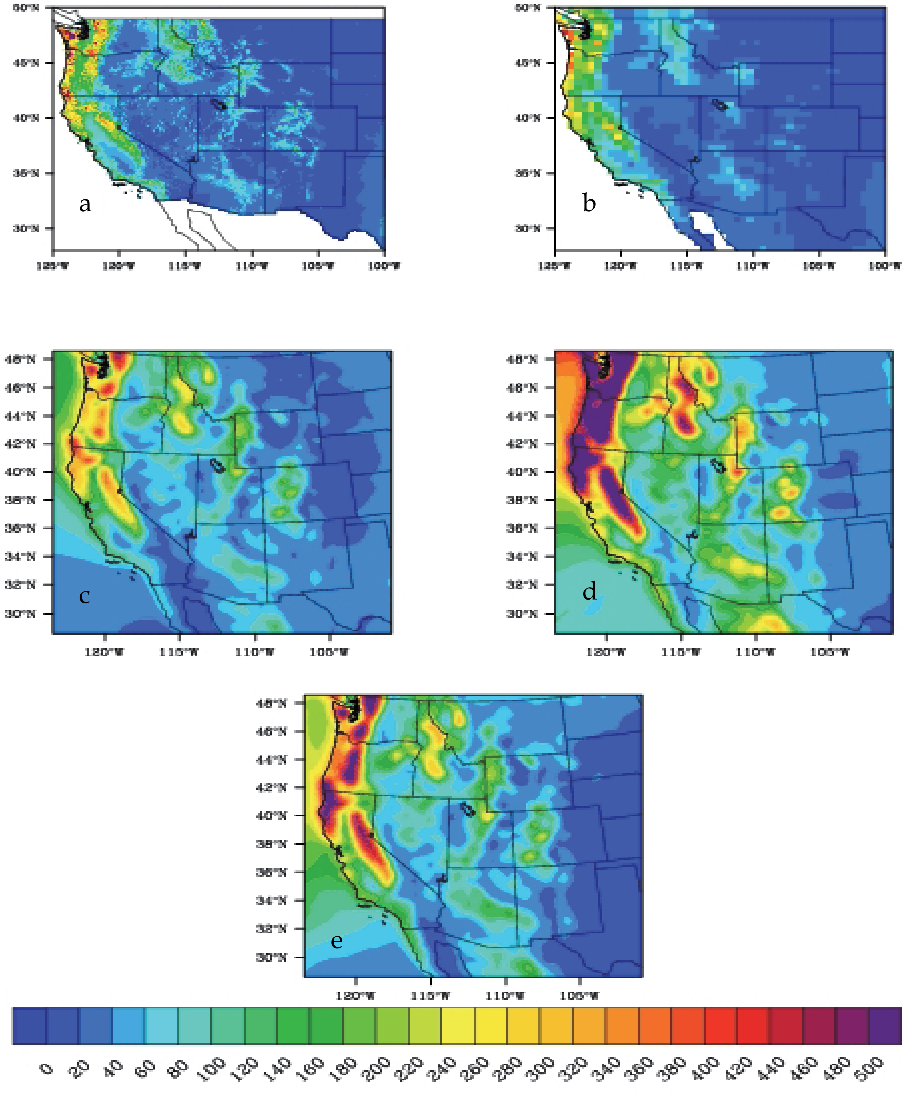

Fig. 10. Winter (December, January, and February) precipitation and observations and simulations avarged over the period of 1989-1999. a) PRISM data; b) University of Delaware observations; c) WRF forced with NCEP; d) WRF forced with original CCSM output; e) WRF forced with the regressed CCSM output.

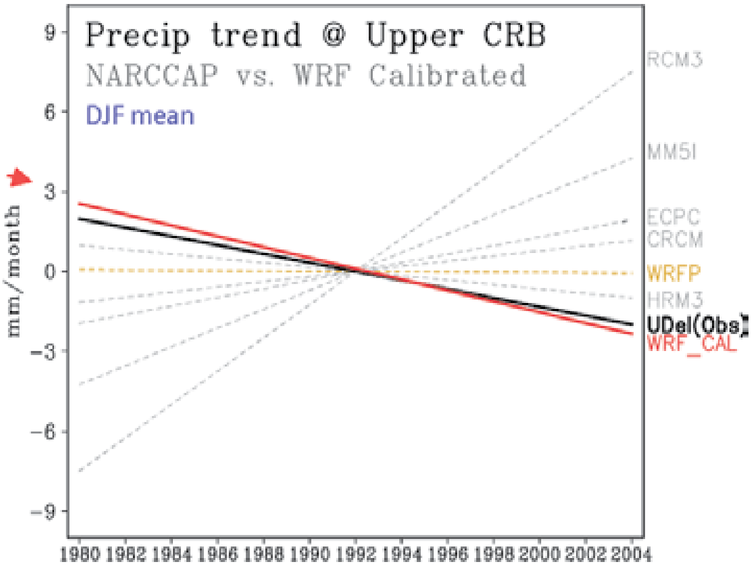

Fig. 11. Least-square trends in winter (December-February) precipitation averaged over Areas B and C (as in Figure 1) simulated by 6 NARCCAP models (grey; WRF in golden), calibrated WRF-CLM forced by NCEP-2 (red), and the University of Delaware observation (black) for the period 1979-2004. Year 1979 is omitted to avoid potential spin-up problems.

5. Summary and conclusions

Proper interpretation of climate projections that exhibit a wide range of uncertainties has been a challenge for the management of water resources. The common detection and attribution method validating GCM simulations is expensive when it comes to dynamical downscaling because of the large ensemble members required. In this chapter we demonstrated an economic approach through effective combination of dynamical and statistical downscaling towards reducing the range of projection uncertainties. The demonstration consists of (1) calibration of a regional climate model (WRF-CLM) towards realistic precipitation seasonal cycles, (2) data correction of a global climate model (CCSM) to minimize climatological biases of the forcing variables, and (3) generation of regional downscaling from (1) and (2) followed by evaluation against existing climate downscaling (NARCCAP) to quantify and reduce the range of projection uncertainties. We focused on the Upper Colorado River Basin of the western U.S. not only because of its critical role in the western water resource, but also because this region has complex precipitation seasonal cycles and that these cycles were not simulated properly by the NARCCAP models.

Our analyses showed that the calibrated simulation successfully reduced overprediction of windward precipitation amounts and reasonably captured the monsoon precipitation. This subsequently improved seasonal variability in precipitation when compared to that produced by the NARCCAP models. The improved simulation revealed a realistic long-term trend in precipitation that was not captured by the same model prior to the calibration. In addition, GCM forcing data corrected from climatological biases produced a downscaled climate that was significantly improved over that driven by original GCM forcing data. Consequently, by comparing the calibrated/corrected regional downscaling with existing ones such as those provided by NARCCAP, the range of uncertainties in those baseline projections (i.e. NARCCAP) can be quantified. Subsequently, the water management community will have a better tool in assessing future water needs. A long-term (2000-2100) climate simulation derived from the calibrated/corrected regional downscaling is being generated with an expected complete date in summer 2011.

6. Acknowledgment

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3

Fuelling Future Emissions – Examining Fossil Fuel Production Outlooks Used in Climate Models

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1. Introduction

The anthropogenic component of projected climate change is dependent on the future emissions of greenhouse gasses. Energy production is, with a roughly 60% share, the principal contributor to mankind's release of CO_2 to the atmosphere. This is predominantly caused by the use of fossil fuels in various combustion processes. Consequently, anthropogenic emissions and global warming are fundamentally linked to future energy production. Projections of how the global energy system will develop over the next century are cornerstones in the assessment of future climate change caused by mankind.

The climate models used by the Intergovernmental Panel on Climate Change (IPCC) and many others rely on various emission scenarios to depict possible trajectories for future fossil fuel production and their correlating release of CO_2. The Special Report on Emission Scenarios (SRES) (the current set of emission scenarios) was published by the IPCC in 2000 and remains an integral part of climate change modelling. This chapter critically reviews the emission scenarios witnessed throughout history, their underlying assumptions on resource availability, production expectations, and compares them with other models and studies that have drawn up projections into the future. Future scenarios with high emissions of CO_2 also display significant increases in world production of oil, natural gas and coal.

As of 2009, world oil production remains at 85 million barrels per day or 3800 million tons of oil equivalents (Mtoe) annually, with coal and natural gas 3400 Mtoe 2700 Mtoe per year respectively (BP, 2010). A tenfold increase in world gas production is foreseen in some scenarios, while others project future oil production to reach 300 million barrels per day by 2100. For example, 16 of the 40 coal scenarios contained in SRES simply grow exponentially until the year 2100. In addition, the emission scenarios also contain assumptions about future prices, technological developments and many other details related to fossil energy exploitation.

Can such assumptions be justified in the light of available fossil fuel resources and reasonable expectations on how fast such deposits can be exploited? Depletion of the world fossil energy resources, primarily oil, is a growing problem and is reflected in recent studies. This chapter also examines whether these results and observations have been incorporated in the emission scenarios used in climate models.

1.1 Historical background

The Swedish Nobel prize laureate Svante Arrhenius (1896) was among the first to theorize about the impact of CO2 on the earth's climate. However, these early ideas were met with criticism and fell into obscurity until the 1950s. Growing concern about mankind's increasing impact on the environment and refined analytical methods revitalized the issue of greenhouse gases after the 1950s. Separate threads of research were pursued by isolated groups of scientists, although an increasing number of studies pointed towards a connection between global warming and anthropogenic emissions of greenhouse gases (Peterson et al., 2008). However, both mainstream media and politicians did not express concern over any of these findings until much later.

In the 1980s, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) began to investigate the role of carbon dioxide and other emissions. Their interest leads to the establishment of the IPCC in 1988. This new organization was given the task of assessing the scientific, technical and socio-economic information relevant for understanding anthropogenic climate change. Their results have been published in several assessment reports and some special reports over the years (IPCC, 1990; 1995; 2001; 2007). However, the results are also dependent upon a number of underlying assumptions about future fossil fuel production and corresponding emissions.

Various future pathways for society, its energy system and the associated release of greenhouse gases are a cornerstone in the assessment of future climate change. Such outlooks are commonly referred to as emission scenarios and are being used as input in to climate models that transform the projected emissions into climatic changes. Throughout its existence the IPCC has used a number of such emission scenarios. The first set, published in 1990, was followed by subsequent sets published in 1992 and 2000. Titles, methods, classifications, assumptions have all changed over time and this has been reviewed by Girod et al. (2009).

The 1995 IPCC review of the old emission scenarios recommended that the full range of scenarios should be used as an input rather than just a single scenario. The conclusion was that there was no objective basis on which to assign likelihood to any of the scenarios (SRES, 2000). Meanwhile, a number of other weaknesses were also identified, such as the limited range of carbon intensities, the absence of a scenario with economic closure in the income gap between industrial and developing countries (SRES, 2000), or how the rapid growth in sulphur emissions did not reflect regional and local air quality concerns that might prompt limits on the future release of sulphur in to the atmosphere (Grübler, 1998).

All scenarios from 1992 where found to exaggerate one or more current climate and economic trends, leading to correspondingly exaggerated atmospheric greenhouse gas concentrations (Gray, 1998). In May 1996, the IPCC decided to develop new scenarios and initiated the painstaking process of developing a new set for use in future climate change assessments (Nakićenović et al., 1998). This resulted in the current emission scenario set - often known as the Special Report on Emission Scenarios (SRES) - being published in 2000. This report is the basis for the majority of all recent long-term climate change projections, including those of the current Fourth Assessment Report (IPCC, 2007).

SRES (2000) presents 40 scenarios and calculates the greenhouse gas emissions associated with those scenarios. These scenarios are based on a literature review, the development of emmission narratives, and the quantification of these narratives with the help of six integrated models from different countries. The IPCC links CO_2 emissions to four specific drivers, namely population; economic activity (gross domestic product or GDP) per capita;

energy intensity (primary energy consumption per unit of GDP); and carbon intensity (CO_2 emissions per unit of energy) (Pielke et al. 2008). Consequently, SRES illustrates that the future emissions, even in the absence of explicit environmental policies, very much depend on the choices that people make, how economies and technologies are structured, the energy sources that are preferred and how people use available land area.

1.2 Scenario probabilities in SRES

Regarding the scenarios, IPCC state that "*they represent pertinent, plausible, alternative futures*" and derive from a descriptive and open-ended methodology that aims to explore alternative futures (SRES, 2000). The emission scenarios are claimed to be neither predictions nor forecasts, even though they are commonly used as such. Additionally, no probabilities or likelihoods are assigned to any of the scenarios. All scenarios are deemed equally plausible and valid as required by the Terms of Reference (SRES, 2000).

The emissions scenarios are used as an input to various climate models to depict how the climate may change under various forms of anthropogenic emissions. Some outcomes are more desirable than others, but the equal probability assumption can act as a potential obstacle. Planners and engineers, who need to make decisions based on the impacts of climate change, must have a grasp of the inherent uncertainties in the guiding projections as well as the probabilities of the different outcomes. Further discussion on these issues can be found in Walsh et al. (2004) or Green et al. (2009).

The absence of likelihoods in SRES triggered critique (Schneider, 2001; 2002; Webster et al., 2002) highlighting that policy analysts and decision-makers need probability estimates to assess the risks of climate change impacts resulting from these scenarios. The SRES team (Grübler and Nakicenovic, 2001) countered with the claim that social systems (important in emission scenarios) are fundamentally different from natural science systems and are largely dependent on the choices people make.

Equally valid scenarios cannot be realistic, since the range is due to a combination of component ranges of uncertainty, and thus the extremes of this range must be less probable than the central estimate (Jones, 2001). The equal probability of each emission scenario is a rather peculiar assumption and has been seen as an attempt to assign unjustifiably high weight to more extreme visions compared to reasonable outlooks (Höök et al., 2010a; Patzek and Croft, 2010). Clearly, the handling of uncertainty and the appropriateness of assigning subjective probabilities to scenarios is a matter of lively debate and an important, unresolved challenge in the application of climate scenarios (Dessai et al., 2007; Groves and Lempert, 2007; Schenk and Lensink, 2007; van Vuuren et al., 2008; Lemos and Rood, 2010).

1.3 The role of fossil fuels in the world's energy system

Throughout the industrial revolution, energy derived from fossil fuel has been the driving force behind the industrialized world and the economic growth. Energy output from fossil fuel has grown from insignificant levels in 1800 to an annual output of nearly 10 000 million tons of oil equivalents (Fig. 1). At present, over 81% of the total primary energy in the world is produced from fossil fuels with oil accounting for 33.2%, coal for 27.0% and natural gas for 21.1% (IEA, 2010). Combustible renewable and waste (10.0%), Nuclear power (5.8%) and hydroelectric dams (2.2%) are the largest contributors to the global energy system after fossil energy, but they account for only a smaller share of the world's primary energy supply (IEA, 2010). Only 0.7% of the world's primary energy is derived from geothermal, wind, solar or other alternative energy sources. More specifically, wind power accounted for only 0.2% of the global primary energy supply with its 340 TWh contribution in 2009 (World Wind Energy Association, 2010).

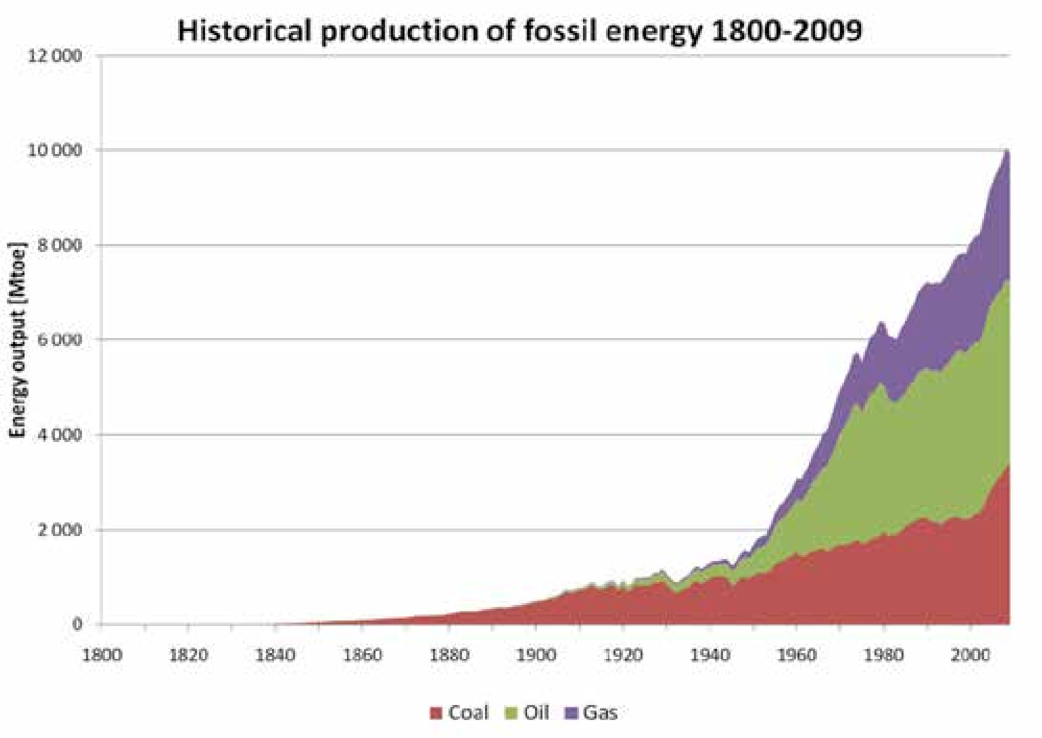

Fig. 1. Production of fossil energy in the world from 1800 to 2009. Based on the author's own compilation of historical data.

1.4 Importance of future energy systems for future emissions

For the foreseeable future, fossil energy will remain the backbone of the world's energy system, given their present dominance. Furthermore, the worlds reliance on fossil energy brings about an associated problem, namely the emissions connected to the combustion of these fossil fuels. In fact, energy production is also the dominating source of anthropogenic greenhouse gasses (GHG), particularly carbon dioxide. In 2008, nearly 30 billion tons of CO_2 were emitted due to fossil fuel consumption (IEA, 2010). Around 57% of all global anthropogenic GHGs derive from fossil fuel combustion, with energy supply as the largest contributing sector (Fig. 2). Anthropogenic global warming and climate change caused by GHG emissions exhibits a strong and fundamental link to fossil energy production and shapes how it will develop over the coming decades. Consequently, examining likely and possible trajectories of the future energy use and production are vital for understanding future climate change based on GHG emissions from human activities.

Lior (2009) reviewed current energy use and possible paths to the future, but without venturing into specific details surrounding upcoming challenges. On the other hand, such visions have been made by many others and there is a growing body of evidence indicating that there will be challenges with supplying enough fossil energy for continued business-as-usual growth. Energy insecurity, i.e. the welfare impact of either physical unavailability of energy or prices that are not competitive or are overly volatile, has often been identified as a major challenge for the world in the 21st century together with anthropogenic climate change (Curtis, 2007; McCartney et al., 2008; Moriatry and Honnery, 2009). How are these two problems interconnected? Can both these challenges haunt mankind at the same time?

Despite awareness of fossil fuel exhaustion and the common knowledge about the finite supply of oil, gas and coal, physical resource availability has not been widely addressed in the long-term outlooks used to assess the risk of anthropogenic climate change. Contrary to common sense, energy is usually treated as a limitless exogenous input to economic planning with the result that energy demand is well defined, but disconnected from the physical and logistical realities of supply (Nel and Cooper, 2009). In essence, SRES (2000) features a set of scenarios not compatible with the possibility that the implied recoverable volumes and extraction rates of fossil fuels are physically impossible. Despite the obvious relevance of peak oil to future anthropogenic emissions it has received little attention in the climate change debate (Kharecha and Hansen, 2008; Crúcz et al., 2010). In many ways, extreme climate change projections are commonly built on the assumption that there will be essentially no issue at all with future supply of fossil energy.

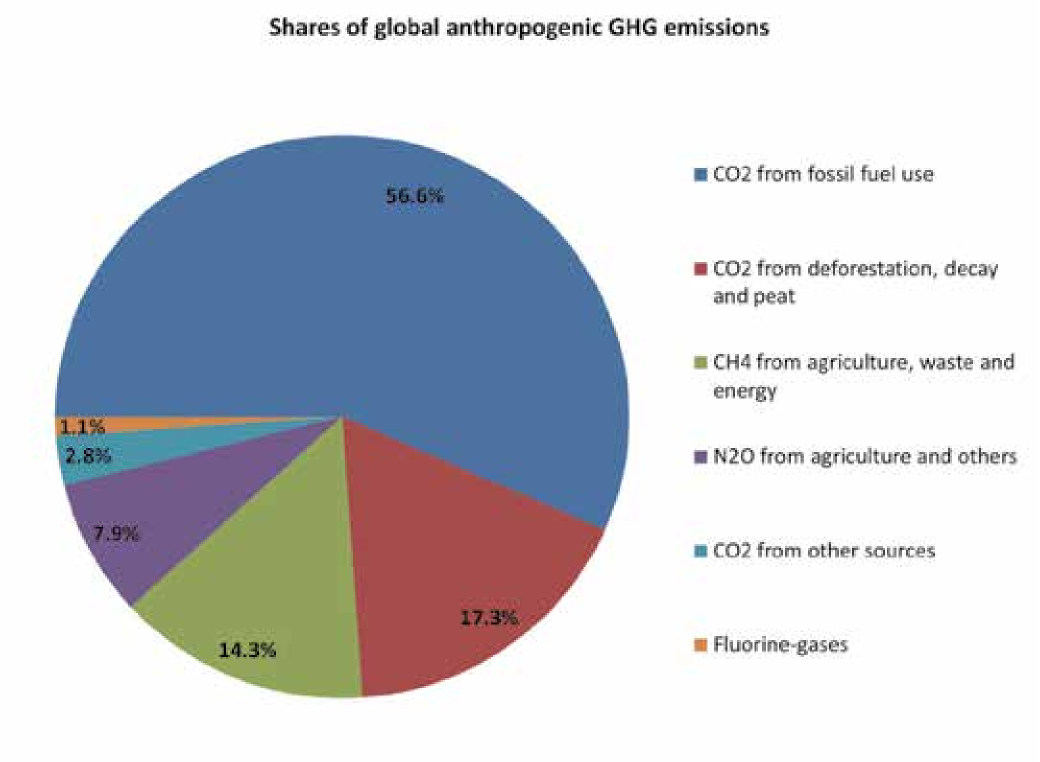

Fig. 2. Shares of global anthropogenic greenhouse gas emissions by origin (IPCC, 2007).

2. A closer look at the emission scenarios

SRES is built around 40 different scenarios for future development of the society, its energy system and emissions. The writing teams formulated the narratives in a process that identified driving forces, key uncertainties, possible scenario families and their logic. Each of the four scenario families is described by a specific storyline to simplify the procedure of depicting alternative future developments. Within each scenario family different variations of global and regional development and their implications for global greenhouse gas emission were explored.

Six different modelling teams (Table 1) used state-of-the-art computer models and experience considering long-range development of economic, technological and environmental systems to generate quantifications of the narratives, which laid the foundation for the different scenarios. SRES storyline titles have been kept simple and are named A1, A2, B1 and B2. They can be straightforwardly shown in a two-dimensional tree, depicting the global-regional focus and the economic-environmental orientation (Fig. 3).

It is important to notice that there is no business-as-usual scenario, even though the A1 family is often used as an example of how continued focus on economic growth in a Western way might evolve globally. In addition, disaster scenarios were also omitted and it was also decided that possible surprises, such as a new world war or major depression, should not be considered. This has been described as a built-in linear logic and utopian thought (Hjerpe and Linnér, 2008). It is also important to highlight that none of the scenarios include additional climate initiatives such as policies to limit GHG gases or to adapt to the expected climate change.

Abbrevation	Full Name	Origin
AIM	Asian Pacific Integrated Model	National Institute of Environmental Studies (NIES), Japan
ASF	Atmospheric Stabilization Framework Model	ICF Consulting, USA
IMAGE	Integrated Model to Assess the Greenhouse Effect	National Institute for Public Health and Hygiene (RIVM), Netherlands
MARIA	Multiregional Approach for Resource and Industry Allocation	Science University of Tokyo, Japan
MESSAGE	Model of Energy Supply Strategy Alternatives and their General Environmental Impact	International Institute of Applied Systems Analysis (IIASA), Austria
MINICAM	The Mini Climate Assessment Model	Pacific Northwest National Laboratory (PNNL), USA

Table 1. Model names in SRES and developing team behind them.

The four main narratives and their corresponding scenario families describe future societies that are significantly wealthier than the current world. There has been a significant discussion around the use of Market Exchange Rates (MER) or Purchasing Power Parity (PPP) and the economic differences it leads to in the long time scales used. For example, McKibbin et al. (2007) show that MER terms can lead to more than 40% higher emission

projections compared to estimates based on PPP. This has been discussed by Castles and Henderson (2003), Tol (2006), and van Vuuren and O'Neill (2006).
Closer discussions on the actual models and the concepts they rely on have been done by van Ruijven et al. (2008). The energy ladder, i.e. a simplified substitution-based concept, as well as the environmental Kuznetz curve, i.e. a U-shaped relation between economic development and environmental impact, are generally consistently used in SRES. However, van Ruijven et al. (2008) stress that the models might need to be reformulated to better capture the dynamics of real world development, since SRES only depicts the world in four large regions and uses a limited amount of socio-economic and energy data. Further analysis of assumptions regarding demographics, economics and social development is beyond the scope of this chapter.

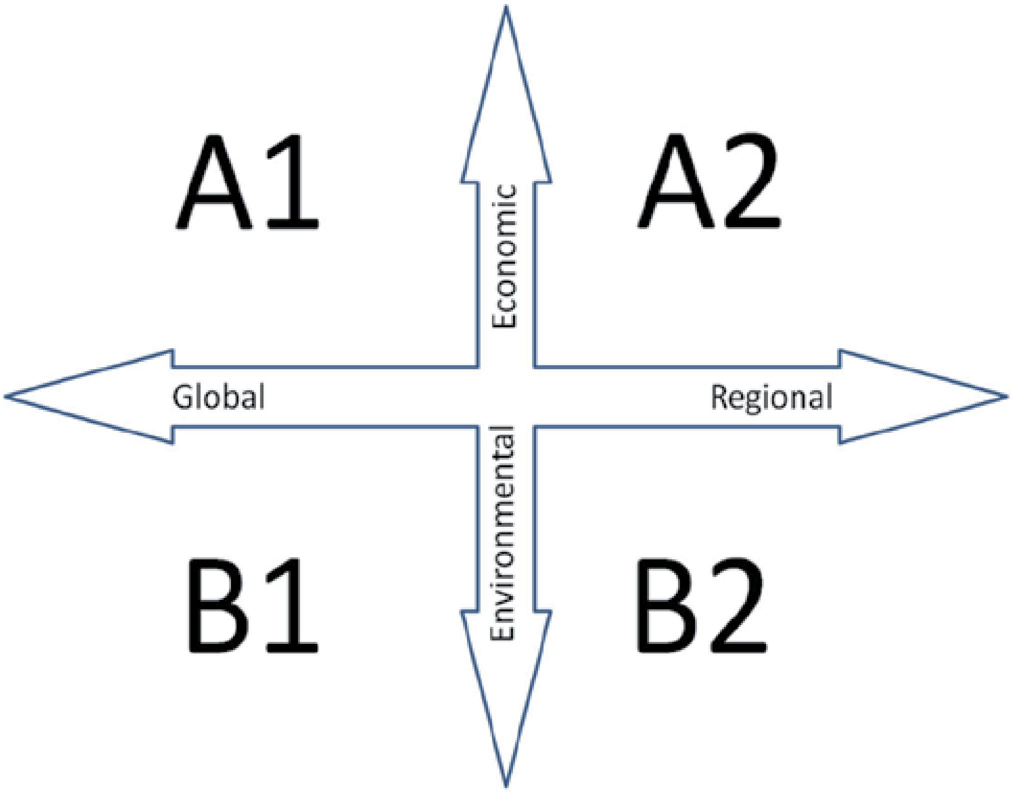

Fig. 3. Schematic illustration of the SRES scenarios. The four scenario families are shown, very simplistically, as branches of a two-dimensional matrix. Each scenario is based on a common specification of the main driving forces such as population, economy, technology, energy, land-use and agriculture. Adapted from SRES (2000).

2.1 The four scenario families

All the qualitative and quantitative features of scenarios belonging to the same family were set to match the corresponding features of the underlying storyline. Together, 26 scenarios were harmonised to have the same common assumptions about global population and gross domestic product (GDP) growth (SRES, 2000; Siversson, 2004). Although the scenarios share a few basic assumptions, they can differ substantially in other aspects, such as availability of fossil-fuel resources, the rate of energy-efficiency improvements, the extent of renewable energy development, and the consequential GHG emissions.

The remaining 14 scenarios are alternative interpretations of the four scenario narratives with different rates of economic growth and variations in population projections. These variations reflect the modelling teams' choice as an option to the harmonised scenarios. Another form of scenario is the marker scenario, which is considered by the SRES writing team to be the most illustrative scenario of a particular storyline, but marker scenarios should not be regarded as more likely than any other scenario either. More detailed descriptions on the scenario families and their characteristic parameters can be found in SRES (2000), even though the main qualities of each storyline can be found in table 2 and are briefly presented below.

Family	**A1**				**A2**	**B1**	**B2**
Subgroup	A1C	A1G	A1	A1T	A2	B1	B2
Population growth	Low	Low	Low	Low	High	Low	Medium
GDP growth	Very high	Very high	Very high	Very high	Medium	High	Medium
Energy use	Very high	Very high	Very high	High	High	Low	Medium
Land-use changes	Low-medium	Low-medium	Low	Low	Medium-high	High	Medium
Resource availability	High	High	Medium	Medium	Low	Low	Medium
Technological development	Rapid	Rapid	Rapid	Rapid	Slow	Medium	Medium
Change favouring	Coal	Oil & Gas	Balanced	Non-fossils	Regional	Efficiency	"Dynamics as usual"

Table 2. Main characteristics of development in different scenario families and groups, as applied to harmonized scenarios. Adapted from SRES (2000)

The A1 storyline and corresponding scenario family is by far the largest of the four scenario families in SRES (2000). This family is characterized by visions of a future world with very rapid economic development, low population growth and swift implementation of new and more efficient technologies. The key plots are convergence among regions, capacity building, and increased cultural and social interactions with a significant reduction in the difference in per capita income. The A1 family is the largest and branches out in several subfamilies, each exploring an alternative future with other preferences. One subfamily, A1C, focuses on coal and its development potential while A1G uses natural gas as the main energy source. A1T explores non-fossil energy sources, while the A1 subgroup uses a balanced energy mix.

The A2 family describes a very heterogeneous world. Here, the main concept is self-reliance and preservation of local identities and cultures. Global fertility patterns converge very slowly which results in high population growth. Economic development is primarily focused on regional growth and per capita economic growth and technology change is more fragmented and slower than in other scenario families.

The B1 scenario family depicts a world with the same low population as the A1 storyline, but with rapid changes in economic structures. The gap between developed and developing countries diminishes as the world economy moves toward a service and information economy. This results in reductions in material intensity, and the implementation of clean and resource-efficient technologies. The key concept here is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 scenario family is similar to the B1 family, but the emphasis is put on local solutions to economic, social and environmental sustainability. It results in a world with moderate population growth, intermediate economic growth and less but more diverse technological change than in the B1 and A1 storylines. B2 is oriented toward environmental protection and social equity, but also focuses on local and regional initiatives.

3. Resource availability in SRES

Fossil fuel use is the dominating source behind GHG emissions and so the assumed availability and future production paths are vital for projecting atmospheric concentration of CO2 and anthropogenic climate change. However, the underlying assumptions and data sources in SRES (2000) are old and even outdated due to new knowledge and changing conditions in the world. This has chiefly to do with the one-sided view on fossil fuel availability expressed by the works that SRES relies on, chiefly relying on economic models rather than geological and technical estimates (Höök et al., 2010a).

The works of Rogner (1997) and Gregory and Rogner (1998) are the major sources for the detailed discussion of available fossil fuel amounts in SRES (2000). Rogner (1997) states that additional occurrences beyond the common resource base, i.e. unconventional hydrocarbons such as tar sands and gas hydrates, makes fossil fuels appear as an almost unlimited energy source, provided that economic and technological development are favourable. Rogner (1997), and thereby SRES (2000), conveys the notion that "*the sheer size of the fossil resource base makes fossil sources an energy supply option for many centuries to come.*" More specifically, the low long-term costs are worth mentioning, as the fossil energy cost is assumed to be not significantly higher than the market price of the 1990s (i.e. crude spot prices of around 17 dollars/barrel).

To arrive at these conclusions, Rogner (1997) compiled a number of hydrocarbon resource estimates prior to 1997, originating from sources such BP, World Energy Council, German Federal Institute of Geosciences as well as academic studies. For conventional petroleum, Rogner (1997) states an ultimate recoverable resource base of 2800 Gigabarrels (Gb) and the aggregated number for unconventional oil occurrence is 16 500 Gb, where unconventional includes heavy oil, tar sands and oil shale. Unconventional oil is expected to become the main source in the long run, given its presence in vast quantities. Comparison between Rogner (1997) and recent estimates of available unconventional oil can be found in Greene et al. (2006).

Rogner (1997) presents a similar picture for natural gas, with only 2900 gigabarrels of oil equivalents (Gboe) of conventional gas (3100 Gboe if natural gas liquids are included) and 142 000 Gboe of unconventional quantities. Over 95% of unconventional gas is assumed to be methane hydrates (primarily residing on sea floors), while coal-bed methane, fractured shale, tight formation and remaining in-situ only constitute minor amounts. As a result, future gas availability must be tightly connected to methane hydrates and their development. Worldwide estimates of gas hydrates have decreased by many orders of magnitude (from 10^{18} m^3 in 1970s to 10^{15} m^3 in 2000s) due to growing geological knowledge (Milkov, 2004), so much of the material used by Rogner (1997) is now outdated. The apparent importance of gas hydrates and the major expectation that is put on them in SRES (2000) appears debatable and should be highlighted for more discussion. The huge global estimates of hydrate methane are suspicious at best, and have nothing to do with the likelihood that hydrates will provide energy supply assurance for the future. An excellent review on facts and myths surrounding gas hydrates and their future as an energy source have been made by Beauchamp (2004).

For coal, Rogner (1997) highlights the many fluctuations in world reserve and resource assessments. The overview is very brief in comparison with oil and gas, mostly utilising the German Federal Institute of Geosciences (BGR) as the main source. The total coal resource is placed at 45 800 Gboe, which would equal 8744 Gt of coal (assuming 30 GJ/ton coal). Nearly 60% of all coal is found in the most uncertain category. A complete summary of how world coal reserves and resources have evolved over time can be found in Höök et al. (2010b).

Gregory and Rogner (1998) rely largely on the resource estimates derived by Rogner (1997) but make a few new additions with resource estimates for renewable and non-fossil fuels. A significant share of the article is devoted to speculation and envisioning the feasibility of future conversion technologies, ranging from fuel cells and hydrogen to unconventional hydrocarbons such as oil shale or gas hydrates. Interestingly enough, Gregory and Rogner (1998) also mentions the "*pessimistic*" view on ultimate recoverable resources, represented by geologists and natural scientists in contrast to the "*optimistic*" view, lead by economists such as Adelman and Lynch. The notion of limits to future oil supply is quickly dismissed by Gregory and Rogner (1997) with grand expectations from new technology as well as economic arguments pointing towards the enormous amount of hydrocarbon molecules available in the Earth's crust. In essence, IPCC ad SRES has chosen to disregard the issues of resource depletion and the concept of geological, physical and technical limits based on little more than economic demand-driven models (Höök et al., 2010a, Valero and Valero, 2011).

3.1 Resource depletion

The term *finite resource* is frequently used but few people seem to ponder what it actually means. When it comes to natural resources, it can be argued that production limits are determined by the extraction and creation rates. If extraction of a resource is faster than replenishment rate the resource will be finite in the sense that it will eventually be exhausted (Höök et al., 2010c). All fossil fuels are finite and non-renewable natural resources, i.e. their deposits are limited either physically or economically. This comes from the simple fact that it takes millions of years for fossil fuels to form and they are rapidly extracted, making it impossible for the rate of creation to keep up with the rate of extraction.

The issue of depletion and overexploitation of the natural resource base are not recent concerns. In fact, discussion has been taking place for quite some time, hailing back to the 18th century where Malthus (1798) discussed the impact of growing exploitation of natural resources in an environment with limited capacity to sustain an ever increasing populace.

Similar reasoning was later expressed by Verhulst (1838) who found that any population subject to growth would ultimately reach a saturation level (usually described as the carrying capacity) and this environmental characteristic forms a numerical upper bound on the growth process. Later on, William Stanley Jevons (1856) foresaw limits to the growth of British coal production as a consequence of limited availability of workable coal.

In the 1950s, Hubbert (1956) was among the first to propose a modern framework for extrapolation of production curves of finite resources, primarily focused on oil. He also accurately predicted the peak of US oil production in 1970s.

More generally, possible limits to growth and how it would affect society were explored through system dynamics by the Club of Rome in their infamous report "*The Limits to Growth*" (Meadows et al. 1972). In hindsight, 30 years of reality actually concurs well with the "*standard run*" scenario (Turner, 2008). Sustained false statements, by mainly economists, discredited the report and made its call for fundamental policy changes and sustainability pass by relatively unnoticed (Turner, 2008). As life after the oil crisis of the 1970s returned to normal many of the issues raised concerning resource depletion were forgotten.

In late 1990s, two former oil company geologists, Colin Campbell and Jean Laherrere, examined reported reserves and extrapolated discovery curves (Campbell and Laherrere, 1998). Their conclusion was that the world is facing the end of cheap and abundant oil and that the maximum rate of oil production would occur somewhere around 2010. Many other studies performed since have arrive at similar dates (Bentley and Boyle, 2007).

Aleklett and Campbell (2003) addressed more issues and created an updated model for oil depletion along with a first expansion of the analysis to cover natural gas. Once again, doomsday accusations and claims of undue pessimism were targeted at these forecasts, mostly from economists. In retrospect, empirical observations show that nearly 60 countries have already passed their maximum production levels of oil (Sorrell et al., 2010). A most comprehensive summary of over 500 peer-reviewed studies on oil concluded that a global peak before 2030 appears likely and there is a significant risk of peaking before 2020 (UKERC, 2009). Sorrell et al. (2010) also found that forecasts that delay the peak of conventional oil production until after 2030 rest upon several assumptions that are at best optimistic and at worst implausible.

Clearly, the risks associated with future oil supply and how it can impacts the global energy system should be given serious consideration but none of this has been highlighted by the IPCC that continues to rely on the outdated material in SRES.

3.2 Production projections made in SRES

Total primary energy production from fossil fuels in the SRES outlooks range from around an increase of a mere 50% from the 2009 level in the B1 family to over 400% in the A1 family (Fig. 4–7). There is a significant spread within the families, in particular among the scenarios belonging to the A1 family. The A1T-scenarios largely replaces fossil fuels with nuclear or renewable and remain at levels around present fossil energy contribution until 2100. Other subgroups depict significant increases of oil, gas and/or coal.

Not a single one of all 40 scenarios in SRES (2000) is projecting a future society with remarkably less fossil fuel dependence than at present. Closer studies, with projections broken up into oil, gas and coal, have been made by Höök et al. (2010a). The spread can also be significant. For example, A1G AIM reaches over 300 million barrels per day of oil production by 2100, while A1 ASF has phased out oil use entirely. Strangely enough, both of these outlooks are deemed equally probable. More than a tenfold increase in world gas and coal production is also projected. These outlooks are in stark contrast to the growing body of evidence that indicate that such high production pathways are unreasonable.

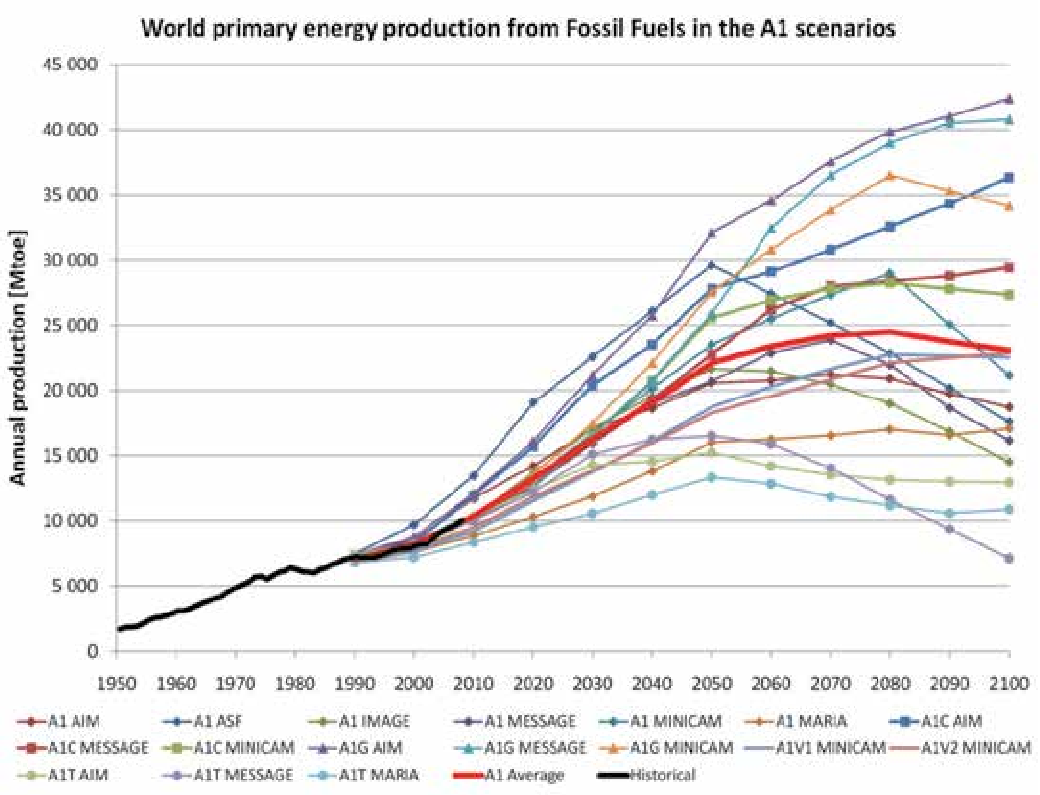

Fig. 4. World primary energy production from fossil fuels in the A1 family.

For coal, Patzek and Croft (2010) examined SRES and found that 2 scenarios peak in the year 1990, 3 in 2020, 3 in 2030, 3 in 2040, 13 in 2050, while in the 16 remaining scenarios coal production simply grows exponentially until the year 2100. What happens after 2100 is not discussed in SRES (2000) and several scenarios simply end with high production levels. By 2100 most of the ultimate reserves of conventional oil, gas and coal discussed in most SRES scenarios will have been depleted (Höök et al, 2010a).

Rogner (1997) and SRES (2000) go to great lengths to point out that there are enough fossil resources, i.e. hydrocarbon molecules in the crust, to theoretically sustain production for a long time. However, the main message of Rogner (1997) shows a misunderstanding of the actual problem as well as avoidance of the question at stake, namely future production. Resources are irrelevant for production, unless they cannot be transformed to reserves and commercially exploited. Vast resources have little to do with the likelihood of significant future exploitation, as this is dependent on more factors than just geological availability.

Society is dependent on fossil fuel flows and future production is about the size of those flows. The size of the tank, i.e. the resource base, is of secondary importance as it is the tap that governs the flow rate and future utilization of fossil fuels in the society. Vast amounts of unconventional hydrocarbons are useless for preventing the coming of a production peak if they cannot be developed fast enough to offset the peaking of conventional flows.

There are also a few important observations that can be made from the arithmetic of growth. Every time a growing production doubles it takes more than all that has been used in all the preceding growth (Bartlett, 1993; 1999; 2004). Taking the average fossil energy production of A1 as an example (Fig. 4), it is projected that the global production of fossil energy in 2040 will be approximately twice as much as in 2010. In other words, it is stated that during these 30 years the world will produce and consume more fossil energy than the total that has been consumed since the dawn of the industrialized age. This is actually quite mind-bending when stated in this way in contrast to the exponential growth rates of a few percent more commonly seen. The amount of miners, equipment, permits, investments, regional issues and social acceptance needed to achieve this huge task is not discussed in SRES in any detail as everything is just aggregated into four large world regions.

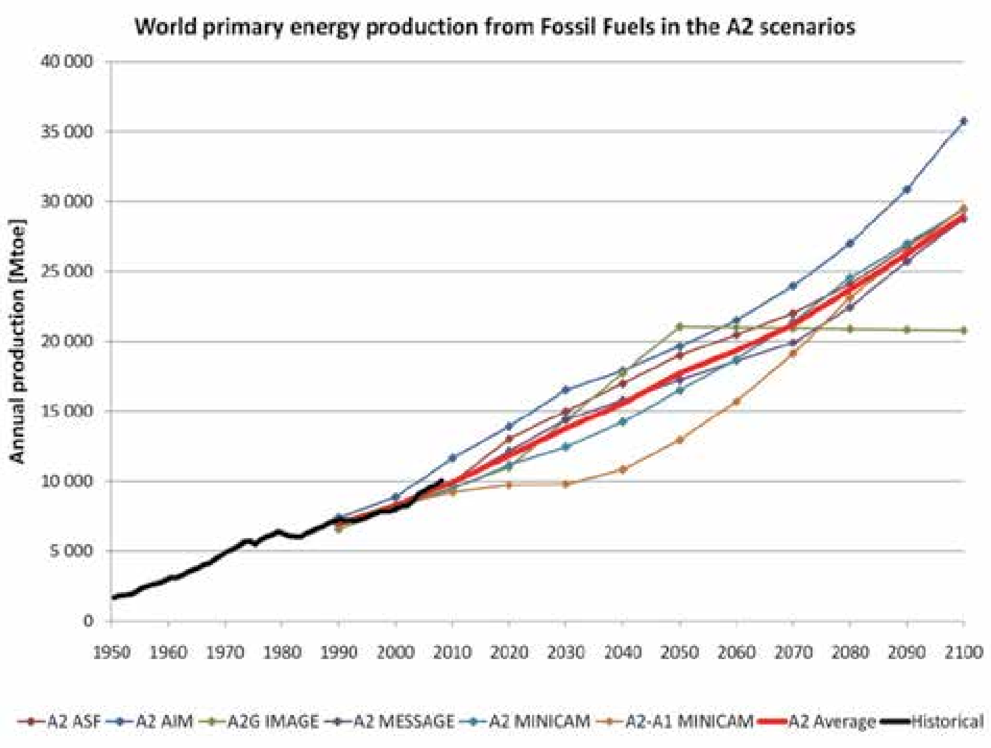

Fig. 5. World primary energy production from fossil fuels in the A2 family.

3.3 Critical views on SRES

Since SRES was published in 2000, there have been a number of critical concerns raised over the fossil fuel production outlooks contained in the emission scenarios. However, this debate did not become especially widespread. The public debate seemed to focus on the outcome of the climate models rather than the underlying assumptions.

One of the first to notice the optimistic production paths were Laherrere (2001; 2002). He compared the IPCC emission scenarios with technical data and found them overly optimistic on future oil and gas supply, both regarding conventional and unconventional oil. By 2100, the A1G scenarios consume around 14 times more natural gas than in 2000 and Laherrere (2001) described this as "*pure fantasy*". He concluded that the IPCC assumptions about abundant volumes of cheap oil and gas were in dire need of revision.

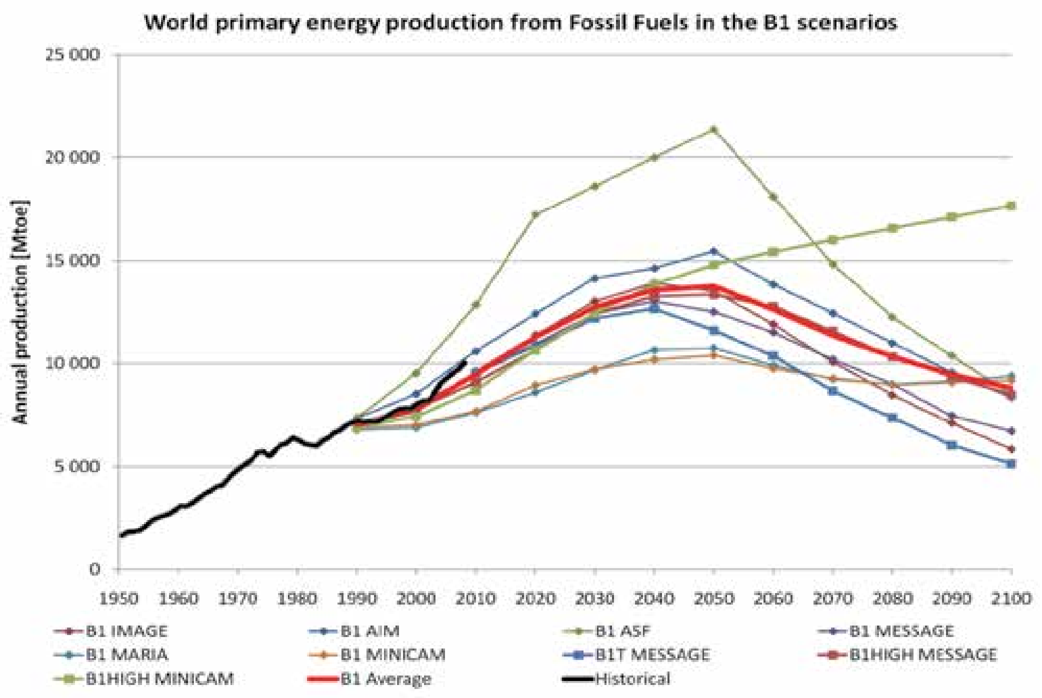

Fig. 6. World primary energy production from fossil fuels in the B1 family.

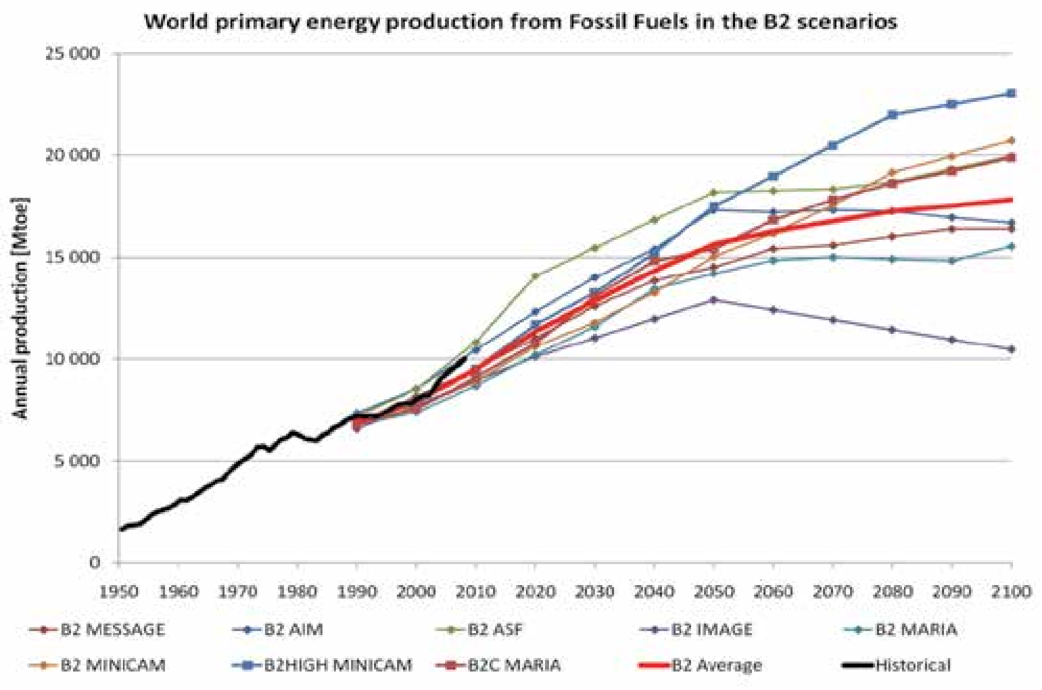

Fig. 7. World primary energy production from fossil fuels in the B2 family.

Similar ideas were expressed by Campbell and Aleklett (Coghlan, 2003), who earlier had questioned the longevity of the world's oil and gas endowment (Aleklett and Campbell, 2003). Sivertsson (2004) was later showing major anomalies between all the 40 emission scenarios and expected future production and discoveries of gas and oil, using an updated methodology and improved data. The authors of SRES responded to this by claiming that the findings were too "*conservative*" and claimed that there was still plenty of coal to exploit.

Rutledge (2007) expanded this analysis by including coal and came to the conclusion that the cumulative energy production and CO2 emissions from coal, oil and gas would be less than any of the IPCC emission scenarios. Different studies on future coal production levels all indicated that historical trends and reasonable production profiles were lower than depicted in SRES (Energywatch Group, 2007; Mohr and Evans, 2009; Höök et al., 2010b; Patzek and Croft, 2010). It was also shown that IPCC had been performing dubious summation of coal resources from the World Energy Council (WEC), despite the fact that WEC gave compelling reasons for not summing that category (Rutledge, 2011).

3.3.1 Rates of change in SRES

SRES (2000) presents a significantly important role for unconventional fossil hydrocarbon sources, justified by the works of Rogner (1997) and Gregory and Rogner (1998). For example, the B1 family assumes that the availability of huge unconventional oil and gas supplies, with a geographic distribution widely different from conventional resources, will have a significant impact on fuel supply and trade flows in the long term. Essentially, the depletion of conventional fossil fuels is expected to be smoothly offset as new technology allows exploitation of unconventional resources such as tar sands, gas hydrates and similar in the emission scenarios used by the IPCC. Another inadequacy is the lack of discussion about the details of the supply of fossil energy.

For oil, the world has a significant dependence on roughly 300 giant oil fields, which account for 60% of world oil production (Höök et al., 2009). The decline in existing production has been determined to be around 6% and this is a commonly accepted figure derived by several analysts, both from "*optimistic*" and "*pessimistic*" standpoints regarding future oil production (Höök et al., 2009 and references therein). This is equal to a required new annual production addition of 3-7 Mb/d and this puts some real numbers on what is required just to offset a decrease in existing production. This lack of detailed discussion on future production in SRES is questionable, because details such as those surrounding the giant fields have significant impact on actual production. The aggregated models and generalized assumptions appear questionable and should be clarified and reinforced to be considered realistic. At this point, IPCC and SRES (2000) seem far more optimistic regarding future oil production than the industry itself.

The attenuation of the peak oil decline requires more than 10% of sustained growth of nonconventional oil production over at least the next two decades (de Castro et al., 2009). Such sustained growth rates have not been seen for any of the global energy systems in history and are not expected by either of the dominating forecasting agencies, i.e. the IEA or the EIA. Even the BGR (2008), the main data source of Rogner (1997), states that: "*after peak oil, the nonconventional oil production will rather modify the decline in oil supply than close the gap between demand and supply.*" More specifically, there appears to be more or less of a consensus about a global peaking of oil production before 2030 (UKERC, 2009). Alas, the foundation of future oil supply used by SRES (2000) is outdated and does not reflect the growing knowledge of the last decade.

Similar optimistic assumptions have also been placed on gas and coal production within SRES (2000). To achieve ten-fold increases in global gas and coal production, an olympian amount of investment must be made but this appears unlikely from available long-term policies and planning documents. For gas, methane hydrates are identified as the important long-term supplier in SRES (2000). In reality, exploitation of gas hydrates is still far from commercially feasible. Beauchamp (2004) points out that, by any standard, gas hydrates will not come cheap - economically, energetically or environmentally.

For coal, the geographical distribution of reserves and resources are very uneven. About 90% of known geological occurrences, both commercially feasible and infeasible, are concentrated to just six countries (Energywatch Group, 2007). In addition, global production is also focused in a few countries (China alone made up nearly 50% of world coal output in 2009). In fact, studies have found that the peaking of Chinese coal production might occur relatively soon (Zaipu and Mingyu, 2007; Mohr and Evans, 2009; Lin and Liu, 2010). It is safe to say that the coal projections made in SRES (2000) would put significant expectations on just a few countries, but detailed studies of the most important coal nations do not indicate that such outlooks are reasonable (Höök et al., 2010b).

Coal-to-liquids (CTL) is assumed to be widely applicable and available at costs that are very low, typically below 30 dollars/barrel and even as little as 16 dollar/barrel in some cases (SRES, 2000). Such assumptions seem rather unsound compared to more recent and updated assessments, which end up around 48-75 US$/barrel (Vallentin, 2009). For example, the world CTL production (32 Mb/d) by 2100 in B2 MESSAGE scenario is higher than the world oil production at the same time. Such an output would require about 10 000 Mt of coal annually, which is more than the entire world coal production at present and has been deemed questionable (Höök and Aleklett, 2010). No details on conversion ratios and other important factors are given in SRES (2000), except for the vague technological possibilities. Is it really reasonable to expect CTL to become such a vital part of the global energy system based on little more than optimistic visions about technical possibilities?

It has also been argued that the IPCC seriously underestimates the technical challenges associated with building a new energy system. Pielke et al. (2008) showed that two thirds of all energy efficiency improvements are already built into the scenarios, as they are assuming spontaneous technological change and decarbonisation. In addition, they also demonstrated that the assumed rate of decarbonisation in 35 of the scenarios agreed poorly with reality in 2000–2010, as the rapid growth of the Chinese and Indian economies actually had increased the global carbon and energy intensities. Smil (2008) also pointed out how the scenarios ignored several key facts about global energy and its future, more specifically the Jevons paradox (Jevons, 1866) which has implied that for the last 150 years all energy efficiency improvements have actually been translated into higher energy use.

Finally, Smil (2000) and Bezdek and Wendling (2002) pinpoint that long range energy forecasters have made many inaccurate projections, mostly as overestimations. Many inaccurate forecasts were done in good faith with state-of-the-art models, competent researchers and good funding, showing the difficulty of long-range energy forecasting. To summarize, it appears as if the assumptions made in SRES are outdated and in dire need of re-evaluation and recalibration with recent historical trends. At best, the outlooks are optimistic and at worst they are unreasonable or even unrealistic.

4. How limited future fossil energy supply may impact climate

Fossil fuel depletion constrains the maximum extent of anthropogenic global warming, although this is very complex to handle in a holistic manner. Energy constraints pose a threat to the economy (Nel and Cooper, 2009), and similarly changes in human energy-related behaviours can lead to a broad range of effects on natural ecosystems (Czúcz et al., 2010). However, energy, economy and ecology are seldom seen as three interconnected problems. The lack of widely spread benchmarks for energy constraints in long-term planning has been a problem often forcing analysts to overlook this factor or oversimplify it into exogenous inputs disconnected from the reality of supply. Consequently, only a relatively limited amount of studies have pursued the effects on climate change that limited future production of fossil fuels may have.

Brecha (2008) highlighted that there are both geologic and economic reasons to expect limits in future production and made simplified emission scenarios to explore the consequences. He found that CO_2 concentrations would end up somewhere between 500 and 600 ppm, corresponding to a 2–3° C temperature increase. This is still above the proposed 2° C climate ceiling, but far less than the large temperature increases generated by the more extreme scenarios in SRES.

Kharecha and Hansen (2008) used a Bern carbon cycle model and a set of peak oil and gas-compatible emission scenarios to explore the implications of peak oil for climate change. It should be noted that they considered coal to be abundant and capable of increasing production up to 2100 in their business-as-usual outlook, resulting in 550 ppm CO_2 in the atmosphere. Four other scenarios had more constrained coal production profiles, somewhat more compatible with published peak coal projections (Mohr and Evans, 2009; Höök et al., 2010b; Patzek and Croft, 2010: Rutledge, 2011). The CO_2 concentration ended up around 450 ppm for these scenarios and they were found to be largely consistent with current assessments of the cumulative 21st century emissions needed to stabilize atmospheric CO_2 at 450 ppm even after factoring in carbon cycle feedbacks.

Another interesting approach was performed by Meinshausen et al. (2009), which used a comprehensive probabilistic analysis. The climatic consequences of burning all proven fossil fuel reserves were explored by time-evolving distributions of 26 SRES and 21 other scenarios. The conclusion was that it was a significant risk to surpass the 2° C rise in global temperature due to the cumulative emissions. Victor (2009) raised critique against the proposed measures and highlighted the political problems of a limit to cumulative emissions.

Nel and Cooper (2009) attempted to make a complete treatment of fossil energy, using logistic production models, to better understand its impact on the economy and climate. The emissions were projected to a peak at 11 GtC by 2020 before diminishing to around 6 GtC by 2100. Climate responses were examined with three carbon cycle models, where the Bern model reached atmospheric CO_2-levels of ~540 ppm by 2100 in contrast to the other two models that gave lower atmospheric concentrations. The model with the best fit to historical data peaked at around 430 ppm by 2060 before slowly decreasing. The consequent warming would be limited to about 1° C above the 2000 level.

The three studies reached somewhat different results and a lot of this can primarily be attributed to different assumptions about climate sensitivity. Zecca and Chiari (2010a) criticised Nel and Cooper (2009) for underestimating future warming, but Ward and Nel (2011) defended their position. Another paper by Zecca and Chiari (2010b) expanded the discussion of carbon cycle models, but also found that despite methodological differences analysts arrived to the same important conclusion: it is likely that fossil fuel depletion will limit the atmospheric CO_2 concentration at levels lower than the ones presented in the IPCC SRES scenarios.

5. Conclusion

Peak oil and related limits to future fossil energy extraction has this far received little attention in the climate change debate (Kharecha and Hansen, 2008). It is certainly about time to change this and stop seeing anthropogenic release of CO_2 as something detached from future energy supply questions. Energy cannot be seen as a limitless input to economic models and remain disconnected from the physical and logistical realities of supply (Nel and Cooper, 2009).

The current set of scenarios, SRES (2000), is perforated by optimistic expectations on future fossil fuel production that are improbable and some of the scenarios can even be ruled out as clearly unrealistic. The utopian thinking in SRES (Hjerpe and Linnér, 2009), is unsubstantiated in the light of recent developments and there are serious issues with the modelling of future production. Future production is dependent on much more than just geological availability. Rogner (1997), and consequently SRES (2000), places great importance on gas hydrates for a future global energy system. However, Beauchamp (2004) highlighted the fact that huge global estimates of hydrate methane are suspicious at best, and have nothing to do with the likelihood that hydrates will provide energy supply assurance for the future.

Some scenarios would also place unreasonable expectations on just a few countries or regions. Is it reasonable to expect that China would increase their coal production by a factor of 8 over the next 90 years, as implied by the A1C-scenarios? More detailed studies on China has actually placed the likelihood of a peaking in Chinese production relatively soon (Mingyu and Zaipu, 2007; Mohr and Evans, 2009; Lin and Liu, 2010). Energy forecasting on a global perspective sometimes overlooks constraints which occur on a smaller geographical level. Given the uneven geographical distribution of coal (Höök et al., 2010b), it is necessary to revise the emission scenarios to better reflect the reality of global coal production.

Similar issues can be found with expected oil and gas production in several scenarios. The grand production increases seen in optimistic outlooks are not compatible with other studies and appears to have missed the growing body of evidence that supports an imminent peaking of world oil production (UKERC, 2009). Needless to say, many of the assumptions used in SRES (2000) are outdated and in dire need of re-evaluation. Although, they are not outside the realm of extreme possibilities, it is certainly not reasonable as a sound projection compatible with historical trends and recent developments in the field of fossil fuel forecasting. The current stance, where SRES (2000) are much more optimistic about future oil supply than the oil industry and other agencies attempting to forecast future oil supply with high levels of accuracy puts the IPCC in a rather odd or even awkward position. The extreme scenarios with high temperature increases can only be obtained by disregarding supply constraints and projecting continued exponential growth extraction until 2100.

It can be argued that numerous SRES scenarios need to be revised, generally downward, regarding production expectations from fossil fuels. Several scenarios agree poorly with reality over the recent years and some can even be ruled out due to this mismatch. SRES is simply underpinned by a paradigm of perpetual growth and technological optimism as well as old and outdated estimates regarding the availability of fossil energy. Although the development of new emission scenarios is underway, there is still a long road left before they are finished and can be implemented.

The golden rule of modelling - "*garbage in – garbage out*" - should always be held dear. The validity of the climate change projections obtained from climate models can be no more than the soundness of the input that was used to derive those estimates. As anthropogenic climate change is dependent on the choices people make and the development of human society, it is necessary to use forecasts and scenarios for a future global energy system. SRES unnecessarily takes the "*optimistic side*", effectively disregarding phenomenological models derived from natural science in favour of economic models, instead of providing a sound and more balanced view on resources availability (Höök et al., 2010a).

The extent and timing of peak oil and other impending peaks are not clear, but it is obvious that these events will have a major impact on mankind's future release of CO_2 and other GHGs given the importance of fossil fuels as a source of anthropogenic emissions. While continued improvement of the understanding of climate mechanisms is being pursued, it is equally important to refine and evaluate the input that is being used in the climate models. Without proper understanding of energy system developments it is unlikely that future anthropogenic emissions can be realistically projected and neither can the climate change caused by human activities.

There are several feedback and climate mechanisms that can potentially cause severe changes in the climate at lower CO_2 concentrations than expected by the IPCC (2007). Consequently, the peaking of fossil fuels should not be seen as something that automatically solves the issue of anthropogenic climate change. Availability and future production paths will, however, put a limit on mankind's ability to emit GHGs and this must be factored into the climate change projections. The current situation, where climate models largely rely on emission scenarios detached from the reality of supply and its inherent problems is problematic. In fact, it may even mislead planners and politicians into making decisions that mitigate one problem but make the other one worse. It is important to understand that the fossil energy problem and the anthropogenic climate change problem are tightly connected and need to be treated as two interwoven challenges necessitating a holistic solution.

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4

Linking Climate Change and Forest Ecophysiology to Project Future Trends in Tree Growth: A Review of Forest Models

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1. Introduction

Climate change is already altering tree species ranges, with tree lines shifting upwards and polewards around the world (Dullinger et al., 2004; Soja et al., 2007; Harsch et al., 2009). A recent analysis of the potential effects of climate change on tree distribution in British Columbia (western Canada) suggested that important timber species including white spruce and lodgepole pine may lose suitable habitat and suffer adversely from a combination of warming trends and reduced growing season precipitation (Hamann & Wang, 2006). In contrast, species such as Douglas fir and ponderosa pine may actually expand their range and potentially show improved growth rates in parts of their existing range. A recent study in the mountains of interior British Columbia showed how at high elevation, trees historically responded positively to increased temperatures, while at low elevations trees showed a negative response to growing season maximum temperature and a positive correlation with growing season precipitation (Lo et al., 2010a, 2010b).

Given these species-specific responses it is not surprising that recent research has failed to identify direct links between warmer temperatures and observed changes in species ranges (Dullinger et al., 2004; Wilmking et al., 2004). The important ecological and socio-economic consequences of such changes have prompted multiple modelling efforts to predict the future location of habitat suitable for tree species and to assess the potential implications for tree growth of changes in climate. Defining such areas and estimating the losses or gains due to climate change in timber production have important consequences on forest management and conservation.

The most popular approaches to project future areas of suitable habitat for commercial tree species have involved analysis of historical records of tree lines in boreal and alpine environments (Dullinger et al., 2004), using climate envelope models (Hamann & Wang, 2006). Similarly, dendroclimatology (studying historical tree growth rates by analyzing tree ring width) has been used to link climate and tree growth rates (Wilmking et al., 2004; Lo et al., 2010a, 2010b). These approaches are based mostly on climatic information, although their combination with other information such as soil or topography has been used to produce maps of potential future habitat suitability (e.g. Iverson et al., 2008). Such predictions are useful to understand the relationships between climate and tree distribution, abundance and growth, and could be a starting point for helping to plan forest management at broad scales under changing climate. However, such approach has several shortcomings, which have been discussed in the scientific literature before but it seems that this discussion has not been translated into the forest management community yet. Readers can find detailed discussions on these shortcomings in Pearson & Dawson (2003) and Thuiller et al. (2008), with only a basic description following below.

2. Basic shortcomings of climate-based models for their use in forest management

The vegetation that can be seen around the globe at the present has persisted through significant climatic changes, especially in forests with ancient trees. Herb and shrub growth and distributions often respond more to changes in soil moisture and nutritional gradients, which are determined by many non-climatic variables. However, additional non-climatic factors such as competition, seed production, invasibility and migration rates will be equally or more important (Davis et al., 1998; Grace et al., 2002; Dullinger et al., 2004), as well as factors only indirectly related to climate such as rate, type and intensity of disturbances (Bergeron et al., 2004). If the ecological effects of these other determinants are well correlated with climate, climate-based models may prove useful for general planning at broad regional scales. However, at landscape and stand scales (the most meaningful for forest planning), topography, geology, slope, aspect and soils will, among other ecosystem characteristics, modify the direct effects of climate on trees (Pearson & Dawson, 2003).

Previous studies have advanced maps of future suitable habitat for commercial tree species under different climate scenarios (Hamann & Wang, 2006; Iverson et al., 2008). These models are based on the assumption that present-day tree distributions are in an equilibrium state determined by the interaction of climate with topographic and edaphic conditions. However, without accounting for dynamic changes in inter-specific competition, migration rates, seedling production, invasibility or disturbances, climate envelope models lack practical utility to support management decisions (Davis et al., 1998; Grace et al., 2002; Thuiller et al., 2008). This issue is increased when moving from continental and regional scales, where climate can be the main driver of current tree abundance and distribution, to landscape scales where local factors can be as important as climate, or even more (Pearson & Dawson, 2003).

Evidence from field studies shows that observed shifts in tree ranges are not always linked to changes in climate. For example, Harsch et al. (2009) found that only 50% of the reported treeline movements were connected to warmer temperatures, mostly because of the importance of non-climatic local factors. Bergeron et al (2004) showed that the limit between mixedwood and coniferous forest in north-eastern North America, which apparently matches climatic boundaries, is actually the result of wildfires. Therefore, climatic conditions of present species distributions are also not necessarily a valid proxy for possible future tree distributions, because forests, especially in the northern hemisphere, have not yet reached equilibrium after the last glaciation, neither fully occupy their current potential habitats (Bergeron et al., 2004; Sveming & Skov, 2004).

Responses to changing climate are species-specific and modulated through the ecophysiological responses of each tree species and their relationships with the rest of the ecosystem. The same change in climate may be beneficial for the growth of some tree species, but detrimental or non-important for other species in the same ecosystem (Lo et al., 2010a, 2010b). At high elevation, trees usually respond with more growth to increased temperatures, while at low elevations trees typically show reductions in growth when growing season water stress increases in warmer environments. While tree growth has been shown to be correlated to climate variables, the direct or indirect causal factors are often less clear. Climate can influence photosynthesis and respiration rates, nutrient dynamics and subsequently productivity through its impact on organic matter decomposition rates. Recent litter decomposition studies have shown that soil temperature and soil moisture influence mass loss and mineralization rates (Trofymow et al., 2002; Prescott et al., 2004).

As climate changes, different species will respond differently and at different speeds: some will migrate, grow faster or stop growing, but many current tree populations will remain in their present ranges (just modifying their growth rates), making it difficult for southern and lowland species to successfully establish themselves outside of their current ranges, unless the present populations at those locations are eliminated via disturbances. In addition, it is known that many species can grow well in environments warmer than their current ranges, but are prevented from doing so through mechanisms of competition with faster-growing species, not because of poor adaption to climate (Hurtley, 1991).

As a result of these changes at species and population levels, new biological communities will be created. These new communities will be established on biotopes also different from the present (i.e., same geology and topography but different climate). As a consequence, new ecosystems will appear, in a process similar to post-glaciation colonization, which in some areas is still underway. Therefore, planning future forest management under the wrong assumption that current ecosystems will just be displaced northwards or upwards and keeping their current species ensemble and growth rates seems condemned to fail (Lo et al., 2010b).

Taking into account the mentioned shortcomings, it is clear that predicting changes in tree distribution and tree growth with models based only on climatic information is not a suitable approach. Predicting geographical changes in soils, trees, lesser vegetation and wildlife at scales meaningful for forest management involves greater complexity than is included in climatic envelope models. Therefore, we advocate the use of more complex, process-based models that incorporate a greater proportion of the key determinants of possible forest futures to deal adequately with the increasing uncertainty of future tree growth and climate change effects on forests, and that account for a more detailed description of the ecophysiological processes involved in tree growth rates (Kimmins et al., 2008). A review of the most important forest models of this kind follows below.

3. Forest models linking climate and ecophysiology

There is a wide variety of forest models available nowadays, simulating ecophysiological processes from leaf to landscape levels. Among them, fifteen stand level models used for predicting climate change effects have been reviewed and compared in this chapter. Although nowadays there are many simulation models capable to access climate change impacts, we have focused our review on those whose conceptual models or model structures are defined at stand level, which is the most meaningful level for forest management. A list of the basic features of these models can be found in Tables 1 and 2.

3.1 PnET

PnET is a process model of stand dynamics. It uses monthly time steps because the developers assumed the aggregation of daily data into months would not cause a significant loss of information. This assumption has been tested and proven before (Aber & Federer, 1992). The model structure focuses on water and carbon balances. It deals with climate change via temperature and precipitation (water balance), but it does not include the effects of atmospheric CO_2 concentration. The physiological process used to produce biomass is similar to the CENTURY model (described below). PnET has similar structures to simulate carbon and water balance to FOREST-BGC and BIOMASS (see below) models, with the exception that their time steps are different (Aber & Federer, 1992). The central concept behind the PnET model is that photosynthesis is a function of foliage nitrogen, and water use efficiency is a function of vapour pressure deficit. Therefore, the function of maximum net photosynthesis per unit leaf area (NetPsnmax, μmol CO_2 m^{-2} sec^{-1}) and foliage N content (N%) is:

$$\text{NetPsnmax} = -5.98 + 4.86 \times \text{N\%} \tag{1}$$

Aber & Federer (1992) assume that the basal respiration of the foliage is 10% of the basic photosynthesis rate, and therefore the maximum gross photosynthesis (GrossPsnmax) is 1.1 times the maximum net photosynthesis. In this model, the authors assumed the actual gross photosynthesis (GrossPsn) would be affected by temperature (DTemp), water stress (Dwater) and vapour pressure deficit (DVPD) as indicated in Equation (2).

$$\text{GrossPsn} = \text{GrossPsnmax} \times \text{DTemp} \times \text{Dwater} \times \text{DVPD} \tag{2}$$

The latest improvement of this model includes the development of a soil organic submodel to enhance the model description of carbon and nitrogen coupling and to study changes in ecosystem carbon storage across a nitrogen deposition gradient (Tonitto et al., 2009).

3.2 Forest-BGC and tree-BGC

Forest-BGC (Running & Coughlan, 1988; Coughan & Running, 1997) is a process-based ecosystem model that runs in a mixed time scale (daily and yearly; Running & Coughlan, 1988; Korol et al., 1995). It is used to predict stand growth and to provide site quality index estimations. The key processes considered in this model are the effects of carbon, nutrient and water availability on forest ecosystems. Short-wave radiation, air temperature, dew point and precipitation are daily input data used to drive the model (Running & Coughlan, 1988). The model calculates daily canopy photosynthesis (PSN; kg CO_2 day^{-1}) by multiplying CO_2 diffusion gradient (ΔCO_2; kg m^{-3}), radiation and temperature-controlled mesophyll CO_2 conductance (CM; m s^{-1}).

$$\text{PSN} = [(\ \Delta CO_2 * \text{CC} * \text{CM}) \ / \ (\text{CC} + \text{CM})] * \text{LAI} \times \text{DAYL} \tag{3}$$

The other parameters of this equation are CC: canopy conductance (m s^{-1}), LAI: leaf area index (m^2 m^{-2}), and DAYL: day length for a flat surface (s day^{-1}). The mesophyll CO_2 conductance (CM) is calculated from three modifier functions: nitrogen (CMn), light (CMq) and temperature (CMt). These modifiers are all scaled from 0 to 1.

$$\text{CMn} = 67.0\ \text{LEAFN} \tag{4}$$

$$CMq = (Q - Q_0) / (Q + Q_{0.5}) \tag{5}$$

$$CMt = (TMAX - TAIR) \times (TAIR - TMIN) / TMAX^2 \tag{6}$$

LEAFN is leaf nitrogen concentration (fraction of dry weight). Q is canopy average radiation (kJ m^{-2} day^{-1}). Q_0 is the photosynthesis light compensation point (kJ m^{-2} day^{-1}). $Q_{0.5}$ is radiation level where CMq is 0.5 of maximum (kJ m^{-2} day^{-1}). TMAX and TMIN are high and low temperature (°C) at photosynthesis compensation points. TAIR is daylight average air temperature. Based on those values, the model calculates daily canopy photosynthesis, then subtracts the value of night canopy respiration (calculated from night average temperature and LAI) and gets daily net canopy carbon fixation.

This model considers respiration because it is a key process of the carbon budget. Daily maintenance respiration of stem and root biomass is calculated from compartment size and average air and soil temperature under a $Q_{10} = 2.3$ assumption

$$R_{l,s,r} = \alpha \exp(0.085\ TEMP) \times C_{l,s,r} \tag{7}$$

where $R_{l,s,r}$ is maintenance respiration of leaf, stem and root compartments (kg day^{-1}); α is scaling factor for leaf, stem and root compartments (0.00015, 0.0010 and 0.0002 $kg^{-1}kg^{-1}$) ; and 0.085 is a scalar that gives a Q_{10} value of 2.34. In Equation 7, TEMP (°C) represents night and daily average air temperature and soil temperature. Night time average temperature is used for leaf respiration, daily average is used for stem respiration, and soil temperature is used for root respiration. $C_{l,r}$ is carbon storage either in the leafs or roots. C_s is stem respiration calculated by the function

$$C_s = \exp(0.67 \ln(\text{stem carbon storage})) \tag{8}$$

The yearly growth respiration is calculated as a fixed fraction of the carbon allocated to the leaf, stem and root compartments. The coefficients are usually obtained from literature and are independent of temperature. Unlike PnET, Forest-BGC considers nutrient cycling and therefore it has a decomposition component. The annual litter decomposition function is:

$$DECOMP = (-3.44 + 0.100AET) - ((0.0134 + 0.00147\ AET) \times LIG) \tag{9}$$

where DECOMP is annual percent weight loss of fresh litter (% $year^{-1}$) and LIG is initial litter lignin concentration (% dry weight). Actual annual evapotranspiration (AET; mm $year^{-1}$) is calculated from a daily model of evapotranspiration.

One of the shortcomings of Forest-BGC is that the canopy is homogeneous. Therefore, although the leaf area index is proportional to the depth of the canopy, it may not capture the water and carbon budgets accurately (Running & Coughlan, 1988). Because of the lack of a management component, it cannot be a management tool for foresters. However, it is a suitable research tool to predict the impact of climate change. In addition, the model offers a link between input data and GIS databases which is useful for application of data collected from regional studies. This model has also been expanded into a series of related models (Tree-BGC, Fire-BGC) and it has also been combined with other models (PnET-BGC) to overcome its weaknesses. Forest-BGC has been widely used to predict climate change effects on natural disturbances, being the latest application of Forest-BGC estimating carbon dynamics in forests in Portugal (Rodrigues et al., 2010).

Tree-BGC, a variant of FOREST-BGC model, is also a stand level, process-based, mixed time scale (daily and yearly) ecosystem model. Most parts of these two models are very similar except the spatial scales are different (e.g. tree-level model vs. stand-level model). The purpose of Tree-BGC is the same as Forest-BGC: to calculate carbon, water and nitrogen flows in forest ecosystems (Korol et al., 1995). The only difference of these two models is that in Tree-BGC, all the simulated processes are based on individual tree physiological characteristics, and it focuses on light competition and ignores decomposition. To scale up the simulation results from individual tree level to the stand level, Tree-BGC has to make an important assumption: the responses of individual photosynthesis processes under different constraining factors at tree level are same at stand level (Korol et al., 1995). Most structures of Tree-BGC are very similar to the ones in Forest-BGC. Therefore, each tree annual canopy photosynthesis (PSNi; kg C tree^{-1} year^{-1}) is calculated as:

$$\mathrm{PSN_i = PSN\ x} \left(\frac{PAR_i}{\sum PAR_i} \right) \tag{10}$$

where PSN is stand annual canopy photosynthesis (kg C stand^{-1} year^{-1}); PARi is individual tree's photosynthetically active radiation (MJ m^{-2}), and the stand annual canopy photosynthesis is the sum of tree annual canopy photosynthesis. Not only the photosynthesis, but also the maintenance respiration has been modified in Tree-BGC compared to Forest-BGC. The maintenance respiration of each stem (MRs; kg C) is multiplied by stem respiration coefficient (f; kg C^{-1} day^{-1} kg^{-1}); temperature (T) controlled function and respiration volume (RV; m^3 ha^{-1}) which is the sum of phloem and live sapwood volume.

$$\mathrm{MRs} = f \exp\,(0.085\mathrm{T})\ \mathrm{RV} \tag{11}$$

The maintenance respirations of leaves (MRLi; kg C) and roots (MRri; kg C) are allocated to each tree (i) proportionally to its leaf and root carbon. Each tree's yearly maintenance respiration (MRi; kg C year^{-1}) is calculated by following the function:

$$\mathrm{MRi = MRLi\ x\ MRsi + MRri} \tag{12}$$

As mentioned before, Tree-BGC does not simulate litter decomposition, and therefore is not suitable to explore the link between tree and soil processes.

3.3 BIOMASS

BIOMASS (McMurtrie et al., 1990) is a stand-level process model that works at daytime steps. It has been used to simulate forest carbon, water-balance and to predict forest growth (McMurtrie et al., 1990; McMurtrie & Landsberg, 1992). The two main components of the model are the canopy assimilation of atmospheric carbon and plant-soil water balance. Canopy carbon assimilation is simulated as a function of an elaborated simulation of stomata processes (involving radiation, CO_2 concentration, temperature, soil water, etc.) and foliage nitrogen content (McMurtrie et al., 1990, 1992; McMurtrie & Landsberg, 1992; McMurtrie & Wang, 1993). Tree respiration is used to estimate biomass production, carbon allocation to different tree components, and litterfall rates (McMurtrie et al., 1989). There is no decomposition component in this model.

The model separates the canopy vertically into three homogenous layers and simulates detailed stomata processes for each layer. BIOMASS can be calibrated with standard daily weather data (McMurtrie et al., 1990). Because it simulates the details of the stomata to control photosynthesis and it uses climatic inputs including CO_2 concentration, temperature and soil moisture, it is a powerful tool for predicting climate change impact as long as the calculated rates of all the physiological process remain the same.

As for the water balance component, BIOMASS considers the impacts of different silviculture strategies on the dynamics of soil water. Therefore, in regions where soil moisture is the major growth limiting factor, BIOMASS can be used as a management tool to explore the impacts of different practices designed to increase water availability for trees. One downside of this model is that BIOMASS is a purely physiological process-based model, which means it shares the strengths, but also the main shortcoming of all mechanistic models: the requirement of many and complex data for calibration (McMurtrie et al., 1990). BIOMASS has been recently used to estimate the carbon balance of coniferous forests in response to different harvesting strategies in Sweden (Bannwarth, 2009).

3.4 LINKAGES

The LINKAGES model is designed to help to understand the ecosystem carbon and nitrogen storage and cycling under climate and soil moisture constraints (Pastor & Post, 1985). It can be seen as an offspring of the JABOWA model (Botkin, 1993). The model time step is yearly, but simulations of the effects of temperature and precipitation are based on monthly data (Pastor & Post, 1985). The model contains two parts: the environment and the tree species population components. The environmental component includes three subcomponents: TEMPE (temperature), MOIST (soil moisture) and DECOMP (decomposition), which are used to determine the site conditions. The population component also has three subroutines: BIRTH, GROW and KILL. These are used to calculate the population dynamics. These two groups are connected by GMULT (modifier for optimal birth rate, annual stem growth and mortality; Pastor & Post, 1985). Although the model structure and concepts are inherited from JABOWA, LINKAGES focuses more on how stand structure changes than on how stand productivity changes (the main focus of JABOWA).

Sunlight is the driving variable for stand dynamics (Pastor & Post, 1985). In the TEMPE subroutine, LINKAGES uses a random number generator algorithm to generate daily temperature based on each month's mean and standard deviation, and sums the number of degree days for the year. In MOIST, it uses Thornthwait and Mather's water-balance method to calculate actual evapotranspiration as the input to DECOMP. LINKAGES also considers soil physical characters (depth, texture), monthly temperature and rainfall to calculate the dry days of the year as an input to the GMULT subroutine. In the DECOMP subroutine, it calculates mass loss, nitrogen immobilization and mineralization, lignin decay and CO_2 loss from decomposing litter cohorts and humus. LINKAGES has been lately adapted to the conditions of New Zealand by McGlone et al. (2010).

As mentioned above, the simulation objective of LINKAGES is different from the other models reviewed. Unlike other models that calculate either GPP or NPP, LINKAGES calculates annual diameter and height increment as a function of site and climate variables (Pastor & Post, 1985). Because it follows the ideas of JABOWA, it could be considered more similar to a plant dynamics model than to a stand production model. Therefore, it does not contain any management tools. As a consequence, it can be considered more of a research model than a model applied to forestry. However, because many stand production dynamic simulation models in use today use the concepts in LINKAGES, it is worth considering.

3.5 G’DAY

G’DAY is more a plant-soil model than a stand simulation model (Medlyn et al., 2000). It describes how photosynthesis and nutrient factors interact with each other (Comins & McMutrie, 1993). The model is designed to predict the forest growth response to elevated atmospheric CO_2 concentrations and temperature. It predicts the response from decadal to century time scales (Medlyn et al., 2000). Earlier versions of G’DAY were linked to CENTURY (Parton et al., 1993). The latest version uses the BEWDY model (Medlyn, 1996) to replace the plant production calculated by CENTURY, but it still keeps other components of this soil model (i.e. soil carbon and nutrient dynamic components). This is because the model developers think BEWDY is more mechanistic and therefore it considers the temperature and CO_2 effects on plant photosynthesis and respiration better than CENTURY (Medlyn et al., 2000). When developing G’DAY, the authors considered two approaches to represent plant respiration biomass loss because how to deal with this process is still under discussion among ecosystem modellers (Medlyn et al., 2000). In the first approach, respiration is separated into maintenance respiration (Rm) and growth respiration (Rg). Maintenance respiration is assumed to be proportional to the non-structural nitrogen content of the plant. The growth respiration is calculated by a ratio (Yg; between 0 and 1) of the difference between potential photosynthesis (or gross primary production, growth canopy photosynthesis; Pg) and maintenance respiration (Rm). Therefore, net primary production (NPP) is the result after potential photosynthesis minus maintenance respiration minus growth respiration:

$$\mathrm{NPP} = (1 - \mathrm{Yg}) \times (\mathrm{Pg} - \mathrm{Rm}) \tag{13}$$

For the second approach, Medlyn et al. (2000) assumed that respiration is a constant fraction of the canopy photosynthesis, similarly to the assumption in PnET (see above):

$$\mathrm{NPP} = f\,\mathrm{Pg} \tag{14}$$

being f a factor of carbon use efficiency independent of atmospheric CO_2 and air temperature (Medlyn et al., 2000). Gross primary production (Pg) is calculated from the BEWDY model in which the photosynthesis rate depends on canopy leaf area index, the intensity of beam (direct) and diffuse radiation, leaf N content, air temperature and CO_2 concentration. Details can be found in Medlyn (1996).

There is no decomposition rate function in the model, but decomposition is implicit in each component of the nitrogen cycle, with the decomposition rates being temperature dependent. G’DAY is an annual time step model dealing with atmosphere CO_2 and temperature effects. No management tools are included in this model, but it does predict long-term forest production as an index of the impact of climate change. The model can also be used to estimate the effects of other human impacts on the environment, such as nitrogen deposition (Dezi et al., 2010).

3.6 3-PG

3-PG (Physiological Principles in Predicting Growth) is a model based on similar ideas on how forest stands grow to the ones used in LINKAGES and other models developed later. It is a physiological process stand-level growth model that uses monthly weather data as input (Landsberg & Waring, 1997). The model is based on well-established physiological principles and empirical data and therefore does not need much local calibration to predict forest growth. Generally speaking, it uses absorbed photosynthetically active radiation to calculate gross primary production (PG) and then uses the ratio (Cpp) of net primary production (PN) to gross primary production (Cpp = 0.45 ± 0.05) to calculate net primary production. The model developers assume that the ratio is a constant. 3-PG employs data and functions of growth effects under different growing conditions from the literature to create a simple relationship between root growth and turnover rate to estimate the below-ground carbon allocation. To simulate the above-ground components, the model uses carbon allometric ratios, age effects and the 3/2 power law to constrain tree growth patterns and stand dynamics (Landsberg & Waring, 1997). Gross primary production is the product of $\varphi_{p.a.u.}$ (utilizable, absorbed photosynthetically active radiation) and α_c (canopy quantum efficiency coefficient = 0.03 mol C (mol photon)$^{-1}$ or 1.8 g C MJ^{-1}). The model uses α_c as a constant. The utilizable, absorbed photosynthetically active radiation $\varphi_{p.a.u.}$ is calculated from modifiers that come from monthly means of day-time vapour pressure deficit, soil water, temperature, and tree age:

$$PG = \varphi_{p.a.u.} \times \alpha_c \tag{15}$$

3-PG does not have a strong nutrient component; the only consideration of nutrients in 3-PG is that nutrient availability will affect root growth therefore changing carbon allocation (Landsberg & Waring, 1997). This nutrient availability is defined by an empirical, site-dependent coefficient. Although 3-PG is not as complicated as other models (BIOMASS, G'DAY, etc.), it incorporates important ideas about how forest stands produce biomass. However, some of the parameters used in the model are not regularly measured in the field and could be very difficult to be accurately calibrated. The model does not consider canopy complexity, does not have a water balance component, and does not attempt to be a management tool, but it contains the simulation of physiological processes which have been proven good enough to produce accurate prediction for some experimental sites (Landsberg & Waring, 1997).

3-PG is becoming an increasingly popular model for forest research, due to its capacity of being used for landscape modelling by linking it to satellite observations, and its relative lower calibration requirements (Coops et al., 2010). However, the model can be very sensitive to parameters that are very difficult to measure and are not easily related to physiological data measured in the field (Rodríguez-Suárez et al., 2010).

3.7 CENTURY, TREEDYN3 and TRIPLEX

Combining the strengths of 3-PG, CENTURY and TREEDYN3, TRIPLEX was built as a meta-model of existing models, to avoid the difficulties of the model development stage. Linkages of existing models as a meta-model instead of spending time and money to develop a completely new model to represent the ecosystem is a global trend (Peng et al., 2002). As we have already introduced 3-PG, here we will introduce CENTURY and TREEDYN3, and then describe the TRIPLEX model.

CENTURY (Parton et al., 1993) is a terrestrial biogeochemistry model. It focuses on the plant-soil linkage, which therefore is the target of the simulation, rather than the forest stand. It has a detailed soil nutrient component (Parton et al., 1993). CENTURY represents the relationship between climate, forest management, soil characters, plant productivity and decomposition. It incorporates key process relating to carbon assimilation and turnover from existing models. It contains three main components: soil organic C model, N submodel and an aboveground production model. The soil organic matter submodel contains three major components: active soil organic matter, a slow organic matter pool, and a passive stable organic component. This well developed submodel, which is used in many other models (G'DAY and TRIPLEX), uses temperature and moisture as two of the factors, which control decomposition rate. For temperature, it uses mean monthly soil temperature as the input. For moisture, the input is the ratio of stored soil water plus monthly precipitation to potential evapotranspiration. The decomposition model is as follows:

$$\text{For I} = 1,2 \qquad \frac{dC_I}{dt} = K_I L_C A C_I \tag{16}$$

$$\text{For I} = 3 \qquad \frac{dC_I}{dt} = K_I A T_m C_I \tag{17}$$

$$\text{For I} = 4,5,6,7,8 \qquad \frac{dC_I}{dt} = K_I A C_I \tag{18}$$

$$T_m = (1 - 0.75T) \tag{19}$$

$$L_C = e^{(-3Ls)} \tag{20}$$

C_I and K_I stand for carbon in different pools and the maximum decomposition rate (year^{-1}) of that pool; I = 1: surface material (K_1 = 3.9); I = 2: soil structure material (K_2 = 4.9); I = 3: active soil organic matter (K_3 = 7.3); I = 4: surface microbes (K_4 = 6.0); I = 5: surface metabolic material (K_5 = 14.8); I = 6: soil metabolic material (K_6 = 18.5); I = 7: slow soil organic matter (K_7 = 0.2) and I = 8: passive organic matter (K_8 = 0.0045). A is the combined effect of soil moisture and soil temperature. Tm is the soil texture effect (silt plus clay content) on the active soil organic matter component. Ls is the structural material and Lc is the impact of lignin content. The nitrogen submodel is similar to the soil C submodel. Organic N is the product of the carbon and the N: C ratios of the soil stable component that receives the C.

CENTURY can simulate plant production for different ecosystems (i.e. grasslands, agricultural crops, forests and savannah). However, the model has been developed to simulate grasslands. The general idea is that above-ground production is a function of soil temperature, available water and self-shading factor. But it also relates the soil nutrient supply (nitrogen, phosphorus and sulphur).

Unlike most of the physiological models, CENTURY does not consider detailed solar radiation effects. The model developers did not consider the effects of changes in the plant community (Parton et al., 1993). Because the time step is monthly, it is not sensitive to daily rainfall patterns and there is a lag effect between nutrient effects and photosynthetic storage in plant. CENTURY is not considered to be a tool for foresters and there is no representation of silviculture strategies in this model, but it has been recently used to explore ecosystem dynamics in grasslands (Feng and Zhao, 2011)

TREEDYN3 is a process model, which predicts tree growth, carbon and nitrogen dynamic in a single species, even-aged forests stand (Bossel, 1996). It also has a description of stand structure. The model is different from other models in that it introduces diurnal and seasonal variation in physiological processes (i.e. photosynthesis; seasonal dynamic of respiration, phenology and soil processes) and it considers energy and mass balance of carbon and nitrogen flow (Bossel, 1996). The reason for using diurnal and seasonal scales is because these physiological processes are sensitive to daily and seasonal variation. TREEDYN3 is designed to explore the effects of climate change, air pollution, and different forest management strategies (Bossel, 1996).

In this model the photosynthate storage A is the result of net photosynthetic production (α_{prod}) and assimilate relocation (α_{reloc}) minus the assimilate consumption from growth (α_{grow}), respiration (α_{resp}) and death (α_{dead}).

$$\frac{dA}{dt} = \alpha_{prod} + \alpha_{reloc} - \alpha_{resp} - \alpha_{grow} - \alpha_{dead} \tag{21}$$

For details of each part, please see Bossel (1996). The respiration submodel calculates respiration consumption from the following function:

$$\alpha_{resp} = k_{Tr}\left[\sigma_L\left(1-\frac{h}{24}\right)L + \sigma_w bW + \sigma_F\tau_F F\right] + k_{Ts}\sigma_R R \tag{22}$$

where k_{Tr} and k_{Ts} are temperature modifiers of air and soil temperatures; σ_L, σ_W, σ_F and σ_R are the respiration rates of leaves, wood, fruits and fine roots; L is leaf mass, b is the proportion of respiring wood volume (sapwood) and τ_F is the respiration period when there is fruit, and R is fine root mass. The model developers considered respiration because it is a limiting factor for tree growth. Litter and humus decomposition (C_{GE}, C_{SE}) are calculated with the following two functions:

$$C_{GE} = (1-\chi)\rho_{dec}k_{Ts}C_G \tag{23}$$

$$C_{SE} = \rho_{min}k_{Ts}C_s \tag{24}$$

where ρ_{dec} and ρ_{min} are normal decomposition rate and specific humus mineralization rate, χ is the humification ratio, C_G is the carbon in litter, and C_S is the carbon in humus.

The TREEDYN3 model has many features different from other models. First, it is the only model considering mass and energy balance of carbon and nitrogen flows as a constraint. Second, it follows the current trend of forest model development; it's a hybrid model (see section 4). Third, it introduces diurnal and seasonal variation. In addition, it is also a management tool for foresters who are considering thinning and harvest effects on forest yield (Bossel, 1996). The major shortcoming of the model is that it is only suitable for even-age artificial forest stands, because during the simulation, all trees are of uniform size. Therefore, when alternative silviculture strategies are simulated, it does not produce realistic results. However, it's still a good tool for predicting long-term effects of climate change, air pollution and managements. TREEDYN3 has also been used to simulate the tree sub-modules in other models (Miehle et al., 2010), with TRIPLEX as the best example of this linkage.

TRIPLEX is a hybrid, monthly-time step, stand model used for predicting forest growth and yield and ecosystem carbon and nitrogen dynamics. As noted above, it integrates three well-developed process-based models: 3-PG (Landsberg & Waring, 1997), CENTURY (Parton et al., 1993) and TREENYD3 (Bossel, 1996). It borrows the soil submodel from CENTURY, and the growth and yield components from 3-PG and TREENYD3. It has four major submodels: forest production submodel, soil C and N dynamics submodel, forest growth and yield submodel and soil water balance submodel (Peng et al., 2002). The TRIPLEX model uses the approach from 3-PG to calculate gross primary productivity (GPP),

$$GPP = k \times I_m \times LAI \times f_a \times f_t \times f_w \times f_d \tag{25}$$

where GPP is a function of monthly received photosynthetically active radiation; PAR (I_m), leaf area index (LAI), forest age (f_a), monthly mean temperature (f_t), soil drought (f_w), percentage of frost days in a month (f_d) and a conversion constant (k). It combines the idea that net primary production (NPP) is a fixed proportion of gross primary productivity (GPP), and NPP is affected by nutrient availability.

$$NPP = C_{NPP} f_r GPP \tag{26}$$

C_{NPP} is a fixed fraction (0.47 ± 0.04) and f_r is the modifier indicating available N. As a result, there is no respiration component in this model. The decomposition part adapts the approach of CENTURY, but it also adds some additional components.

$$R_i = K_i x\, C_i x\, M_d x\, T_d \tag{27}$$

$$R_{i'} = \min\left(R_i, \frac{K_i S_N (B_s B_t)}{(pB_s - pB_t - (1-p)B_t R_e)}\right) \tag{28}$$

where R_i and $R_{i'}$ are potential decomposition and actual decomposition of each carbon pool respectively; K_i, C_i, M_d and T_d are maximum decomposition rate, carbon stock in particular pool, soil moisture and temperature modifier respectively. In the restriction function, decomposition is obtained from the lower value between potential decomposition and restricted decomposition. In this function, S_N is soil mineral N, B_s and B_t are C:N ratio of source and target C pools, p is the proportion of decomposed C which flows into other pools and R_e is the fraction of soil organic N generated from C decomposition process which flows into the mineral N pool.

The approach developed in TRIPLEX is new in that it combines existing models instead of building a new model to predict the climate change effects. The difficulty with this approach is the need to combine different time scales. However, comparing the simulation results with observed data suggests good model performance. As TREEDYN3 incorporates silviculture strategies, TRIPLEX can be used as a management tool, as in its latest application to simulate forest response to pre-commercial thinning (Wang et al., 2010).

3.8 Carbon flux models: BEPS, EASS and CLASS

The common features of these models are that they are research tools that try to simulate short time spans (usually time steps are hours). These models can simulate large regions by using satellite data on vegetation cover combined with weather data as inputs. However, there are no management tools included in the models. This, together with the complex methods required to measure carbon fluxes (flux towers, eddy covariance measurements, etc.) make these models unsuitable for forest management.

BEPS (Boreal Ecosystem Productivity Simulator; Liu et al., 1997) was developed at the Canadian Centre for Remote Sensing (CCRS) and the University of Toronto for short-term carbon cycle simulations. This model has been used with remotely sensed estimates of leaf area index (LAI) and land cover, and with Soil Landscapes of Canada (SLC), forest inventory and gridded meteorological data to make regional and national estimates of NPP, NEP and net biome productivity (NBP) (Chen et al., 2003). CO_2 fixation in BEPS is constrained by leaf stomatal conductance, calculated empirically from canopy temperature, humidity and global radiation (Humphreys et al., 2003).

EASS (Ecosystem–Atmosphere Simulation Scheme) is a remote sensing-based ecosystem model, developed at the University of British Columbia (Chen et al., 2007). EASS has the following characteristics: (i) satellite data are used to describe the spatial and temporal information on vegetation, and in particular, the use of a foliage clumping index, in addition to leaf area index to characterize the effects of three-dimensional canopy structure on radiation, energy and carbon fluxes; (ii) energy and water exchanges and carbon assimilation in the soil–vegetation–atmosphere system are fully coupled and are simulated simultaneously; (iii) the energy and carbon assimilation fluxes are calculated with stratification of sunlit and shaded leaves to avoid shortcomings of the "big-leaf" assumption.

CLASS (Verseghy, 2000) was developed by the Meteorological Service of Canada (MSC) for coupling with the Canadian General Circulation Model (CGCM) in regional climate–ecosystem interactions. This model includes physically based treatment of energy and moisture fluxes from the canopy as well as radiation and precipitation cascades through it, and incorporates explicit thermal separation of the vegetation from the underlying ground. Seasonal variations of canopy parameters are accounted for. The morphological characteristics of the 'composite canopy' associated with each grid square are calculated as weighted averages over the vegetation types present. Each grid square is divided into a maximum of four separate subareas: bare soil, snow-covered, vegetation-covered, and snow-and-vegetation covered. CLASS has participated in the International Project for Intercomparison of Land–Surface Parameterization Schemes (PILPS). Versions of the CLASS biospheric component (C-CLASS) are being developed at McMaster University (C-CLASSm) (Arain et al., 2002) and the University of Alberta (C-CLASSa) (Zhang et al., 2004). In C-CLASSa, soil water deficits effects constrained CO_2. In CCLASSm, CO_2 fixation was constrained directly by soil water content.

4. The hybrid modelling approach: FORECAST climate

As we have shown in the previous section, simulation models can organise the complexity of information and data into a coherent tool for analysing systems at these various scales (Messier et al., 2003). The process-based models described in the previous section use the scientific knowledge available to link several ecosystem variables trough equations, but the difficulty in getting the right coefficients used in those equations usually produces unrealistic or unreliable predictions. On the other hand, statistic, simple growth and yield models are based on field data and they usually produce good estimations if the simulated conditions are similar to the recorded ones, but they do not contain explanation and therefore cannot be used to explore ecological interactions or to generate estimations in areas outside of the range of recorded data (Kimmins, 2004). To reduce the inconvenient of both types of models but keeping the advantages of both approaches, hybrid models have been developed. Combination of historical bioassay models with process simulation can give it sufficient flexibility to produce believable yield predictions under the types of changed growth conditions that are expected. A more detailed analysis of the philosophy behind hybrid predictors is given in Kimmins et al. (2010).

One example of process-based, ecophysiological model that accounts for the effects of climate change but that is designed for real forest management applications is FORECAST-

Climate. This model has been developed and designed to give it the capability to explicitly represent the potential impacts of climate change on forest growth and development. In the general version of FORECAST (Kimmins et al., 1999), tree growth is limited by light and nutrient availability, and no climate is represented. The projection of stand growth and ecosystem dynamics is based on a representation of the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources (Figure 1). The rates of these processes are calculated from a combination of historical bioassay data (biomass accumulation in component pools, stand density, etc.) and measures of certain ecosystem variables (e.g. decomposition rates, photosynthetic saturation curves) by relating 'biologically active' biomass components (foliage and small roots) with calculations of nutrient uptake, the capture of light energy, and net primary production. The model generates a suite of growth properties used to model growth as a function of resource availability and competition (Kimmins et al., 1999). They include (but are not limited to): 1) Photosynthetic efficiency per unit of foliage biomass; 2) Nutrient uptake requirements; 3) Light-related measures of tree and branch mortality. Nutrient cycling is simulated through a mass balance approach. Nitrogen that is incorporated into the soil solution through atmospheric deposition, seepage, mineral weathering, and litter mineralization is calculated.

Model	**Scale**		**Climate input**			**Physiological processes**				**Driving function**		**Nutrient Cycling**
	Spatial	Temporal	Tem.	Moist.	[CO2]	Photosynthesis[1] GPP	/ NPP	Resp.	Decom.	LAI	Foliage [N]	N
PnET	stand	monthly	Y	Y	-	2nd	1st	Y	-	-	Y	-
FOREST - BGC	stand	daily / yearly	Y	Y	Y	1st	2nd	Y	Y	Y	-	Y
TREE-BGC	tree to stand	daily	Y	Y	-	1st	2nd	Y	-	Y	-	Y
BIOMASS	stand	daily to monthly	Y	Y	Y	1st	2nd	Y	-	Y	?	-
LINKAGES	tree to stand	monthly	Y	Y	-	-	1st	-	Y	?	-	Y
G'DAY	stand	yearly	Y	-	Y	1st	2nd	Y	Y	Y	Y	Y
3-PG	stand	monthly	Y	Y	-	1st	2nd	-	-	Y[2]	Y[2]	-
CENTURY	stand	monthly	Y	Y	-	Y[3]	Y[3]	-	Y	Y[4]	Y[4]	Y
TREEDYN3	stand	monthly/ seasonal	Y	-	-	1st	2nd	Y	Y	Y[5]	Y	Y
TRIPLEX	stand	monthly	Y	Y	Y	1st	2nd	-	Y	Y	-	Y
FORECAST	stand	yearly	-	-	-	-	1st	-	Y	-	Y	Y
FORECAST Climate	stand	daily	Y	Y	-	-	1st	-	Y	-	Y	Y

Table 1. Comparison of different ecosystem processes, climate input included and main features in several stand-level models. Abbreviations: Y: Yes, Tem: Temperature, Moist: soil moisture, [CO_2]: atmospheric CO_2 concentration, Resp: respiration, Decom: litter decomposition, LAI: Leaf Area Index, Foliage [N]: N concentration in foliage. Notes: 1) Photosynthesis 1st / 2nd indicates the order in which GPP and NPP are calculated; 2) Driving function is Canopy Quantum Efficiency Coefficient; 3) Potential production; 4) Driving function is biomass; 5) LAI affects radiation.

Model	**Stomata**	**Canopy Layers**	**Ecological levels**			**Manage ment tool**	**GIS input**	**Reference**
			Soil	Tree	Forest			
PnET	-	Y	-	-	Y	-	-	Aber & Federer (1992)
FOREST-BGC	Y	-	Y	-	Y	-	Y	Running & Coughlan (1988)
TREE-BGC	-	shade effect	-	-	Y	-	-	Korol et al. (1995)
BIOMASS	Y	Y	-	-	Y	Y	-	McMurtrie et al. (1989)
LINKAGES	-	shade effect	-	-	Y	-	-	Pastor & Post (1985)
G'DAY	Y	shade effect	Y	-	Y	-	-	Medlyn (1996)
3-PG	-	-	-	-	Y	-	Y	Landsberg & Waring (1997)
CENTURY	-	-	Y	Y		-	-	Parton et al. (1993)
TREEDYN3	-	Y	-	-	Y	Y	-	Bossel (1996)
TRIPLEX	-	-	Y	-	Y	Y	Y	Peng et al. (2002)
FORECAST	-	Y	Y	Y	Y	Y	-	Kimmins et al. (1999)
FORECAST Climate	-	Y	Y	Y	Y	Y	-	Seely et al. (1997), Kimmins et al. (2010)
BEPS	Y	-	Y	-	Y	-	Y	Liu et al. (1997)
EASS	Y	clumping index	Y	-	Y	-	Y	Chen et al. (2007)
CLASS	Y	shade effect	Y	-	Y	Y	Y	Verseghy, (2000)

Table 2. Comparison of main features in several process forest models; Y: Yes.

If this amount is more than what the combination of what the soil can retain (as defined by the cation and anion exchange capacities) and trees can uptake, the difference leaches out of the system. Soil fertility in FORECAST is represented based on a bioassay approach in which empirical input data describing decomposition rates and changes in chemistry as decomposition proceeds allow for calculation of nutrient release from litter and humus (Fig. 1). Carbon allocation in response to soil fertility and tree nutrition is based on empirical biomass ratios and biomass turnover rates (e.g. number of years of leaf retention for evergreens) for sites of different fertility, and on literature or locally-obtained values for variation in fine root turnover along fertility gradients. Moisture limitation on growth is currently based on moisture-determined maximum foliar biomass and thus maximum foliar N. FORECAST has shown high accuracy when applied to real management operations (Blanco et al., 2007).

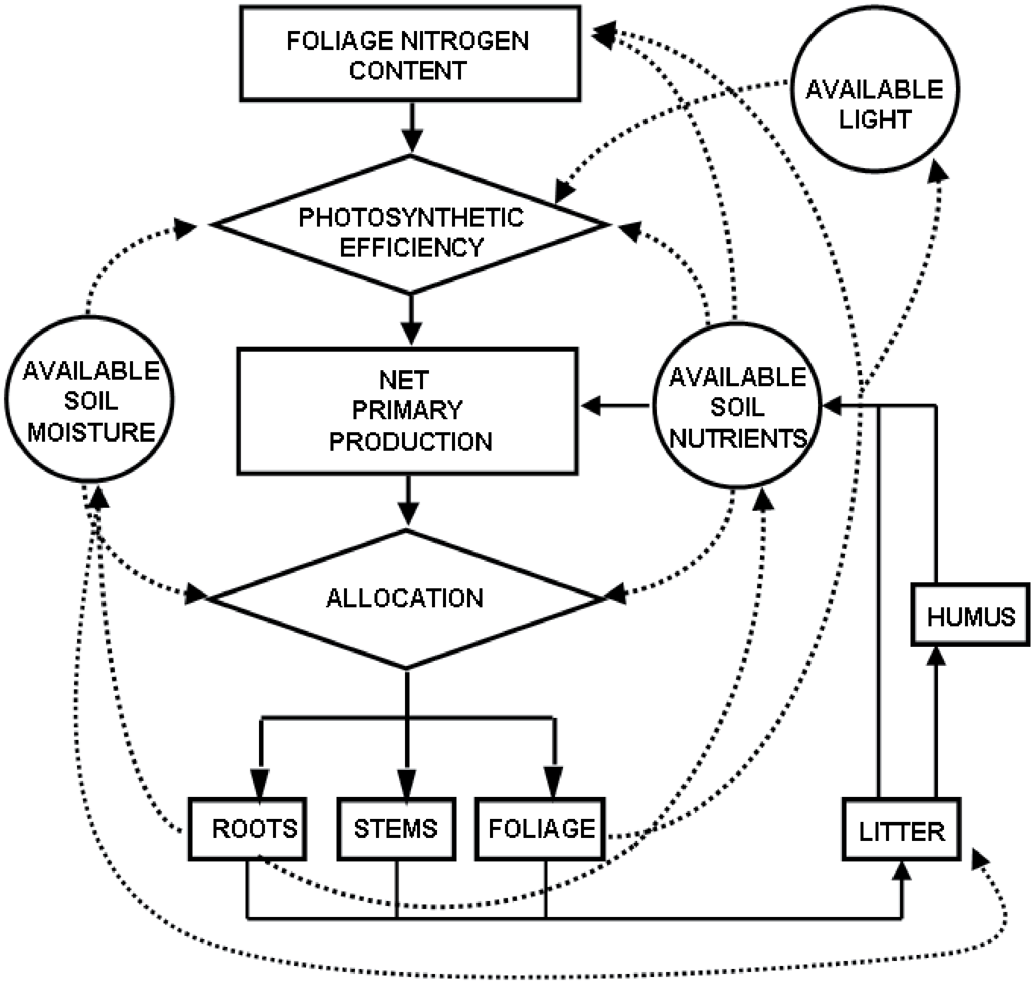

Fig. 1. Diagram representing FORECAST and FORECAST-Climate main processes and pools. The difference between both models is the influence of Available Soil Moisture, simulated in FORECAST-Climate but not in FORECAST (modified with permission from Kimmins et al., 1999).

The improved FORECAST-Climate model includes an explicit representation of soil moisture and forest hydrological processes based on a linkage to the Forest Water Dynamics (ForWaDy) model (Seely et al., 1997). ForWaDy is a vegetation-oriented model originally developed as a companion forest hydrology model to FORECAST. The model was designed to provide a representation of the impacts of forests management activities on water competition among different tree species and between trees and minor vegetation. Potential evapotranspiration (PET) in ForWaDy is calculated using an energy balance approach. Incoming radiation is partitioned among vertical canopy layers (vegetation type) and the forest floor to drive actual evapotranspiration (AET) calculations. A schematic of the model showing the various flow pathways represented in the model is provided in Fig. 2.

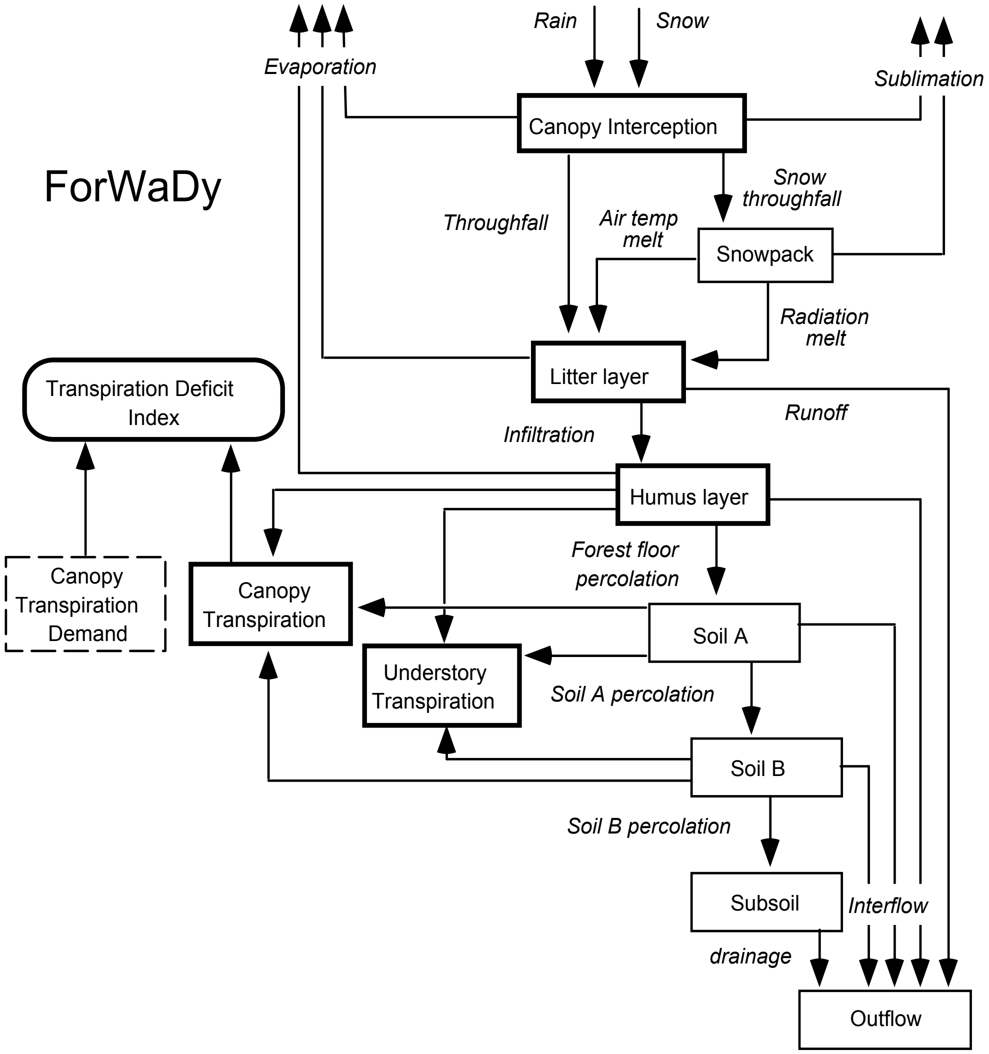

Fig. 2. Diagram representing energy and water flows in ForWaDy (adapted with permission from Seely et al., 1997).

The model is structured for portability, with minimum soil data requirements and parameter values that are relatively easy to estimate. It has a simplified representation of the soil physical properties dictating moisture availability, storage, and infiltration. ForWaDy is a forest hydrology model used to simulated forest water dynamics under given climate and forest stand structure conditions. It uses a daily time step to capture precipitation events (Seely et al., 1997). ForWaDy uses an energy budget approach to calculate PET as a function of climate (solar radiation, mean air temperature, precipitation and snow depth), stand structure and soil texture (Seely et al., 1997). It simulates precipitation interception by the vegetation canopy and competition between plants for water in the soil under different forest stand conditions, and calculates water demand by different canopy layers and within different soil layers. After calculating the difference between water supply and water demand of the tree, ForWaDy provides a tree water stress index: TDI (transpiration deficit index), which will be used as a modifier of tree growth in FORECAST. The advantages of this model are that it is written in a user-friendly language (i.e. STELLA) and it does not have a high input data requirement to run the model. Also, the processes within the model come from well-tested existing models or equations where possible (Seely et al., 1997) and it has been successfully tested in Canada and Argentina (Dordel, 2009; Kimmins et al., 2010). A detailed description is provided in Seely et al. (1997).

The linkage of FORECAST with ForWaDy to create FORECAST-Climate provides an additional feedback on tree growth rates based on a climate-driven quantification of tree water stress (Fig. 1). Moreover, the simulation of soil and litter moisture content in FORECAST-Climate facilitates a climate-based representation of organic matter decomposition and associated nutrient mineralization rates. These developments in combination with a simulation of temperature effects on length of growing season and forest growth rates will provide the foundation for the representation of climate impacts on forest growth in FORECAST. The completed model allows users to explore the potential impacts on varying climate scenarios on indicators of multiple forest values and it is directly applicable as a forest management.

5. Conclusions

Process-based models could be important tools to support decisions in forest management (Blanco et al., 2005). Such modelling tools are required to help forest planners navigate the potential implications of climate change on timber supply through the use of scenario analysis and case studies. Although detailed physiological models have been useful in exploring climate impacts on tree growth and ecosystem processes at research level, they are often data intensive and difficult to apply for management related applications (e.g. Grant et al., 2005). These models also have to be supported by accurate weather records or estimations (Lo et al., 2011). To be effective for guiding management, such tools must be able to capture the current understanding of the effect of specific climate variables on ecosystem processes governing forest growth, but still be practical for estimating impacts on tangible projections of forest growth and yield and other ecosystem values (Landsberg, 2003; BC Ministry of Forests and Range, 2006). Only then meaningful assessments for forest managers of the effects of climate change on forests could be carried out.

6. References

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5

Climate Change Detection and Modeling in Hydrology

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1. Introduction

Detection of a change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. Attribution is defined as the process of evaluation of the relative contribution of multiple causal factors to a change or event with an assignment of statistical confidence. However, the observed changes must be able to be detected (IPCC 2010).

Attribution to a change in climatic conditions includes the assessments that attribute an observed change in a variable of interest to a specific observed change in climate conditions based on the process knowledge and relative importance of a change in climate condition in determining the observed impacts (Hao et al. 2008; Liu and Xia 2011). The associated confidence levels should be evaluated for the data, model, methods, and the factors used in the study (IPCC 2010).

Seibert et al. (2010) used the three different approaches for change detection modeling employing a modified version of the HBV (Hydrologiska Byråns Vattenbalansavdelning) model (Bergstrom 1976, 1992) to conclude that catchment-scale runoff increases following severe wildfire. The application of the HBV model as a change detection tool indicated the increases in peak flows following severe wildfire and the related road building and harvesting of the dead and damaged forest vegetations.

The parameter uncertainty of various parameter sets is commonly known in hydrologic and climatologic modeling. It is an issue seldom addressed in modeling approaches for detecting changes (Pappenberger and Beven 2006; Seibert and McDonnell 2010). Employing a large number of parameter sets rather than a single set of parameter values facilitates the assessment of the associated uncertainty.

The detection of climate change impacts on the observed climate and elements of the hydrological cycle have made a great progress, recently (Amiri and Eslamian, 2010). Based on the climate model simulation, the optimal methods have been used to detect the responses of observed change to Green House Gas emissions from the other external forcing at large spatial scales. Presently, the detection of anthropogenic influence is not yet possible for all of the climate variables. It is still difficult to attribute the observed changes in climate or variables of interest on a spatial scale lower than five thousands kilometers and temporal scales of less than fifty years. For the basin aquifers recharged by precipitation or surplus irrigation and influenced by artificial and strong human activities, the detection studies mainly focused on analytical approaches to link physical impacts to changes in temperature or precipitation as a tool. For the basins with better observational data and more sensitivity towards climate change, the use of formal detection methods to identify the pattern responses of the hydrological cycle to external forcing is a valuable and promising area of further research (Liu and Xia 2011).

Xoplaki et al. (2008) investigated data requirement for climate change detection and modeling research in the Mediterranean. They indicated that data availability allows the validation of scientific results on climate change detection and attribution.

The need for long measurements of climate and hydrologic data for studies of climate variability and change is very important. New et al. (1999, 2000) have developed the fields for many climate variables and it is essential to develop these further and extend them to some hydrological variables such as discharge and runoff, for both climate variability and change studies and also climate model validation.

Most of the investigations in climate variability and change detection have focused on only temperature, due to well representation by the available network. The temperature measurement exhibits the relatively high correlation decay lengths. Both upcoming impacts and those of previous events are, however, much more dependent upon the changes in precipitation. The changes are not only vital for hydrology, but are also much more important than temperature for many other sectors, such as agriculture and range management. The studies of large-scale changes in precipitation are hampered by the requirement to obtain access to considerably more precipitation data than is conventionally available. A similar case can also be met for runoff data. Climate change detection studies need to be undertaken on a global scale, and both the available networks of runoff and precipitation data are inadequate. Presently, the best that can be achieved are the investigations on the regional and catchment scales (Cihlar et al. 2000).

A method for detecting the impacts of disturbance on catchment-scale hydrology is the paired catchment approach. The method combines rainfall-runoff modeling to account for natural fluctuations in daily streamflow, uncertainty analyses using the generalized likelihood uncertainty estimation method to identify and separate hydrologic model uncertainty from unexplained variation, and GLS regression change detection models to provide a formal experimental framework for detecting changes in daily streamflow relative to variations in daily hydrologic and climatic data (Zégre et al. 2010).

Precipitation data indicate both increasing and decreasing trends for different regions of the world. Zhang et al. (2007) detected the human influence on twentieth century precipitation trends.

The main objective of this study is to describe the statistical techniques for detecting changes in hydrological events. The flood records are selected for this purpose. Statistical tests and distributions, significance levels and confidence intervals, risk and uncertainty and nonstationarity are discussed in detail for the flood series.

2. Detection of change in flood records

Graphical analysis is generally the first attempt at detecting change in a flood record. Unfortunately, the natural variation of year-to-year flooding greatly exceeds the variation expected due to climate change of recent years. Thus, the latter would likely not be visually evident from a graphical portrayal of a flood record. In comparison, it takes a considerable level of urban development before the hydrologic effects of urbanization can be graphically detected, especially if the trend is temporally gradual rather than abrupt. Whether change is due to global warming or urbanization, we can not be certain whether the nonstationarity factor will cause a change in the probability distribution of floods or just its moments. Thus, more sophisticated methods of detection are needed.

Commonly, the next step in detection of change is with statistical methods. Some of the problems with statistical detection of the effects of climate change include uncertainty in the distribution from which the sample was drawn, outliers, poorly measured values, no knowledge as to when the climate change began to significantly influence flooding, and the compounding effects of land cover change such as deforestation. In addition to these factors, identifying a statistically significant change requires the specification of a statistical level of significance. The value selected is a central factor in statistical decision making, yet a systematic way of identifying the optimum level of significance is not known. The selection of a level of significance is not a trivial decision as the power of the test will depend on the level selected.

Eslamian et al. (2009) investigated to detect an existing trend in wind speed and to evaluate the effect of climate change on frequency analysis of wind speed in Iran. The purpose of this study was to present the recent trends and variations in measured wind speed at twenty-two gauging stations along the whole country of Iran. In addition, the effect of climate change was evaluated in frequency analysis and heterogeneity. For understanding wind behavior in time periods, the trend test and frequency analysis were performed for evaluating wind magnitude and duration.

3. Selection of statistical method to detect trend

Statistical methods are generally designed to be most sensitive to one type of change, such as the change in central tendency, the change in dispersion, or the change in the statistical distribution. Change can be gradual or abrupt and different statistical methods should be applied to such data. A change in a data set that is characterized by gradually varying flows may not be detected if the statistical method applied is more sensitive to abrupt change. Evidence does not currently exist as to the distributional effect that climate change introduces to a flood record. For example, will prolonged climate change cause annual maximum floods to follow a Generalized Extreme Value (GEV) distribution rather than the commonly accepted log-Pearson type III distribution (LP3)? Bulletin 17B, which was developed to estimate flood frequencies and, therefore, flood risk, assumes that hydrologic data follows a LP3 (Interagency 1982). However, many recent studies in regards to precipitation data are based on other distributions. For example, Koutsoyiannis (2004), Stedinger (2000), Gellens (2002), and Karin and Zwiers (2005) selected the GEV distribution to model extreme events while Wilby and Wigley (2002) and Semenov and Bengtsson (2002) chose the gamma distribution to model daily precipitation events. Therefore, if agreement does not currently exist on the appropriate distribution to represent hydrologic data, it will be difficult to determine the appropriate distribution as the concept of nonstationarity is introduced. To compound the problem, climate change is expected to be gradual and thus, the distribution may be subject to continual change.

In addition to the appropriate distribution, the effects of climate change on the moments of a distribution are unknown. The studies have suggested that climate change will increase the more intense rainfalls but have little effect on total annual rainfalls (Hennessy et al. 1997; Karl and Knight 1997; Wilby and Wigley 2002). Kharin and Zwiers (2005) found a significant change in the location and scale parameters for the GEV distribution in a global analysis of precipitation extremes; however, the effects of climate change are expected to vary regionally. Therefore, global analyses may not be applicable at the regional level. Since the expected changes in the statistical distribution as well as the moments are not known and, therefore, must be assumed, this reduces the ability of statistical tests to effectively decide whether or not change has occurred. Without this knowledge, the best statistical method to detect climate change can not be selected without recognizing the importance of this type of uncertainty.

4. The assumption of a start time

Before the problem of modeling can be solved, the first issue that must be addressed is detection of change. The most obvious question is: when did the effect of climate change begin to significantly influence the hydrologic variable of interest, e.g., annual maximum peaks? For example, Olsen et al. (1999) varied the start and end dates of flood records analyzed for gauges in the Missouri and Mississippi River basin. Based on the linear regression results, they found that different record lengths within the same flood record influenced the significance of the trend detected. Therefore, knowledge of the time at which nonstationarity began is necessary in order to correctly identify trends.

Identifying the start time of nonstationarity is important because the time that climate change is assumed to have become influential will influence the model used to represent the hydrologic change. If incorrectly selected, the model type can greatly affect projected changes in hydrologic data. For example, let's assume that we know that climate change will introduce a linear trend in the hydrologic variable. If the start date is quite uncertain, then the slope of the linear trend will be biased depending on the assumed start time. An incorrectly assumed early start time will lead to an underpredicted slope. Likewise, assuming a late start time would result in a relatively steep slope and long-term overprediction. Figure 1 shows the mean annual discharge (cfs) for the USGS gauge 05464500 at Cedar Rapids, Iowa. A linear trend was fit to the data with two start times: 1903 and 1960, represented by the solid and dashed regression lines, respectively. If extrapolated to the year 2050, the model based on a 1960 start time projects a mean discharge that is 12% greater than the model based on a later start time. Therefore, the uncertainty of predictions due to inaccurate start times can be significant. A statistical test that is sensitive to the start date needs to have high statistical power. Otherwise, incorrect start times will result, with the subsequent impacts on models, future projections, and risk estimation.

The Anacostia River at Hyattsville, MD, can be used to illustrate the effect of start time on the trend of peak discharge rates. Figure 2 shows the annual maximum peak discharge from 1939 to 1988. In the late 1950's, urban development influenced flood flows, with the effect apparent in Figure 2. Linear models were used to model the trend in flood peaks as a function of time:

$$\text{1955-1988: } q_p = 344 + 54.11 * t \qquad t=1 \text{ in } 1955 \tag{1}$$

$$\text{1960-1988: } q_p = 4178 + 29.57 * t \qquad t=1 \text{ in } 1960 \tag{2}$$

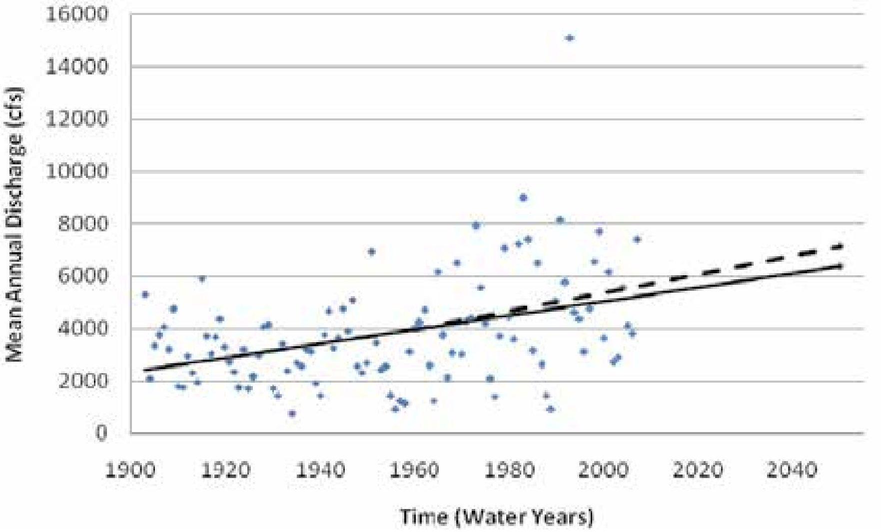

Fig. 1. Variation in Trend Modeled based on Different Start Times for the Mean Annual Discharge (cfs) for the USGS Cedar Rapids Gauge (05464500) with the Dashed and Solid Line Representing a 1960 and 1903 Start Time, Respectively

While the record lengths are similar (34 and 29 years, respectively), the equations are quite different. The estimated floods for the year 2011 would be 6528 cfs (185 m^3/s) and 5716 cfs (162 m^3/s) for Eqs. 1 and 2, respectively. This represents a difference of 13% based solely on the start time. This example illustrates the sensitivity of estimated flood magnitudes to the start time for modeling time trends.

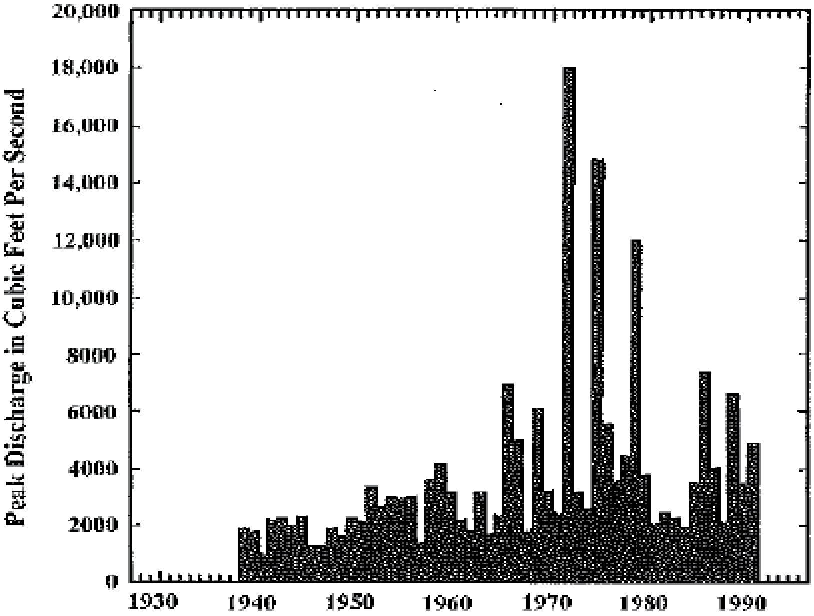

Fig. 2. Peak Discharge Data for Annacostia River at Hyattsville, Maryland.

Assuming that the start time can be reasonably estimated, the next question of interest is: What affect will climate change have on the physical processes that determine the nature or characteristics of the climate change? Will the climatic change influence the statistics of the hydrologic variable, e.g., increase the mean or the variance, or will it change the distribution, e.g., from a LP3 to a GEV? The accuracy of projected discharges will greatly depend on the change assumed, which will subsequently influence the accuracy of risk estimates.

5. Selection of statistical distributions

As mentioned in the discussion of statistical method selection, the appropriate distribution for hydrologic data is unknown. While this leads to difficulties in trend detection, it also influences the projection of hydrologic events, such as flooding. Bulletin 17B currently recommends the LP3 distribution; however, the GEV distribution is recommended by many studies as well (Martins and Stedinger 2000). Both distributions represent extreme data; however, the extreme events projected by each distribution can vary. For example, Figure 3 compares the frequency curve fit to the Cedar Rapids annual maximum peak discharge at the USGS gauge 05464500 with both the LP3 and GEV distributions. The GEV distribution projects a 100-yr flood that is 12.6% greater than that of the LP3 distribution. Therefore, depending on the distribution selected, engineers may over or underestimate the 100-yr storm designing flood management structures. Therefore, it is important that the correct probability distributed is selected for hydrologic data for design and policy development.

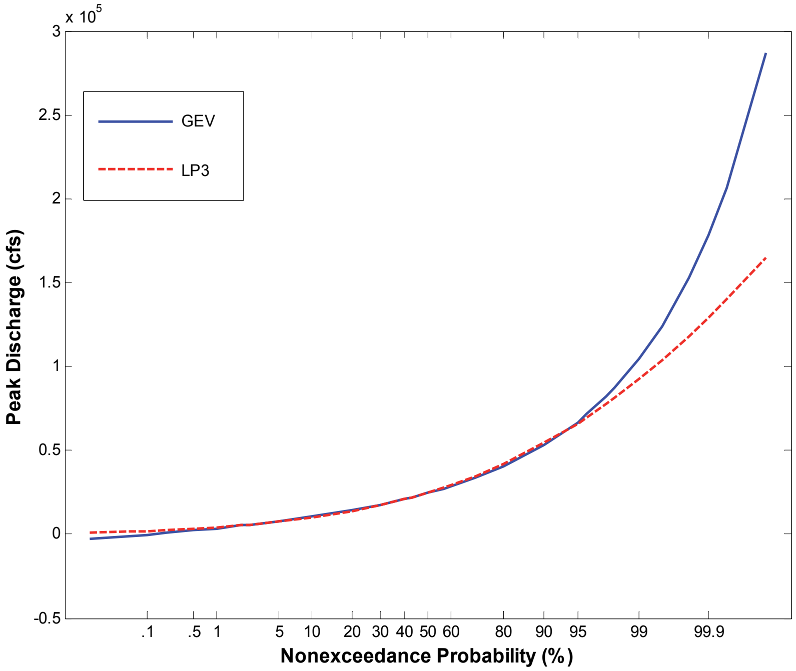

Fig. 3. Frequency Curve for LP3 and GEV Distribution of Cedar Rapids Annual Maximum Peak Discharge Data.

6. Selection of statistical models

In addition to the start time and distribution selection, uncertainties in future predictions will result from the model form selected to represent the change being analyzed. For example, evidence points to a nonlinear trend in hydrologic data as the result of climate change, but some global models suggest an increasing function while other models suggest a decreasing function because of policies that control CO_2 emissions. Likewise, even when urbanization is known to influence measured flood magnitudes, it has been difficult to identify the model structure that approximates the temporal effects of changes in the physical processes associated with urban land cover change. Linear trends are often assumed as other more complex functions do not lead to greater accuracy. Yet, the assumed model structure will dictate the magnitude of floods projected for future land cover conditions. Assuming an incorrect function form to represent the trend of increasing flood discharge rates will influence peak discharge estimated for the future. This is another source of uncertainty as an incorrect model structure can lead to overprediction or underprediction of design floods and their associated risks.

To illustrate the potential effect of model structure on floods estimated for future times, the flood series for the Anacostia River (see Figure 2) was fitted for the 1955-1988 period using a linear model (Eq. 1) and the following power or log-linear model:

$$\text{1955-1988: } q_p = 2384 * t^{0.153} \tag{3}$$

Based on this power model form, the 2011 estimated discharge would be 4425 cfs (125 m^3/s), which differs from the discharge estimated using Eq. 1 by 2103 cfs (59.5 m^3/s), or 38.4%. The effect of model structure is significant and this issue is must be considered in an attempt to model the effects of climate change on hydrologic data.

This same problem will influence the accuracy of modeling the effects of hydrologic nonstationarity due to a changing climate. It is difficult to even detect whether or not climate change has introduced systematic variation into a flood record let alone identifying the structural form of the temporal change induced by the climate change. Much effort will need to be expended on the detection of change and to identify the best model structure will be a central modeling issue. The model structure finally adopted will greatly influence assessments of future flood risk and the design of hydrologic and hydraulic infrastructure with design lives that will cover the period of climate change.

7. Confidence intervals under changing conditions

The third issue important to the modeler and to policy makers is: How can confidence intervals be computed on projected discharges when the distribution and parameters of future discharges are unknown? Given the lack of certainty in the distribution of climate-affected discharges, the most obvious choice of methods for computing confidence intervals would be those used for linear regression analysis. This approach requires a minimum of inputs, such as the standard error of estimate, the sample size of the existing record, and the standard deviation of the time variable. One problem with this approach is the lack of stationarity. Confidence intervals computed using traditional methods assume stationarity. A new approach will be needed. Uncertainty associated with the nonstationarity will likely lead to much wider confidence intervals on hydrologic variables such as peak discharge rates. An approach based on Monte Carlo simulation for different levels of nonstationarity may be necessary to produce more accurate assessments of the confidence of projected discharges.

With the current state of the art, nonparametric methods are the generally accepted approach to detection of change. Numerous tests are available, but many of these lack statistical power. For example, the Runs Test, which was designed to assess the presence or lack of randomness, i.e., independence, could be applied over portions of a flood record to identify the portions of the record that were not homogeneous. If the other causative factors, such as urbanization can be ruled out, then the test may detect an approximate time at which nonstationarity began. Given the low statistical power of the test, the best estimate of the start date will likely be very imprecise.

The Kendall Tau Test is one of the more commonly used tests for detecting nonrandomness. This test is often preferred because it is designed for data with a monotonically increasing trend, as opposed to an episodic change. It can be applied to either long or short flood records, although the accuracy of the decision will depend on the record length.

Tests for serial independence, such as the Pearson Test and the nonparametric Spearman Test, can be effective for identifying the existence of trends. However, when the Spearman Test is applied to hydrologic data where the data are ordered by year of occurrence, the critical values generally available do not apply. Some analyses have correlated the hydrologic variable with the integer of time, i.e., 1 to n, used as the second variable. The Spearman Test statistic has a different distribution function when the integer of time is applied as one of the variables rather than the adjacent value of the discharge value (Conley and McCuen 1997). Both of these tests should use only the peak discharge sequence rather than correlating discharge and time.

8. Level of significance for detection decisions

The above are all important issues to those involved in assessing the effects of climate change, yet they may not be the most important issue. Regardless of the distribution assumed or the statistical test selected, the significance of an effect will depend on the level of significance adopted for decision making. Karl and Knight (1997) used the 5% level of significance to determine whether increases in precipitation within the United States were significant in the 20th century. Burns and Elnur (2002) reported hydrologic trends detected based on a 10% level of significance. Olsen et al. (1999) identified trends detected in flood records with both a 1% and 5% levels of significance. Traditionally, a 5% level is used, but evidence that this is really appropriate for hydrologic variables has not been addressed. It is unlikely that a 5% level of significance would lead to detection of hydrologic change due to a changing climate, as the sampling variation is generally quite dominant and would overwhelm the effect of climate change. Additionally, use of a 5% level will likely lead to a test having low statistical power. For example, Figures 3a and b display two time series simulated based on normally distributed errors and the same intercept and slope coefficients; however, the standard error for was increased by 100% from the Figure 3a to the Figure 3b time series. The Kendall Tau Test was applied to each data set and Z-values equal to 2.85 and 1.31 were calculated for the data in Figure 3a and 3b, respectively. Therefore, at the 5% level of significance, the null hypothesis was rejected for Figure 3a and accepted for Figure 3b. The null hypothesis was rejected at the 10% level of significance for Figure 3a. Therefore, the variation within the data influences the level of significance at which a trend will be detected, which is a concern when dealing with variables that contain high variation, such as hydrologic data. Before any statistical test is adopted, the issue of statistical power and the level of significance needs to be studied.

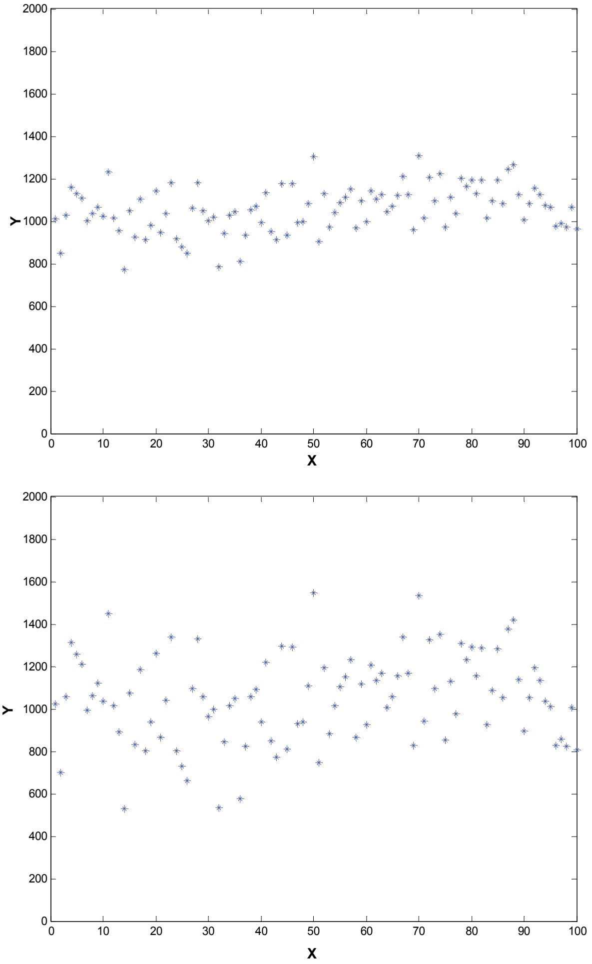

Fig. 3. a and b. Simulated Time Series with Intercept = 1000, Slope = 1.25, and Se = 100 and 200., respectively, with Resulting Kendall Tau Statistics equal to 1.31 and 2.85, respectively.

The null hypothesis of interest to this issue is: climate change has not introduced nonstationarity into the flood series. The alternative hypothesis would be that the flood series is nonstationary. Using a small level of significance of 5% or 1% gives some assurance that a true null hypothesis will not be falsely rejected, but it also increases the chance of not identifying an effect and accepting the null hypothesis, when, if fact, it is false. A 5% level of significance will then likely lead to not making an adjustment of the flood series for nonstationarity, whereas use of a higher level of significance would dictate making such an adjustment. It seems that adjusting a series with a minimal effect of climate change would be preferable to failing to make a needed adjustment, even if the adjustment is small. Thus, the proper level of significance to be used in climate change analyses need to be investigated.

9. Nonstationarity and flood risk

Engineering designs are commonly based on an estimate of the 100-yr discharge, where the discharge is based on an analysis of the historic flood record or on a regression model fitted using regional flood records. Assuming that global climate change models are correct and that extreme rainfalls are expected to increase over time, then it is reasonable to assume that the time series of annual maximum discharges will increase over the next century. Under these conditions, storms of the size on which a design was based will occur more frequently. Thus, the 100-yr discharge of future times will be larger than the current 100-yr discharge. Likewise, under nonstationary conditions the current 100-yr flood event will occur more frequently (Olsen et al. 1998). The likelihood of the bridge opening passing runoff magnitudes will decrease, which means that the risk of failure will continuously increase with time.

Engineering design and risk assessments need to consider this nonstationarity of the T-yr discharge, where T is the return period used in design, e.g., T = 100yrs. A design made in 2010 based on the 100-yr discharge assessed using current information and knowledge will not have the same risk of failure as the climate changes. This should be considered in the design. If the design life for the 2010 project is 50 years, it may not be appropriate to design for the estimated 100-yr event for 2010 meteorological and hydrological conditions as then the project would be underdesigned. Similarly, designing for 2060 climate conditions would assume overdesign for each of the 49 years between 2010 and 2059. The optimal design discharge under these nonstationary global climate conditions would need to account for the rate of change of discharge over time. As many climate change scenarios show an increasing trend with time, the nonlinearity of the nonstationarity would require a temporally adjusted risk analysis.

Analyses have shown that the location and scale parameters of annual maximum flood series are expected to increase with increasing global climate change. These would raise the frequency curve and increase the exceedence probability of a flood magnitude. This is easily shown using a binomial risk analysis. Consider the case of a site where the 2010 conditions indicate a flood skew of 0.3 with the log moments shown in Table 1 for the decades that define the design life of the project. Assume that a project is designed to control the 100-yr flood magnitude of 1411 cms (49821 cfs). Assuming climate change will cause the log moments to increase as shown, then the return period of the design discharge increases over the 30 year period from the current 100 years to a 41-year event in 30 years. The binomial risk for each decade would change from 9.56% in the first decade, to 14% in the second decade and 19.1% in the third decade. Therefore, over the design life of the project, the project as designed has an increased likelihood of being exceeded. This change in the expected exceedence probability would provide a benefit-cost ratio of the project that was less than the ration on which a design based on stationary conditions would provide. Failure to account for the effect of climate change in the design would lead to long-term under design.

This conclusion is not intended to suggest that the project should be designed to the 100-yr flood condition at the end of the design life, as this would reflect a long-term design that would exceed the 100-yr protection. For example, if the project were designed for the 2040 flood moments, with a discharge of 2733 cms (96521 cfs), then the annual exceedence probability for current conditions would suggest a design exceedence probability of 0.00383, which reflects a return period of 261 years. Except in the last year of the design life of the project, the facility would have a protection that exceeds the required value. Using this value in a project benefit-cost ratio would provide a value that would exceed the long-term ratio that could be expected over the design life.

Decade	Log mean	Log sd	Flow (cfs)	Flow (cms)	K	p	T (yrs)	Prob.
2010	3.12	0.62	49821	1411	2.544	0.0100	100	0.0956
2020	3.15	0.63	56605	1603	2.456	0.0126	79	0.1074
2030	3.21	0.65	73070	2068	2.288	0.0177	57	0.1416
2040	3.28	0.67	96521	2733	2.116	0.0242	41	0.1908

Table 1. Binomial Risk over Time

If the intent is to provide, on average, 100-yr protection, then an integrated procedure is needed. Such a method would need to consider the temporally changing flood potential at the site, as indicated by the changing moments. The continually changing flood risk would need to be estimated. A method developed to integrate the effect of the changing flood risk would be expected to account for these changes in flood potential.

10. Conclusions and recommendations

An important benefit of the modeling approach is that, in addition to quantification of change resulting from a disturbance, comparison of model parameters between pre- and post-event periods provides an indication of hydrological processes alteration by a severe event.

Detecting the effect of climate change in measured hydrologic data is a difficult, but important, task (Eslamian 2006). It has ramifications to assessing flood risk, the design of water resource infrastructure, and the avoidance of assigning too much weight to other nonstationary factors, such as urbanization, that contribute to hydrologic change. If the effect of climate change is even marginally significant, but not accounted for when attempting to assess the effects of urbanization in hydrologic data, then the effects of urbanization will likely be overstated. The results of such analyses will lead to biased designs. Infrastructure design that fails to account for climate change can be inadequate to meet the safety needs of a community, as the likelihood of severe flooding will increase because of climate change. Thus, floods that occur over the design life will likely be larger and more frequent than designed for. These situations are central to the issue of assessing flood risk, which has obvious implications to public safety, resource allocation, and the disruption of facility use.

The implications of global warming are significant, as policies will be made to address the issue and climate change may have significant economic effects. Therefore, uncertainties in projections of the effects of climate change must be considered in designing infrastructure, establishing public policies, and in economic decisions. A few of the uncertainties have been discussed in this paper, with an emphasis on uncertainties related to climate change modeling. Projecting to the future represents extrapolation, and given the uncertainties in modeling procedures, data, and our theoretical knowledge of the underlying processes, decision makers must consider these uncertainties. Record lengths of data used to calibrate climate models are short and contain very significant levels of nonsystematic variation. Such uncertainty will be carried over to projections made to the year 2100. The nonsystematic variation often reflects our lack of a full understanding of causal factors. Efforts through research need to be made to reduce these uncertainties in order to increase the accuracy of projections into the future.

Given the uncertainties of and interactions between the different model parameters, such explanations need to be approached with caution. Nevertheless, these suggestions of altered processes can direct further investigation and hypothesis formulation.

The following observations are especially important for the further climate variability investigations:

- Daily runoff series for a few hundred smaller natural catchments, about 1000 km^2 catchment area, employed for research purpose distributed over the globe.
- Monthly runoff series for the top few hundred catchments around the world, possibly having natural flows.
- Long time series of hydrological records

Impacts of climate change on water quality are also largely determined by hydrological changes and by the nature of pollutants as flushing or dilution-controlled. The most significant impact of urban development on water resources is an increase in overall surface runoff and the flashiness of the associated storm hydrograph. The increase in impervious surface area associated with urban development also contributes to degradation of water quality as a result of non-point source pollution. The modelling studies on the combined impacts of climate change and urban development have found that either change may be more significant, depending on scenario assumptions and basin characteristics, and that each type of change may amplify or ameliorate the effects of the other (Praskievicz and Chang 2009).

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6

Automatic Generation of Land Surface Emissivity Maps

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1. Introduction

The remote sensing measurement of the land surface temperature (LST) from satellites provides an overview of this magnitude on a continuous and regular basis. The study of its evolution in time and space is a critical factor in many scientific fields such as weather forecasting, detection of forest fires, climate change, etc.

The main problem of making this measurement from satellite data is the need to correct the effects of the atmosphere and the land surface emissivity (LSE). Nowadays, these corrections are usually made using a split-window algorithm, which has an explicit dependence on land surface emissivity.

Therefore, the aim of our work was to define an enhanced vegetation cover method and develop a computer system that used it, in order to calculate and generate, automatically, maps of land surface emissivity from images of the AATSR (Advanced Along Track Scanning Radiometer) onboard the ENVISAT satellite.

The most innovative part of our method is that we provide it with the resources and the capability to calculate the most accurate coefficients according to the specific characteristics of each area (vegetation cover fraction, vegetation type, season, etc.). This allows the method to be applied to generate large-scale maps of this magnitude (Caselles et al., 2009).

On the other hand, the current procedure (global, fully operational and supported by ESA) for obtaining the emissivity from an AATSR pixel (Noyes et al. 2007) causes systematic errors when calculating the temperature of 2 to 5 K (Coll et al. 2005), showing that the current classification and the vegetation cover maps made with a resolution of 0.5° x 0.5° could be highly improved and provided with the same spatial resolution of the AATSR images (1km x 1km). This is the main reason of this paper.

In this chapter, this new method is presented, with its algorithm, and it is applied to several different types of vegetation in AATSR images of Europe, making all the calculations automatically with the developed software.

Eventually, an on field validation of the method was carried out by comparing the data of the generated emissivity maps (as the one in figure 6) with the values obtained in previous campaigns (Coll et al. 2005) carried out in the area of rice fields of Valencia, Spain (Caselles et al., 2009). An error of less than ±0.01 in the land surface emissivity assessment was successfully obtained.

Its validation was made by comparing the obtained results and the values measured in previous field campaigns carried out in the area of rice fields of Valencia, Spain.

2. Methodology

So far, different methods to obtain the land surface emissivity based on different ideas have been purposed (Caselles et al., 1997). The main disadvantages they present, especially when your final aim is to calculate this magnitude automatically, are:

i. Their high complexity, since it is difficult to apply them operatively, carrying out huge computational calculations.
ii. Their error, because the propagation of errors is bigger in complex algorithms.
iii. Their bias, which can be introduced if the approaches of the model are not fulfilled exactly.

For that reason, an enhanced mathematically simple method (Caselles et al., 2009) was defined, without important bias, to obtain the surface emissivity from satellite images, inspired by the results of Valor & Caselles (1996), who purposed a relation between thermal emissivity and the Normalized Difference Vegetation Index (NDVI).

The general philosophy of this new method is similar to some extent to the algorithm for LSE estimation used by the LST product of Terra-MODIS (Snyder et al. 1998), and for LSE estimations in Meteosat-SEVIRI (Peres & DaCamara 2005; Trigo et al. 2008)

2.1 Enhanced land surface emissivity model

As we have already mentioned, to produce the emissivity maps, we used an improved geometric model based on the one described in Valor & Caselles (1996). This model can be summarized in the following equation (1).

$$\varepsilon = \varepsilon_v P_v + \varepsilon_g (1 - P_v) + 4 < d\varepsilon > P_v (1 - P_v) \tag{1}$$

where ε_v and ε_g are, respectively, the vegetation and soil emissivities, $<d\varepsilon>$ is the effective cavity term and P_v is the vegetation cover fraction. It allows us to calculate the effective emissivity in a heterogeneous surface from a land use map and vegetation cover fraction image.

Therefore, we need to know the pure surfaces emissivities (ε_v and ε_g), that is, the emissivity of the vegetation and the existing ground under it, as well as the effective cavity term ($<d\varepsilon>$). Since we do not have field measures from all over Europe and our system is aimed to be applied to the whole planet, the only existing possibility is to use average values obtained considering the possible variation ranges, experimentally observed.

In order to estimate the vegetation cover fraction (P_v), if we know the reflectivity values and i_v and i_g are the NDVI values obtained for a full vegetated surface and for a bare soil one, respectively, and K is given by:

$$P_v = \frac{1 - i/i_g}{\left(1 - i/i_g\right) - K\left(1 - i/i_v\right)} \qquad K = \frac{\rho_{2v} - \rho_{1v}}{\rho_{2g} - \rho_{1g}} \tag{3}$$

being ρ_{2v} and ρ_{1v} the near infrared and red vegetation reflectivities, respectively, and ρ_{2g} and ρ_{1g} the same measurements made on bare soil.

2.2 The land cover classification

In order to be able to obtain the most accurate values for the coefficients that have some dependence on vegetation and ground properties, we made our own collection, because we needed a concrete and adapted classification to the purpose of this chapter.

For that purpose, we studied some of the most famous existing land cover classifications, specially the Corine Land Cover (Buttner et al. 2004) of the European Environment Agency and the Ionia GLOBCOVER (Bicheron et al. 2008) of the European Space Agency. It is possible to read a complete analysis of both of them in Neumann et al. (2007). Eventually, we decided to use the second one, obtained from MERIS images, as our starting point, since it was updated recently to a newer version 2.2 (year 2008) and its higher spatial resolution (300 meters).

Furthermore, we made our own collection (see Table 1), by grouping the GLOBCOVER classes with similar emissivity characteristics (see Table 2), because we needed a more concrete and adapted to the purpose of this work classification. We did this following the land cover classification methodology explained by the FAO in DiGregorio & Jansen (2000).

Emissivity Class	**AATSR-11 µm**	**AATSR-12 µm**
Flooded vegetation/ crops/grasslands	ε_v =0.983±0.005 ε_g =0.970±0.005 (ground) ε_g =0.991±0.001 (water) <dε>=0	ε_v =0.989±0.005 ε_g =0.977±0.004 (ground) ε_g =0.985±0.001 (water) <dε>=0
Flooded forest/shrubland	ε_v =0.981±0.008 ε_g =0.970±0.005 (ground) ε_g =0.991±0.001 (water) <dε>=0.014±0.004 (ground) <dε>=0.004±0.001 (water)	ε_v =0.982±0.009 ε_g =0.977±0.004 (ground) ε_g =0.985±0.001 (water) <dε>=0.010±0.003 (ground) <dε>=0.007±0.002 (water)
Croplands/grasslands	ε_v =0.983±0.005 ε_g =0.970±0.005 (ground) <dε>=0	ε_v =0.989±0.005 ε_g =0.977±0.004 (ground) <dε>=0
Shrublands	ε_v =0.981±0.008 ε_g =0.970±0.005 (ground) <dε>=0.014±0.004 (ground)	ε_v =0.982±0.009 ε_g =0.977±0.004 (ground) <dε>=0.010±0.003 (ground)
Broadleaved/needleleaved deciduous forest	ε_v =0.973±0.005 ε_g =0.970±0.005 (ground) <dε>=0.019±0.006	ev=0.973±0.005 ε_s =0.977±0.004 (ground) <dε>=0.015±0.004
Broadleaved/needleleaved evergreen forest	ε_v =0.989±0.005 ε_g =0.970±0.005 (ground) <dε>=0.019±0.005	ε_v =0.991±0.005 ε_g =0.977±0.004 (ground) <dε>=0.015±0.004
Urban area	ε =0.969±0.006	ε =0.976±0.004
Bare rock	ε =0.93±0.05	ε =0.95±0.05
Water	ε =0.991±0.001 (water)	ε =0.985±0.001 (water)
Snow and ice	ε =0.990±0.004	ε =0.971±0,014

Table 1. Emissivity classes with the values for the parameters of the method in the 11 and 12 µm channels.

Emissivity Class	GLC Class	GLC Label
Flooded vegetation/crops/grasslands	11	Post-flooding or irrigated croplands (or aquatic)
	13	Post-flooding or irrigated herbaceous crops
	180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water
	185	Closed to open (>15%) grassland on regularly flooded or waterlogged soil - Fresh or brackish water
Flooded forest/shrubland	170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water
Croplands/grasslands	14	Rainfed croplands
	15	Rainfed herbaceous crops
	20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)
	21	Mosaic cropland (50-70%) / grassland or shrubland (20-50%)
	120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)
	140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)
	141	Closed (>40%) grassland
	150	Sparse (<15%) vegetation
	151	Sparse (<15%) grassland
Shrublands	16	Rainfed shrub or tree crops (cash crops, vineyards, olive tree, orchards…)
	30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)
	130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)
	131	Closed to open (>15%) broadleaved or needleleaved evergreen shrubland (<5m)
	134	Closed to open (>15%) broadleaved deciduous shrubland (<5m)
	152	Sparse (<15%) shrubland
Broadleaved/needleleaved deciduous forest	40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
	41	Closed (>40%) broadleaved deciduous forest (>5m)
	50	Closed (>40%) broadleaved deciduous forest (>5m)
	60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)
	90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)

Emissivity Class	GLC Class	GLC Label
	91	Open (15-40%) needleleaved deciduous forest (>5m)
Broadleaved/needleleaved evergreen forest	32	Mosaic forest (50-70%) / cropland (20-50%)
	70	Closed (>40%) needleleaved evergreen forest (>5m)
	92	Open (15-40%) needleleaved evergreen forest (>5m)
	100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)
	101	Closed (>40%) mixed broadleaved and needleleaved forest (>5m)
	110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)
Urban area	190	Artificial surfaces and associated areas (Urban areas >50%)
Bare rock	200	Bare areas
	201	Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)
	202	Non-consolidated bare areas (sandy desert)
	203	Salt hardpans
Water	210	Water bodies
Snow and ice	220	Permanent snow and ice
	230	No data (burnt areas, clouds,…)

Table 2. Correspondence between GLOBCOVER classes and the emissivity classes.

A reduction from the 22 initial classes of the GLOBCOVER classification (Bicheron et al. 2008) was carried out to 10 classes, taking into account similarities between related classes from the point of view of its components and their typical structure. So, for each vegetated area we calculated average values of the ground (ε_g) and vegetation emissivity (ε_v) in each spectral band (11 and 12 μm) from the spectra of soils and vegetation emissivity given in the ASTER spectral library version 2 (Baldridge et al., 2009).

Along with these coefficients, it has been calculated an average value of the cavity term ($<d\varepsilon>$) too, taking into account the structure of each vegetation type as described in the GLOBCOVER classification (Bicheron et al., 2008) , by using the procedure defined in Valor & Caselles (2005).

In the case of water surfaces, snow and ice, or bare soil it has been allocated directly emissivity values from samples of the ASTER library. On the other hand, for urban areas, it has been used the effective value proposed by Valor et al. (2000), determined by the emissivity values of urban materials (mainly concrete, asphalt, ceramics) and the structure of buildings. Table 1 shows the defined classes, their descriptions, and the values applicable to the equation (1).

2.3 The automatic developed system

The software developed to produce the emissivity maps uses the land cover map, a table with the information for each land cover class and the different AATSR images of the area we want to produce the map. So, it extracts the required data from them, in order to be able to apply the mathematical model (1), previously explained.

These AATSR images have its own format, defined in the specification of the sensor. The system obtains the coordinates of the studied surface and the measured values at each channel of the sensor.

The land cover classification map used is similar to the GLOBCOVER v2.2 one (see Bicheron et al. (2008)). It uses the GeoTIFF format (as detailed in Richter & Ruth (2000)) and the system uses it to obtain the ground type of a pixel given by the coordinates of an AATSR image. This image has a spatial resolution of 300 m, while the ones produced by the sensor have a 1 km resolution. That is the reason why the system has been equipped with an **interpolation by proportion of occupied areas algorithm** to be able to combine them accurately, knowing the geographical coordinates of both images or maps.

A detailed example of the interpolation that this algorithm does between an AATSR pixel (red square) and its correspondent GLOBCOVER pixels (black edge squares) is shown in figure 1. Since the algorithm know the geographical coordinates of the center of the AATSR pixel and the geographical coordinates of the GLOBCOVER pixels, it knows where the surface of this pixel is in the GLOBCOVER image. In the example, it is centered in the coordinates (15.75, 20.32). Then, knowing the resolution of both pixels, the algorithm will detect which GLOBCOVER pixels are completely or partially inside by the AATSR one and the actual proportion of each of the firsts is occupied by the second one.

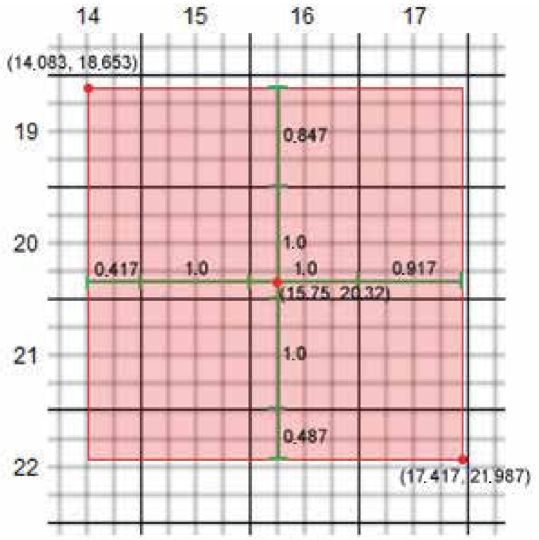

Fig. 1. Example of an AATSR pixel (1 km) in red interpolated with GLOBCOVER pixels (300 m) with black edge, according to the interpolation by proportion of occupied areas algorithm. Numbers between parentheses represent coordinates where the AATSR pixel is located in the GLOBCOVER image. Numbers near the green lines are the portion of the size of each side of every GLOBCOVER pixel inside the AATSR one.

The proposed interpolation algorithm obtains the different types of vegetation and soil that form each AATSR pixel and very accurately estimates the proportion of the area that each vegetation and soil type represents. First, the pixels of 300 m that the 1 km one overlaps with are obtained, identifying the GLC class each of them belongs and therefore the emissivity coefficients associated with them.

Subsequently, the exact area of each GLC pixel overlapped by the AATSR pixel is calculated based on their geographical coordinates and resolutions. eventually, the algorithm is able to estimate the values that need to be applied to each coefficient of equation (1), calculating each one as the weighted average of the values for that coefficient related to all the emissivity classes involved, and determining the influence of each emissivity class by the percentage that its area represents in the total area occupied by the AATSR pixel.

Therefore, the system processes all the pixels for each AATSR image, one by one, using the following algorithm (see flowchart in figure 2), reading the reflectivities (in the red and infrared channels) of each pixel and applying to them the mentioned model (1) to obtain the emissivity. Once all the pixels of one AATSR image are processed, a map with the calculated emissivities is generated for the same original surface studied by the sensor.

Finally, the system produces an output file, also following the mentioned GeoTIFF format, where it is stored: the average emissivity map, a confidence band, a land cover map, one NDVI map and one vegetation cover fraction (P_v) map, all of them for the original AATSR studied area. Any interested reader may ask the authors for a copy of this program, if desired.

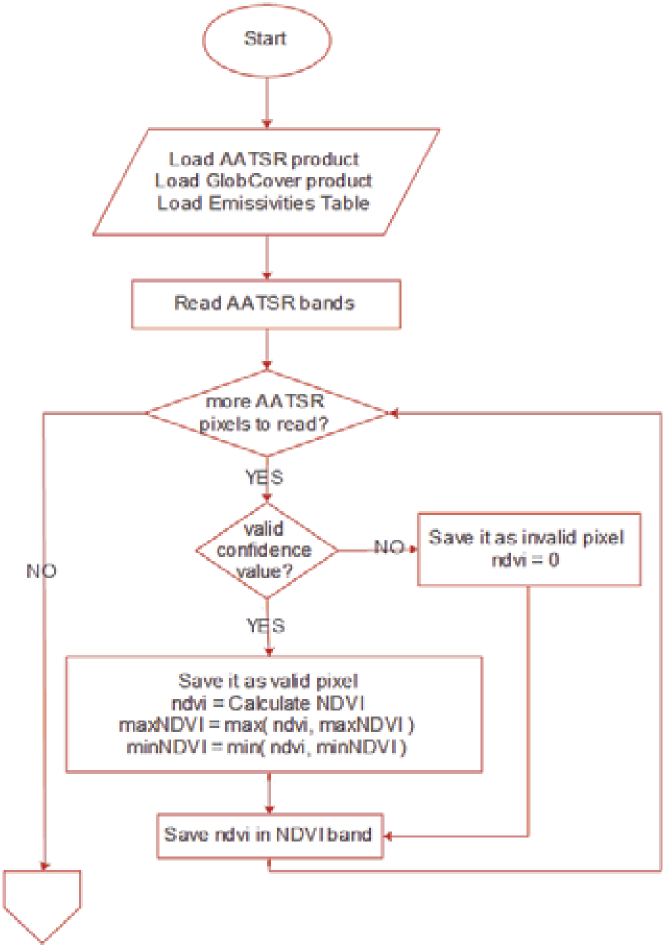

Fig. 2. a. Main flowchart of the system designed to produce emissivity maps.

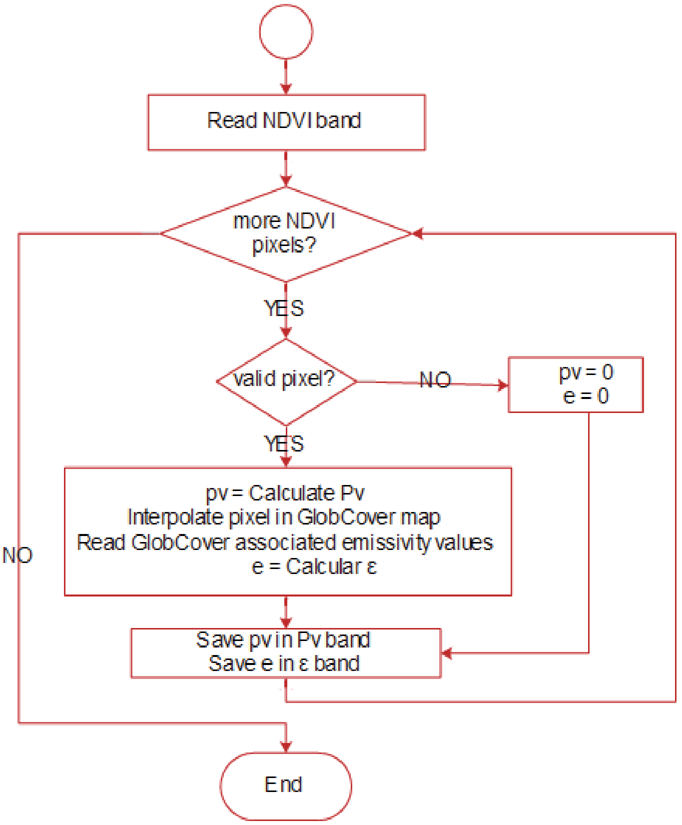

Fig. 2. b. Main flowchart of the system designed to produce emissivity maps.

3. Results

Once the enhanced method to calculate the land surface emissivity and the algorithm used by the system developed are defined. In this chapter, they are applied to Europe, in order to obtain a map of mean emissivities to a particular month of summer. Subsequently, a validation of that image is carried out to evaluate the system, comparing its results with actual measures.

3.1 Emissivity maps for Europe

As a result of using the above explained system, we have produced the emissivity map for Europe shown in Figure 3. It has been generated combining the output products of the system (in GeoTIFF format) for a set of 183 AATSR images, measured by this sensor in July, 2007. So, for each AATSR image, we have obtained the corresponding emissivity product and finally, we have joined them to create this composite. Also, figures 4 and 5 give the vegetation cover fraction and the confidence band for the same European area, respectively.

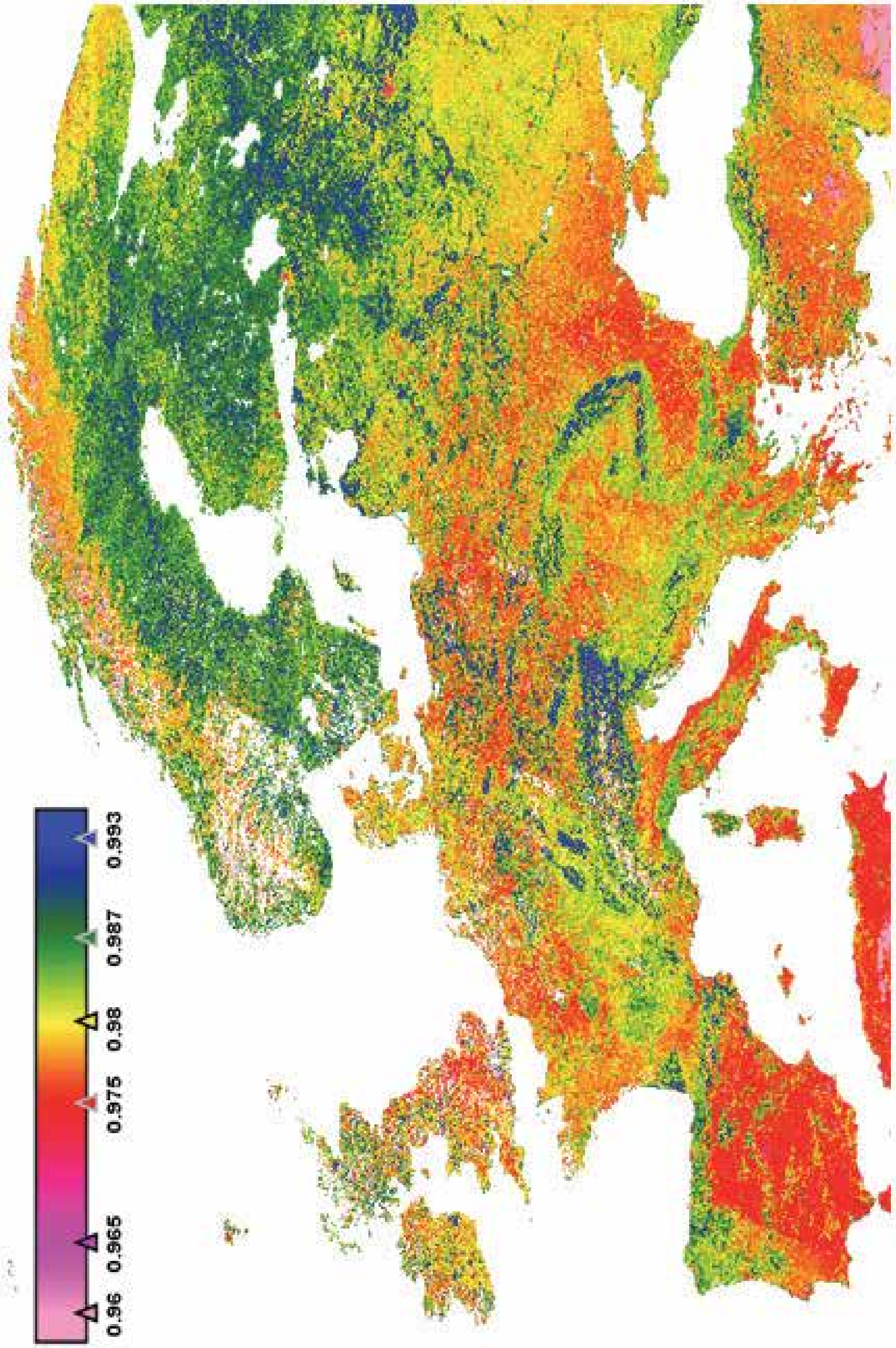

Fig. 3. Average emissivity map (between channels 11 and 12 μm) for Europe (July, 2007).

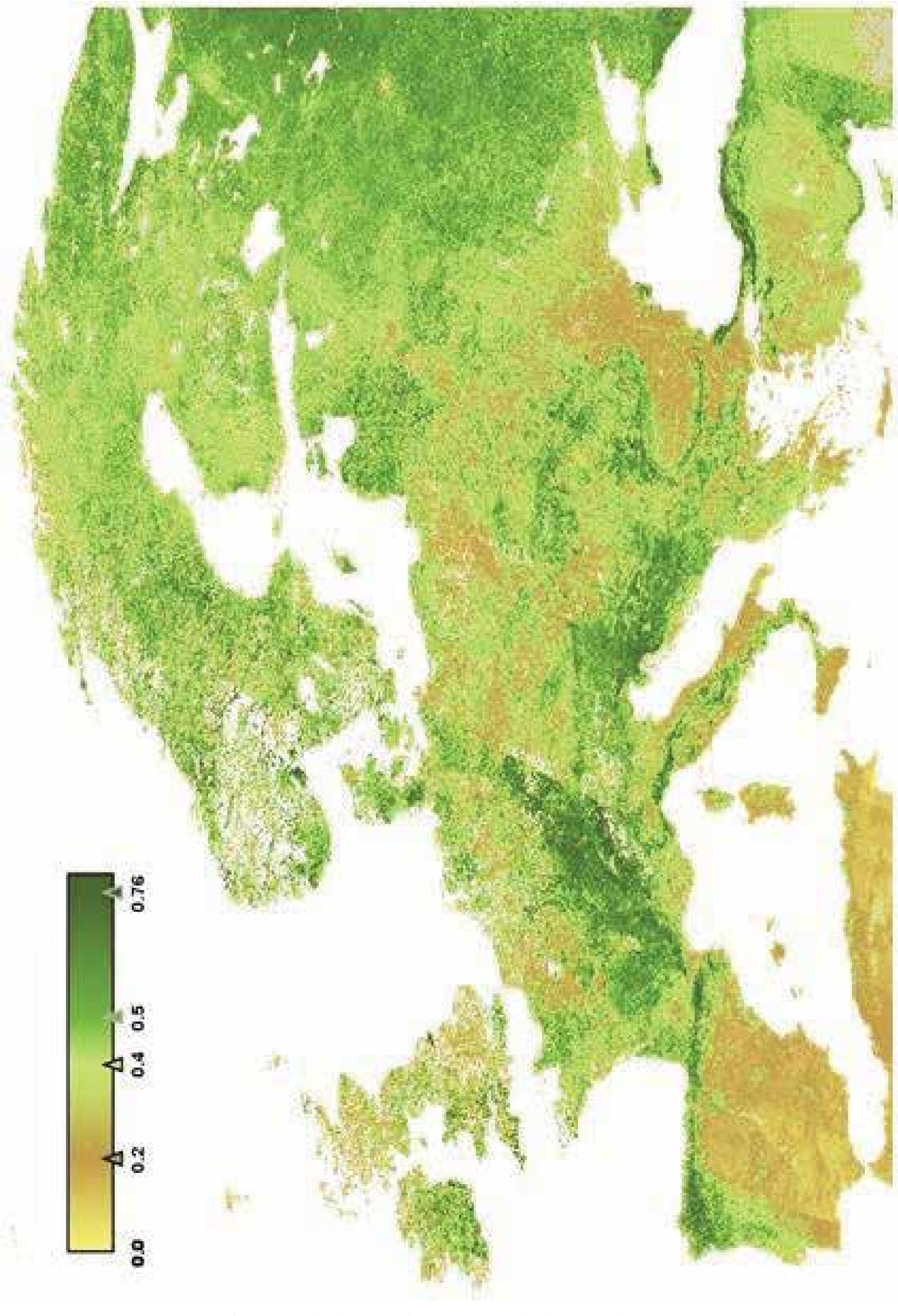

Fig. 4. Vegetation cover fraction (P_v) map for Europe (July, 2007).

Fig. 5. Confidence band for the product (valid pixels are in black).

3.2 Validation with field measurements

The validation of the whole system was carried out by comparing the data of the generated emissivity maps (as the one in figure 6) with the values obtained in previous campaigns (Coll et al. 2005) carried out in the area of rice fields of Valencia, Spain (Caselles *et al.* 2009). In order to compare them, we took all the measures data and the corresponding (by geographical coordinates) emissivity pixels and calculated the mean and the range of error for all, in each channel, as shown in Table 3.

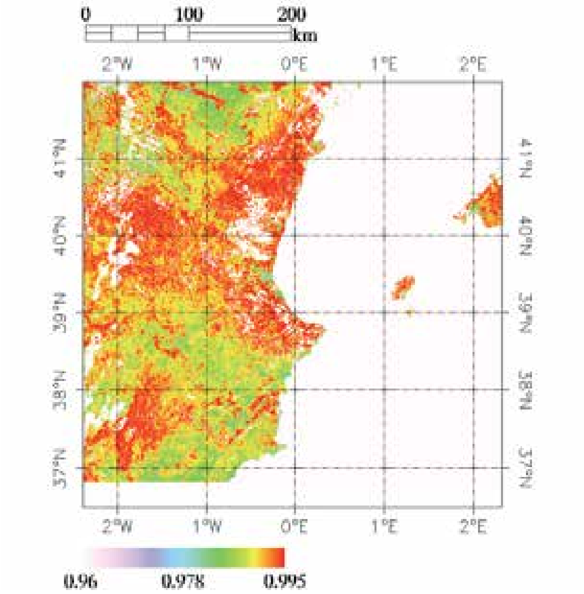

Fig. 6. Average emissivity map (between channels 11 and 12 µm) for the AATSR sensor of the validation area (Valencian Community, Spain, 20/07/2007).

Channel (µm)	Measured value	System's value
10.5-11.5	0.985 ± 0.002	0.982 ± 0.001
11.5-12.5	0.980 ± 0.005	0.988 ± 0.002

Table 3. Comparison between experimentally measured values of emissivity and the ones obtained by the system for the same area of rice fields (Valencia, Spain).

Comparing both values, a difference of less than 1% (see Table 3) is obtained. This difference is derived from the original model, as explained in Valor & Caselles (1996), and it represents an error of ±0.5 K (Mira et al. 2007) when studying the temperature.

Since the magnitude of the error of this model is very important because the emissivity error determines the temperature error and the temperature is a determinant input parameter in a wide number of models, such as circulation models, global change models, energy balance models, climatic models, etc. Therefore, our present research objective is to work to keep reducing the magnitude of this error in the future. Some possible lines to investigate are the emissivity angular dependence and the emissivity soil water content dependence.

4. Conclusions

In this work, we have developed a system able to obtain, automatically, the surface emissivity with an ±1% error (as explained in Valor & Caselles (1996)). Although we have validated it in the area of Valencia, so we have verified that commits this error; in the future we hope to be able to validate it with field measures of other European regions.

Our algorithm combines, automatically, the data measured by the sensor onboard a satellite with the information contained in the land cover classification maps. We believe this algorithm, as the developed system that implements it, come to fill the gap that nowadays exists between the different methods and techniques to generate emissivity maps from satellite images.

This new model, by using the simple interpolation function between areas measured by the satellite and the land cover classification maps, could be the best solution, since it is easy to understand that finding the correct type of soil and vegetation for each area, in order to obtain and apply the most appropriate coefficients for it is always a more accurate procedure than considering a single value of emissivity or fixed coefficients for all the surfaces.

It would also be interesting to make the system capable of differentiating between images from different months of the year, since not all surfaces remain with the same characteristics of vegetation and soil along the different seasons. So we would be able to perform more accurate calculations, according to the date on which the original AATSR image was taken.

In this chapter, this method is applied to the European territory, but it is important to remember that it was developed always keeping in mind the need to allow it to be used worldwide in a near future. Despite there are several differences that should be taken into account, we already have the right tools to do it. So this should not be a really hard process.

Although the AATSR sensor has been used as the source of the required satellite data to apply this model, one can see that this algorithm has been developed to be applied to any other similar sensors. It would be only necessary to recalculate the parameters for the required channels.

On the other hand, as we said at the beginning of this document, this method will be used as the first step, in order to be able to use a split-window algorithm (with the purpose of correcting the atmospherical effect in satellite measures) to obtain the land surface temperature automatically.

All this effort provides an important advance in the study of climate change, weather forecasting, forest protection, fire detection, etc. All of them processes that have been traditionally tedious and cost intensive to implement, while remote sensing allow us to make this studies in a faster and more affordable way. This can be determinant in sparsely populated zones, areas of difficult access such as large forests and especially in developing countries, whose resources are often more limited.

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7

Space Technology as the Tool in Climate Change Monitoring System

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1. Introduction

Today the climate change as an important issue is discussed widely around the world. Many scientists relate global warming and its consequences to human activities and not to natural fluctuations. The reasoning of this approach is the time scale of climate change.

Recent warming of the earth is considered to be abrupt compared to the time scale usually accompanied with natural climate change episodes. As obvious the Earth's natural climate changes happen gradually in a long period of time (tens of thousands to millions of years) but we are witnessing an abrupt change over the past 200 years. The main reason is the industrial revolution with fossil fuels as its main source of energy which is setting a steady emission increase of Carbon dioxide and other greenhouse gases which trap heat causing an increase of temperature in the lower atmosphere. Climate change is recognized as the significant aspect for investigation and international communities through the United Nations created special groups to focus on climate change effects and initiated protocols to organize a global response to deal with its consequences. Unusually behaviors of the strong tropical storms, heavy precipitations causing a devastating floods, more frequent heat waves, frequents drought and other similar natural events are connected to a modern climate change. The UN Secretary - General Ban Ki-moon, refer to climate change as the "defining issue of our era". This calls, among others, for implementation of commitment to stabilize greenhouse emissions and furnish a report about the current status of climate change to the UN Framework Convention on Climate Change (UNFCCC) on the status of greenhouse gases and climate change impacts and mitigation.

Climate change problem has a global scale which must be addressed with global models and global data are needed as input to these models. Currently there are sufficient space data sources with different spatial resolution which successfully implementing and applying for climate change monitoring and study purposes. Earth Observation from Space has a unique capacity to provide such global data sets in a continuous way. However the Earth Observation from Space also provides data on national and local scales which can successfully support in an implementation of the convention and protocol and encourage the Parties in their reporting duties. Currently some of countries develops and operates Earth Observation satellites which are monitoring the environment of the Earth.

For the successful climate change monitoring is required to be identified necessary indicators needed to be monitored. The vegetation indices, fire location, timing and area affected as well as additional information on the vegetation growth cycle (timing, duration, spatial and temporal variability) are being estimated globally within the GlobCarbon project implementing for the purpose of climate change.

In the meantime the greenhouse gases and aerosols are the primary agents in forcing climate change; continuous observations that are spatially and temporally homogeneous are therefore required.

Currently global climate change is recognized as one of the most urgent and crucial issues for humankind's sustainable future. In this regard application space technology is playing an important role as a key source of critical data because of its global monitoring capability. At the same time space is expected to be contributed much more extensively from various points of view in the future.

Space technologies have led to a number of inventions that benefit the environment and save energy. Satellite - based systems are reducing vehicles carbon dioxide emissions, remote sensing technology is making wind turbines more efficient and information from weather satellites is helping solar cells to produce more energy. These are just some examples of how spin - offs from space technology and satellite services can make a difference.

Undoubtedly climate change can occur over longer periods of time such as centuries and millennia or rapidly over decades. Monitoring of climatic parameters during past decades has revealed significant changes in the Earth climate. For example, sea levels increased by 0.1 to 0.2 m during the 20th century, global average temperature increased between 0.4 and 0.8°C during the last decade. The decadal precipitation increase was observed in the Northern Hemisphere and salinity anomalies have been detected in the North Atlantic Ocean. Recently there has been growing concern among scientists with respect to the possible role or influence of human activities in changing the Earth's climate.

It is necessary to use most effective technology and methods for climate change investigations in order to get advantage on analyzing and evaluation of the huge of different data sources. There are number of methods and technologies are used for climate change studies. For instance most LiDAR (Light Detection and Ranging) applications focus on remote sensing of the atmosphere and Earth surface but several oceans - related parameters allowing the calculation of the mass - balance of ice sheets can also be measured. Radar altimetry data assist both in deriving dynamic sea surface topography, including large - scale ocean currents and eddies (to within a few centimeters accuracy) and in inferring sea surface wind speeds and significant wave heights. Gravity sensors improve the physical model of the Earth used for ocean current modeling, ice sheet thickness analysis and geodynamic studies. Synthetic Aperture Radar (SAR) is used to detect the snow and ice properties, ice melting and ice type. Interferometric SAR data provides information about the flow and movements of sea ice. Wind speed is deducted from the ocean surface by measuring wave patterns. Microwave scatterometers measure the two-dimensional velocity vectors of near - surface sea winds. The design concept of this study involves continuous, space - based, ice and salinity monitoring capability by three proposed remote sensing payloads on a near polar inclination platform:

i. L - band radiometer for measuring sea surface salinity,
ii. LiDAR for high resolution ice topography, and
iii. Advanced Synthetic Aperture Radar for all - weather monitoring of ice topography.

Today is possible the use of a new technologies such as formations of a small satellites with single payloads for combining the data from LiDAR and SAR instruments as an another alternative. For example, LiDAR high - resolution capabilities could be combined with SAR all - weather capability on a single satellite platform although this would result in a relatively large and heavy platform. Based on this methods of remote sensing are successfully using for different areas of climate changes investigations. It is collection of data, analyzing and processing for the aim of problem solving.

At the same time climate change is a geographic problem and we assure solving it takes a geographic solution. Geographical information system (GIS) has a long history of driving environmental understanding and decision making. Policymakers, planners, scientists, and many others worldwide rely on GIS for data management and scientific analysis. GIS users represent a vast reservoir of knowledge, expertise and best practices in applying this cornerstone technology to climate science, carbon management, renewable energy, sustainability and disaster management and other wide areas of human life and industry.

Scientists for years have been using sophisticated computer models such as general circulation, atmosphere - ocean interaction and radiative convective process models in an attempt to visualise the future of the Earth's climate. The output of a particular model can be enlightening but combining data from multiple sources both past and future, gives us the best chance for a comprehensive and accurate vision of what the future holds and expectations for our planet.

It is required to clarify that how our dynamic climate may change in the coming decades and centuries. For this reason we have to understand and undertake the following aspects:

- the Earth temperature, atmospheric pressure and other required parameters definitions;
- the stress human populations impact on the planet contributing to climate change;
- potential factors can significantly contributing our ability to thrive and survive as a species;
- additional type of environmental monitoring doing today to improve climate change in the future.

It is obvious that there is just one way through careful observation of data, application of scientific principals and using the advance technologies give the hope and opportunities of truly understanding the stressors and impacts on Earth's climate change variations.

2. Advances of space technologies and methods – remote sensing and geographic information system

Undoubtedly two general types of data are useful in studying climate change: past observations and future predictions. Examining and cross - referencing past and future data can help us identify changes already occurring, as well as help us predict patterns and trends that could impact our long - term fate.

Careful observation and analysis of past records might help us answer questions such as: Are recent weather phenomena a short - term blip or a long - term trend? What past climate changes are due to the Earth’s natural cycle versus what changes may have been caused by volcanic eruption, meteorite impact, or other cataclysmic disasters?

The key to understanding our dynamic climate is creating a framework to take many different pieces of past and future data from a variety of sources and merge them together in a single system. Information technology brings together data from these many different sources into a common computer database. A geographic information system (GIS) is a sophisticated technology tool used by planners, engineers and scientists to display and analyze all forms of location - referenced data including meteorological information merged into coordinate system. GIS creates a new framework for studying global climate change by allowing users to inventory and display large, complex spatial data sets. They can also analyze the potential interplay between various factors, getting us closer to a true understanding of how our dynamic climate may change in the coming decades and centuries.

One of the important issues is the Earth getting hotter or colder? Is the stress human populations are putting on the planet contributing to climate change? What potential factors may significantly impact our ability to thrive and survive as a species? What additional sorts of environmental monitoring can we be doing today to improve climate change tomorrow? Only through careful observation of the data, application of scientific principals and by using the latest and advance technology do we have any hope of truly understanding the stressors and impacts on the incredibly complex system of Earth’s climate.

It is important to identify a suitable indicator or indicators with significant impact influence on climate change. It can be create a good environment for clear understanding of climate change reasons. The study of ocean and consequences of the changing some of parameters is a very useful instrument of climate change investigations.

Most organizations involved in studying climate change focus on observations and recommendations useful for long - term actions. New research programs should be initiated to improve the understanding of those aspects of the climate system that are thought to have participated in past abrupt changes and are likely to trigger such changes in the future (Alley et al. , 2003).

Due to the complexity of the processes involved in climate, numerical models are the primary tools for testing the hypotheses about Abrupt Climate Change (ACC). Current climate models range in complexity but the majority of them are complex, comprehensive, coupled models of the ocean and atmosphere. However, model complexity and reliability are often compromised by:

i. the lack of sufficient appropriate old data for further compare and analyzing with existing data;
ii. integration times, limited resolution and insufficient computing power;
iii. little understanding of several small - scale processes in the oceans and atmosphere and ;
iv. the lack of paleoclimatic data for model validation.

Climate change is an issue that will increasingly require policy consideration but for which knowledge and information at the local or landscape scale is either lacking or largely inaccessible. It is necessary to explore the scope for reinterpreting climate impacts information and presenting it through GIS - based visualizations in a manner that might assist decision - making at the local level. Such initiatives are possible because improvements in computer technology and the availability of digital databases have made it practical to generate realistic landscape views and virtual environments in much easier (and cheaper) ways (Ervin and Hasbrouck , 2001; Appleton et al., 2002).

One of the priority of the monitoring system is also including a measurements of the vertical profiles of oxygen and CO2 content in water, dissolved nutrients, or human induced tracers as they would assist in determining flow paths and identifying possible changes in circulation. Ocean surface temperature and salinity are important for understanding the small - scale processes involved in ocean circulation. While global measurements of sea surface temperature are taken from several remote sensing satellites, ocean circulation science is lacking global surface salinity measurements.

The need for the following ocean - based paleoclimatic scientific goals has been identified, which includes and extends some recommendations from the Committee on Abrupt Climate Change (NAS, 2002):

i. higher spatial and temporal resolution of paleoclimatic data;
ii. substantial and independent duplication of data for validation and reproducibility;
iii. generation of a high resolution, North Atlantic, marine record comparable with the Greenland ice records; and
iv. improved modeling simulations of past warm climates.

2.1 Monitoring systems based on satellites data

The development of models for accurate simulation of Abrupt Climate Change (ACC) is highly dependent on the collection of good - quality observational data used both for model initialization and validation.

Data acquired by passive microwave radiometers are used to infer the temperature of the sea surface, to delineate sea ice and to observe pollutants, oil spills and slicks. Proposed future satellite missions also aim at providing global sea surface salinity data.

Most LiDAR (Light Detection and Ranging) applications focus on remote sensing of the atmosphere and the Earth surface but several ocean - related parameters allowing the calculation of the mass - balance of ice sheets can also be measured. Radar altimetry data assist both in deriving dynamic sea surface topography including large - scale ocean currents and eddies (to within a few centimeters accuracy) and in inferring sea surface wind speeds and significant wave heights. Gravity sensors improve the physical model of the Earth used for ocean current modeling, ice sheet thickness analysis and geodynamic studies. Synthetic Aperture Radar (SAR) is used to detect the snow and ice properties, ice melting and ice type. Interferometric SAR data provide information about the flow and movements of sea ice. Wind speed is deducted from the ocean surface by measuring wave patterns.

2.2 Geographic information system functionality

It is identified that approximately about 80% of all available information has a spatial or geographic component. In other words, most information is tied to a place integrating into the coordinate system. So when making decisions about sitting new facilities, creating hiking trails, protecting wetlands, directing emergency response vehicles, designating historic neighborhoods or redrawing legislative districts, geography plays a significant role.

Geographic Information Systems (GIS) technology is a computer - based data collection, storage, and analysis tool that combines previously unrelated information into easily understood maps. But GIS is not limited only map development. A GIS can perform complicated analytical functions and then present the results visually as maps, tables or graphs, allowing decision - makers to virtually see the issues before them and then select the best course of action for problem solving.

Add the Internet and GIS offers a consistent and cost - effective means for the sharing and analysis of geographic data among government agencies, private industry, non - profit organizations, and the general public. Climate change is a geographic problem and it is obvious that it solving makes a necessary of a geographic solution.

GIS users represent a vast reservoir of knowledge, expertise and best practices in applying this cornerstone technology to the science of climate change and understanding its impact on natural and human systems.

A GIS - based framework helps us gain a scientific understanding of earth systems at a truly global scale and leads to more thoughtful, informed decision making:

- Deforestation analysis spurs successful reforestation programs and sustainable management.
- Study of potential sea level rise leads to adaptive engineering projects.
- Emissions assessment brings about research into alternative energy sources such as wind turbine sitting and residential solar rooftop programs.

GIS has the robust capacity and capability to design the building blocks for carbon accounting systems including data, models, and delivery systems. It provides the tools needed for analyzing environmental practices as well as developing and monitoring sustainable greenhouse gas reduction plans.

An attempt to use GIS technology (ArcGIS 9.2) to compare the present climate to the future is carried out using local meteorological data and output data from an advanced climate model. Surface temperature, precipitation, surface evaporation, surface wind speeds, and runoff will be studied to gain insight on the impacts of climate change on water resources of needed to be considered in the climate change investigations.

3. Space technology and climate change / natural disaster correlations

The gradual warming of the earth's atmosphere has become one of the main reasons of increasing a frequency and severity of climate - related disasters, such as drought, flooding, and catastrophic storms. The impacts of the climate change are reflected on ecosystems, forest and wetland conservation, water supply and sea level change etc.

An identification of the correlation between climate change and natural disaster is a highly important and key issue in point of view global warning prognosis.

The study of flooding as a very sensitive natural disaster to the climate change impacts is very interesting instrument which needed to be monitored for understanding of a huge of processes. In the meantime the use of advances in information systems, satellites imaging systems and improved software technologies open a wide opportunities for investigation of a very sensitive natural phenomena. The integration of this data provides a wide scale of analysis tools and information products on the base of developed geographical information system (GIS) created on application of space technology.

This presented research work has been dedicated for study of the river flood. During exploration of above indicated impacts of the natural disaster river flood has been carefully classified and analyzed. The outcomes of the conducted researches have shown a direct dependence and relation of the river flooding on climatic conditions based on the meteorological data for the indicated region selected for investigation.

The forecasting, mitigation and preparedness of the natural disaster impacts require relevant information regarding the disaster desirable in real time. In the meantime it is requiring the rapid and continuous data and information generation or gathering for possible prediction and monitoring of the natural disaster. Since disasters that cause huge social and economic disruptions normally affect large areas or territories and are linked to global change. The use of traditional and conventional methods for management of the natural disaster impact can not be effectively implemented for initial data collection with the further processing. The space technology or remote sensing tools offer excellent possibilities of collecting vital data. The main reason is capability of this technology of collecting data at global and regional scales rapidly and repetitively. This is unchallenged advantage of the space methods and technology.

The satellite or remote sensing techniques can be used to monitor the current situation, the situation before based on the data in sight, as well as after disaster occurred. They can be used to provide baseline data against which future changes can be compared while the GIS techniques provide a suitable framework for integrating and analyzing the many types of data sources required for disaster monitoring.

Developed GIS is an excellent instrument for definition of the social impact status of the natural disaster which can be undertaken in the future database developments. This methodology is a good source for analysis and dynamic change studies of the natural disaster impacts.

Like in all other countries, rivers have different feeding sources in Azerbaijan. Most rivers are fed by snow, rainfalls and ground waters. Snow is the predominant feeding source for the rivers of the Major Caucasus, while ground waters contribute the most to water supply of rivers in the Minor Caucasus. The Kura and Araz rivers pass Azerbaijan in their lower and middle courses.

There is a highly important of implementation of the permanent monitoring of Kura River condition in any climate season where it is directly related to the issue of the economy of Azerbaijan. In the meantime the other significant issue is to safe the human life and those properties.

3.1 Methodology

The geographical area of interest is the Kura River basin in Saylan district of Azerbaijan (Figure 1). The area comprises approximately 24 km2. The Kura watershed is one of Azerbaijan's most important agricultural production areas. During the last 10 years, it was affected by 5 excessive floods, causing a lot of damage to people and goods. The one of major source of Azerbaijan freshwater is the Kura River.

For carrying out of the goals undertaken within the framework of the project execution the following methods have been used:

- The use of ALOS space imagery to be created the land use / land cover basic map for the investigated area using urban, agriculture, garden, scrub, open area, river, stream, canal, road, railroad basic classes;
- The use of Landsat ETM space imagery to be detected potential flood inundation areas within the Kura River watershed in the Salyan district of Azerbaijan using a tasseled cap transformation;
- The derive 1 m Digital Elevation Model (DEM) from contour lines and elevation points of the investigated area to be generated a deterministic model of potential inundated areas for the region using the DEM and a convex-areas surface;
- The evaluate the sensitivity of each approach to be characterized the flood inundations through statistical tests involving comparison of flooding areas extracted from an inventory of soils and a geomorphology maps.

The results presented in this chapter have been mainly based on the project carried out within the framework of the ProVention Consortium programme ("Research & Action Grants for Disaster Risk Reduction, 2007-2008") developed in association with the University of Wisconsin-Madison, Disaster Management Centre.

Fig. 1. ALOS imagery of the selected area

The results of the carried out project "Application of Remote Sensing and GIS Technology to Reduce Flood Risk" is concerned to the high technology application. It is important to note that the space technology, project development approach used for the project implementation are very useful issues which definitely will be find out a place in our future activities for the similar problem solving.

3.2 Potential flood inundation areas identification and mapping

3.2.1 Space image processing

ALOS imagery was acquired 10 June 2007 (Figure 1). The image was georeferenced to UTM zone 39 North, WGS84 using a first degree polynomial rectification algorithm with 30 ground control points (GCPs) extracted from a digitized topographic map at the scale of 1:100 000. The root mean square (RMS) error was equal to 0.5 pixel (5 m).
The image was classified between follow general classes (Figure 2):

1. Urban or Built-up Land
2. Agricultural Land
3. Garden
4. Scrub
5. Open area
6. River
7. Stream
8. Canal
9. Road
10. Railroad

One Landsat Enhanced Thematic Mapper (ETM) satellite image from June 2000 (path 167, row 32) was selected for analysis. The image was georeferenced to UTM zone 39 North, WGS84 using a first degree polynomial rectification algorithm with 25 ground control points (GCPs) extracted from a digitized topographic map at the scale of 1:100 000. The image pixels were resampled to 28.5 x 28.5 m using a nearest-neighbor interpolation method to preserve radiometric integrity. The root mean square (RMS) error obtained in the rectification process was less than 1 pixel (28.5 m).

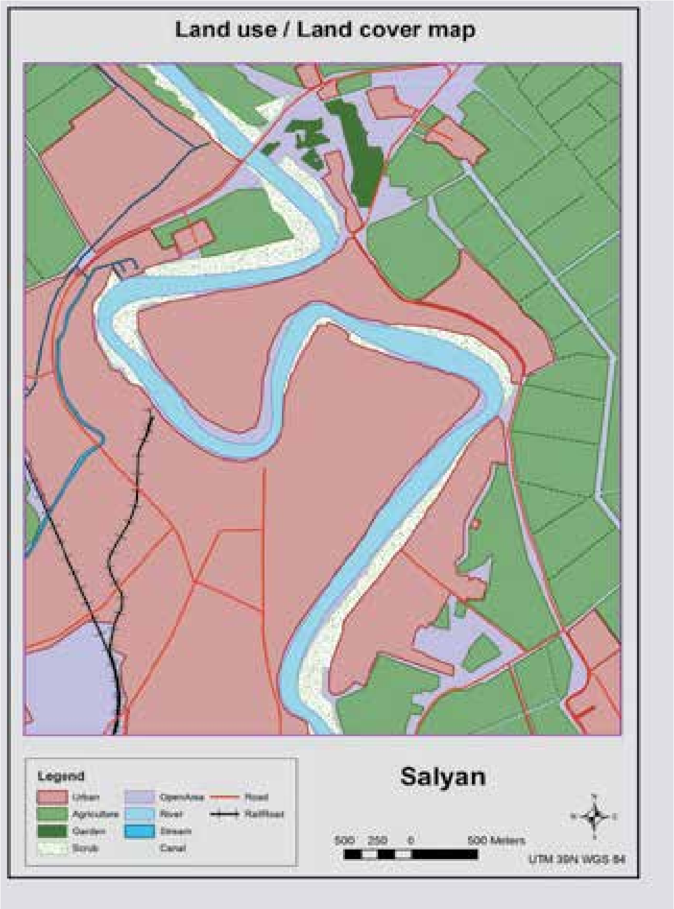


Fig. 2. Land use/Land cover map

3.2.2 Tasseled cap transformation

A tasseled cap transformation was applied to this image to optimize data viewing (Figure 3). The tasseled cap transformation offers three types of data structures axes that can be used to define vegetation information content (Crist and Kauth, 1986):

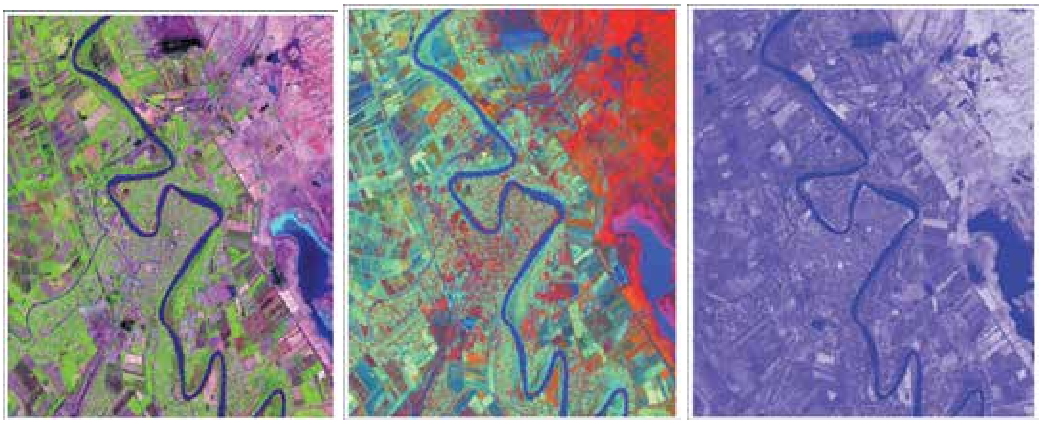
Brightness: a weighted sum of all bands defined in the direction of the principal; variation in soil reflectance.

Greenness: orthogonal to brightness, a contrast between the near-infrared and visible bands that strongly related to the amount of green vegetation in the scene.

Wetness: relates to canopy and soil moisture and effective to discriminate wet areas (Lilesand and Kiefer, 1987).
The tasseled cap algorithm using coefficients for ETM imagery are:
First Landsat-7 image was converted to at-satellite radiance using equation (1),

$$L_{sat} = \frac{L_{\max sat} - L_{\min sat}}{DN_{\max} - DN_{\min}} \cdot \left(DN - DN_{\min} \right) + L_{\min sat} \tag{1}$$

where,
$L_{\max sat}$ – is band-specific spectral radiance scaled to $DN_{\max}$,
$L_{\min sat}$ – is band-specific spectral radiance scaled to $DN_{\min}$,
$DN_{\max}$ – is maximum quantized calibrated digital number (255), and
$DN_{\min}$ – is minimum-quantized calibrated digital number (0 for LPGS data, 1 for NLAPS data).
Equation (1) accounts for gain state (i.e., high/low setting) by using the respective published LMIN/LMAX values (Landsat 7 Science Data User's Handbook).
After conversion to at-satellite radiance, the image was exposed to Tasseled Cap transformation. The Tasseled Cap operation (also known as Kauth's Tasseled Cap) computes the three Kauth biophysical indices (greenness, brightness, and wetness) from raster objects that contain the six spectral bands of ETM imagery: ETM1, ETM2, ETM3, ETM4, ETM5, ETM7. This spectral information is translated into values that represent a site's biophysical properties. The process produces three output raster objects that represent greenness, brightness, and wetness using a set of linear combinations of Landsat ETM spectral bands.



RGB composite with bands 5,4,3

RGB composite with layers brightness, greenness, and wetness

Pseudo color composite with wetness index

Fig. 3. The original ETM image, the image applied the tasseled cap transformation, and the derived wetness layer.

Output is generated according to the following formulas:
Brightness = 0.3561(ETM1) + 0.3972(ETM2) + 0.3904 (ETM3) + 0.6966 (ETM4) + 0.2286 (ETM5) + 0.1596 (ETM7)

Greenness = -0.3344 (ETM1) - 0.3544 (ETM2) - 0.4556 (ETM3) + 0.6966 (ETM4) - 0.0242 (ETM5) - 0.2630 (ETM7)

Potential flood inundation areas determined by the wetness index of the tasseled cap transformation have been reflected in the Figure 4.

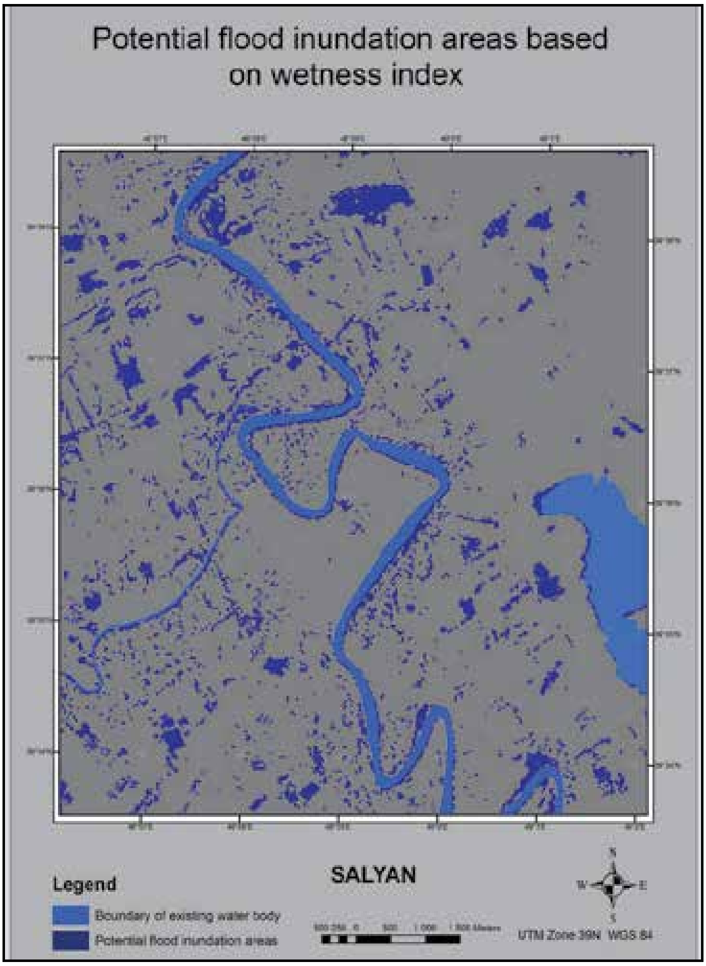


Fig. 4. Potential flood inundation areas based on wetness index

3.2.3 Digital Elevation Model development

The digital elevation model (DEM) was developed using the common method of digitizing of the contour lines and elevation points from topographic map (Figure 5). The digitized lines in shapefile format were converted to points in ArcGIS 9.2 using the “Feature to Point” transformation tools. The points were interpolated using the IDW – inverse distance weighting method.

GIS neighborhood operations make available to calculate the mean DEM. The selected potentially flooding areas where discovered of convex and fall of an elevation range between -26 m and – 21 m, which is approximately the elevation range corresponding to the lower alluvial plain. It is the generally affected when occurs of the severe flooding.

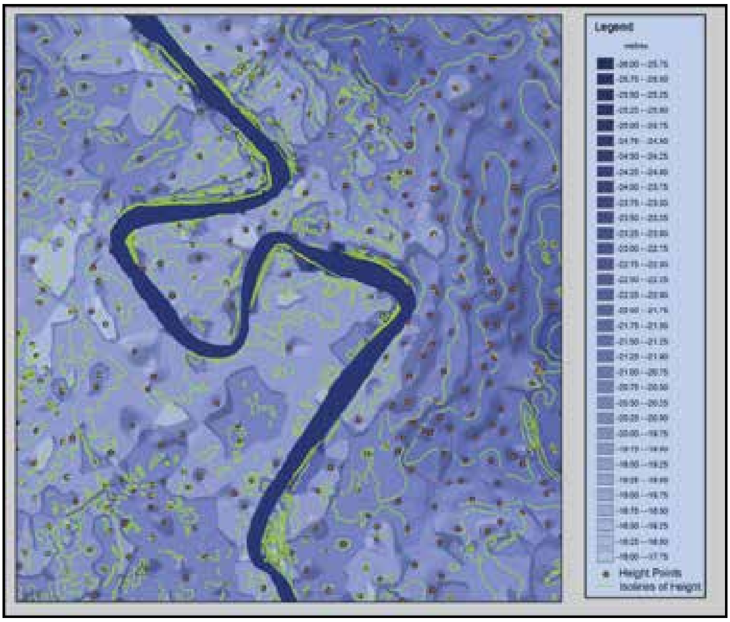


Fig. 5. Digital Elevation Model of the selected area with high points and isolines.

3.2.4 Potential flood inundation areas mapping

The study and identification of the potentially flood inundation areas in advance is a useful and important aspect of the natural disaster impact reduction.

For this reason the areas potentially flood inundation with a high probability of flooding has been developed and mapped. In this measurements and calculations the staring point has been undertaken as -26m.

The result reflects the potential flood inundation areas based on the height data supposed being as -22m. The result of data calculation and processing from DEM has been demonstrated in a Figure 6. RF indicated zones reflect potentially flood inundation areas in case of the river level will be increased up to 4m.

This methodology can be successfully applied for potentially flood inundation areas after implementation of geodetic measurements related to the river level for acceptance of the high accuracy data.

All processed information was compared with the meteorological data in order to find appropriate correlations between natural disaster particularly river flood and climate condition for the selected period. It has been confirmed that there is uncertainties for the climate phenomena which was not common for the area. For this period the river flood was observed with no expected impact. It assures that natural disaster impact can be used as a key instrument for the identification and correlation of the climate change.

3.2.5 Modification of the 3D model of the selected areas

3D model of the selected areas for the zones of Z5 and Z8 has been developed. The main reason of this development was the achievement of the more effective views of the selected areas. The result of this developments have been reflected in the Figure 7a and 7b.

For this modeling the vertical exaggerations have been identified 5 and 8 consequently for Z5 and Z8.

Fig. 6. Forecasting of the potentially flood inundation areas.

a) For Z8.
b) For Z5

Fig. 7. 3D modified view of the selected area.

The main target has been undertaken to assist the local authorities to build useful database in disaster risk reduction in particularly for the selected area with a more sensitively part of country in point of view the river flood.

In the meantime has been demonstrated a contribution of the possibility and advantage of remote sensing methods and GIS technology use based on space image data collection and data processing for application of similarity problem solving.

Using the higher resolution of space imagery and change detection analysis natural disaster awareness and damage assessment can be conducted rapidly and accurately.

On the base of the developed database using the remote sensing methods and GIS technology there is resources and opportunities of prediction, reduction of natural risk due to the timely implementation of appropriate engineering and technological activities.

Based on those results as well as existed database for the river level change there is approach of study and identification of the dynamic change of the Kura river level. It is an advantage of development of GIS which can be play a significant place on river flood problem solution especially valuable and extremely important instrument for decision maker of the local authorities.

It has been correlated all above results with data reflected climate circumstances for the appropriate period of investigations and has been found relationships between river flood natural disaster and climatic parameters for the selected area.

The results of project presented in this paper have the following key findings:

- Space technologies are to develop of an advance tool for monitoring, data collection, data processing, review and report on progress and challenges in the implementation of disaster risk reduction and recovery actions undertaken at the national level.
- As a further step a wide scale of river monitoring is required for successful and effectively forecasting, preparedness and reduces of the natural disaster impact.
- Awareness information program of this hazard has to be developed and implemented in order to safe the human life, properties as well as to reduce disaster damage impacts.
- Potential flood inundation areas can by identified by satellite imagery and ground-based measurements.
- The mapping of potential flood areas can help for further settlement planning in this region.

All this indicated accepts have to be undertaken for further successful management in order to be able to reduce the effect of natural disaster on river flood. An appropriate sufficient with high accuracy database has to be developed for local authorities for decision making.

4. Regional approach of the global climate change problem

4.1 Objective

As it has been already identified the climate of the Earth system is a consequence of a complex interplay of external solar forcing and internal interactions among the atmosphere, the oceans, the land surface, biosphere and cryosphere. As far as obvious the human activities are increasingly recognized as a potential factor influencing the change in the global system by altering the chemical composition of the atmospheric concentrations of powerful greenhouse gases mainly such as CO2 and CH4 are predicted to lead to accelerated global climate change, a central environmental issues of concern to Governments around the World. Particular interests are the potential regional impacts of such changes on coastal areas, fresh water resources, food prediction systems and natural ecosystems.

Space based technology has advanced to a point that we are able to accurately observe and sense globally the entire Earth system and to understand Earth system processes that are central to Earth's climate. We need to document and understand an interrelations between Sun-Earth as an external forcing of the Earth's climate and also need to better understand the Earth's intricately linked internal processes such as the global water, energy and carbon cycles. Space based platforms with their unique capacity to observe the Earth on global bases, complement surface based and in-situ measurements. Together with advances in computing and information systems technology, modern data assimilation techniques, diagnostic and prediction models, they provide a powerful combination of tools for understanding of the Earth system and applying the knowledge and tools to the management of natural resources and the mitigation of natural hazards.

4.2 Implementation

Use of the space science and technologies and applications offer and provide opportunities a wide scale of possibilities in a huge of areas of human life and industry. User communities are often not aware of the potential synergies, savings and new operations enabled through space.

Recent innovations and advances in space science and technology have dramatically changed the nature and structure of space-related development applications in recent years, making space a more versatile and flexible tool for the development community. Much has been accomplished in this area, but little is known about these successes that is availability of a wide applications in the needed areas of human society. Space applications must be a perfect tool for the development projects and offer a veritable path to sustainable having an excellent outcomes with a high accuracy and comparatively immediate feedbacks.

The success of advances space technology applications in a variety of areas of our life depend of the degree use of those capacities. Integration of the capacity of the countries would be much better contributed for natural resources investigations, natural disaster, climate change, security and many other strictly important problems.

Cooperation can be likely developed within the framework of existed programmers. For instance, as per identified Global Monitoring for Environment and Security (GMES) is a joint initiative of the European Commission (EC) and the European Space Agency (ESA), designed to establish a European capacity for the provision and use of operational information for Global Monitoring of Environment and Security (GMES).

The UN SPIDER capacity is a one more opportunity for the enhancement of the foregoing mentioned issue for the success of the international cooperative relationship establishment.

It is obvious that there is a highly need for collection of appropriate processed data for the indentified purposes and the main issue is to share of data among the communities who needs for this data.

Inviting efforts from different countries are undertaking a necessity of integration within the Black and Caspian Seas region as a testing region for a global climate change identification. Development and implementation of projects, as a first step, for common needs would be an excellent way for significant contribution of scientists and professionals in application of space science and technology for natural disaster studies.

The following approach can be considered for project implementation:

- Conduct of global and regional reviews of global climate changes research needs and opportunities in the context of development issues;
- Creation of alliances among institutions to increase their effectiveness and to coverage of urgent issues;
- Facilitation of national collaborative research networks;
- Stimulation of the creation of new centers and networks where gaps are found;
- Mobilization and coordination of resources.

The eight Millennium Development Goals have been adopted by the international communities as a framework for the development activities of over 190 countries divided for a ten regions. They are eradicate extreme poverty and hunger, achieve universal primary education, promote gender equality and empower woman, reduce child mortality, improve maternal health, combat HIV/AIDS, malaria and other diseases, ensure environmental sustainability and develop a global partnership for development. The targets for each foregoing goals implementation are undertaken:

- Halve, between 1990 an 2015, the proportion of people whose income is less than $1 a day: achieve full and productive employment and decent work for all, including woman and young people: halve between 1990 and 2015 the proportion of people who suffer from hunger;
- Ensure that 2015, children everywhere, boys and girls alike will be able to complete a full course of primary schooling;
- Eliminate gender disparity in primary and secondary education, preferable by 2005 and in all levels of education no latter than 2015;
- Reduce by two thirds between 1990 and 2015 the under-five mortality rate;
- Reduce by three quarters between 1990 and 2015 the maternal mortality ratio: achieve by 2015 universal access to reproductive health;
- Have halted by 2015 and begun to reverse the spread of HIV/AIDS: have halted by 2015 and begun to reverse the incident of malaria and other major diseases;
- Integrate the principles of sustainable development into country polices and programmes and reverence the loss of environmental resources: reduce biodiversity loss, achieving, by 2010 a significant reduction in the rate of loss: halve by 2015 the proportion of the population without sustainable access to safe drinking water and basic sanitation: by 2020 to have achieved a significant improvement in the lives of at least 100 million slum dwellers;
- Address the special needs of the least developed countries land locked countries and small island developing states: develop further an open, rule – based, predictable, non – discriminatory trading and financial system: deal comprehensively with developing countries debt: in cooperation with pharmaceutical companies, provide access to affordable essential drugs in developing countries: in cooperation with the private sector, make available the benefits of new technologies, especially information and communication.

Within the framework of indicated above goals and developed targets are the sources for the successful investigations of the global climate change problems. We must strengthen global cooperation and redouble our efforts to reach the MDGs and advance the broader development agenda. In the meantime the use of the existed international communities in the area of the global monitoring of the Earth and atmosphere studies with application of the recent advance space technologies and methods can provide and develop a wide opportunities for study and exploration of the climate change impacts.

It is understandable that the global phenomena demands use and application tools available to provide a significant contribution for solution. Problem of global climate change is a problem with a wide scale impact for the human society needed to be investigated with tools which creates of the operative collection of the appropriate data with further processing. In this connection the use and application of space technology mainly Remote Sensing methods and GIS technology needed to be applied for this purpose.

Taking into account a big scale of the problem it is my vision that the success in this developments depends how luckily will be integrated and engaged of the countries divided into regions in data collections, processing and sharing of this data among country participants.

The importance of water and air in our daily life is clear to everyone, though they represent fragile earth resources that can change abruptly at times. Understanding the mechanics of climate change provide us with an essential need to prepare for the future.

4.3 Providing Regional Climates for Impact Studies

Providing Regional Climates for Impact Studies (PRECIS) is a regional climate modeling system that can be run on a PC. The United Kingdom Met Office's Hadley Center for Climate Prediction and Research is the provider and the developer of this software. The data for the boundary condition is supplied by the Hadley Center Global Climate Model (GCM), UK Met Office. PRECIS comes with a user interface to carry on climate experiments. Prediction of future climate change is done globally with world wide support through United Nations organizations. Very few countries have the capability to designate a dedicated group of highly trained scientists and provide extremely fast computers to run GCMs' models to generate climate change scenarios, and perform the necessary analysis to investigate the regional impacts of climate change on their specific regions. The United Nations Development Program (UNDP), The UK Department for Environment, Food and Rural Affairs (DEFRA), and the UK Department of International Development started funding PRECIS to be available to developing countries to generate their own climate change scenarios with using a personal computer only. The UK Met Office's Hadley Centre will supply the software, the boundary conditions and other fields of global quantities required to run PRECIS [**Jones R.G., Noguer M., Hassell D.C., Hudson D., Wilson S.S., Jenkins G.J. and Mitchell J.F.B., 2004, Generating high resolution climate change scenarious using PRECIS, Met Office Hadley Center, Exeter, UK, 40pp**]. Emission scenarios describing population, energy, and economics are taken from IPCC SRES (A1T, A1FI, A1B, A2, B1 and B2).

4.4 Methodology used for plan development PRECIS implementation

There are three parts for this research. First is to set up the regional climate model (PRECIS) and run the three experiments.

Second is to do basic analysis to the output data to get specific information about climate fields and calculate the predicted state of the future from the simulation and the historical data. Third is to use ArcGIS 9.2 to present the climate variables outputs and do further analysis.

It has been installed the Linux operational system (open SUSE 10.2) and Precis (version 1.4.6) into three separate personal computers. Two of them have processors (CPU): Intel® Pentium® 4 with speed 3.2 GHz. The third one is with an Intel centrino core duo processor with speed of 2.16 GHz. Three experiments were designed to perform present, future and reanalysis data in order to get proper statistical information. Present and future experiments were based on Hadley Center's GCM data. The final experiment is dedicated to get a high resolution of ECMWF reanalysis data (ERA40).

4.5 Analysis of results

The science of climate change requires running huge amount of world wide data, and presently few places conduct climate modeling for a hundred years of the future which is regarded as climatologist's common sense of research. It is widely accepted to take the period spanning 30 years from 1961 to 1990 as a baseline in carrying out model simulations. The future climate fields are determined from the results of the regional climate model simulation of present day carbon dioxide concentration value and the future when the concentration of CO_2 is doubled. The following are the calculations carried out by Loa´iciga H.A [**Loa´iciga H.A., 2007, Climate Change and Groundwater, available at http://ncsp.va-network.org/section/resources/resource_water]:**

$$T_{scenario} = T_{historical} + \left(T_{f2\times co2} - T_{b1\times co2}\right) \tag{1}$$

$$W_{scenario} = W_{historical} + \left(W_{f2\times co2} - W_{b1\times co2}\right) \tag{2}$$

$$P_{scenario} = P_{historical} \times \left({P_{f2\times co2}} \Big/ {P_{b1\times co2}} \right) \tag{3}$$

$$E_{scenario} = E_{historical} \times \left({E_{f2\times co2}} \Big/ {E_{b1\times co2}} \right) \tag{4}$$

$$\left(P-E\right)_{scenario} = \left(P-E\right)_{historical} \times \left\{ \left(P-E\right)_{f2\times co2} / \left(P-E\right)_{b1\times co2} \right\} \tag{5}$$

$$Q_{scenario} = Q_{historical} \times \left({Q_{f2\times co2}} \Big/ {Q_{b1\times co2}} \right) \tag{6}$$

Where T, W, P, E, (P-E) and Q accordingly represent temperatures in degrees Celsius, wind speeds in meters per seconds, total precipitation, surface evaporation in millimeters per day, the resultant of subtraction of surface evaporation from total precipitation in millimeters per day, and the mean runoff in millimeters per day. The subscript (f) is for future simulation, and the subscript (b) is for the baseline simulation.

5. Conclusion

The means of climate fields were created as features in every region and every meteorological station. Historical, predicted, and percentages of climate change results were viewed as multi variable bar charts by implementing "symbology" in layer's properties. The technique of applying "Spatial Analyst" from "Toolbars", interpolating the data to Raster, and using Kriging option to produce filled contours was carried out on climate variables for comparison and study.

It is easy to push a lot of technology into the climate change corner - in a catch all way. But there are many other important and useful reasons for using GIS technology.

1. Environmental Pollution / Health: The quality of the environment is only ascertained through the use of technologies that can measure environmental factors. GIS not only holds this information, but enables the processing of environmental data between places over time;
2. Water: On any given day can be seen the shortage of water around the planet growing. This means it must either be able to create more water or use the existing water available, more efficiently. GIS provides a toolset that enables the monitoring and management of water more effectively;

3. Transport Planning: Obvious that people are moving toward public transportation. But before that even happens, a need exists to understand where to build transport infrastructure. To determine that means that we understand where people are and where they are going to be 10, 20, 30 years ahead of time. GIS can determine these pieces of information. We are already seeing increases in investment in transport;
4. Food: While food prices increased last year, we are not out of the woods yet. You can expect to see agricultural production increase in cost because producers are currently having a more difficult time to acquire lending to support future crops – due to the bank situation. It feedback will on future production, necessitating increased agricultural management and efficiency. GIS is a tool of choice for land management and variable rate farming;
5. Energy / Efficiency: Current low prices have taken the edge off of renewable resources – slightly. This is not bound to last long and prices for non - renewable will rise. At minimum they are limited resources. Now is actually a good time to be investing in energy because of lower prices. GIS is useful for all energy types, from wind turbines and solar arrays, to geological analysis and bio - production, these tools enable 2-D, 3-D and 4-D analysis and visualization;
6. Oversight and Accountability: The current financial climate is going to result in increased accountability and transparency. People will demand more exacting answers and have many more critical questions about processes and investments. Quality data and accuracy will be increasingly important. Tools and technologies that enable that will be in high demand;
7. Inventory: As the news is telling, many companies and organizations do not know the resources they own and control. Strange as this may seem, the shift is underway to find out – now. GIS will enable inventory control;
8. Risk Management: Few people are willing to risk under the current operating environment. Fewer are even willing to invest. Tools that help to understand and reduce risk are going to become popular;
9. Visualization: Data is showing that people are travelling less, conserving funds and reducing costs. But they are also showing that people are engaging each other through virtual technologies, games and visualization. GIS are graphical environments that link databases to visualization;
10. Convergence of data: A large number of high resolution data sources are now coming together. To really leverage their value (which is substantial) will mean greater processing of the data and understanding society in new ways. Part of this is research, part is integration and part is political change. The winds of change are happening and tools that enable understanding change are critically important.

In climate or systems modeling, the value of geographic analysis and spatial visualization is well recognized because it is able to improve interpretation of the overall modeling outcomes as single site simulation has limited applicability. Therefore, use of GIS software is widespread, but is not an easy task with many potential users not equipped to take advantage of the comprehensive spatial and visualization analysis features. One possible solution is to develop a simplified task - specific system that can be easily used by non-GIS users. Such a system can either incorporate GIS ActiveX controls or embed GIS software such as ArcGIS . These GIS enhanced systems can be useful for specific tasks. For example, the GIS - based Sediment Assessment Tool for Effective Erosion Control (SATEEC) was developed to estimate soil loss and sediment yield and can be used to identify areas vulnerable to soil loss and to develop efficient soil erosion management plans. However, it is difficult to implement in a portable end - user tool if the database is very large and/or the format of input data differs from the embedded tool.

Studies on potential impacts of climate change on agriculture and/or the environment have rapidly increased in recent years. Understanding the regional impacts of climate change on biophysical systems requires a modeling approach incorporating Global Climate Model data, the cornerstone of the climate change research. However, climate model projections at higher temporal and spatial resolutions are not adapted to describe local effects and thus statistical methods are needed to correct the projections from the GCM using historical climate information.

In particular, many climate and agricultural indices are used to describe the system being investigated and are therefore useful to translate the large - scale climate change information to model the impacts of climate change and develop the appropriate adaptation strategies. A GIS framework provides an enhanced ability to assess the possible responses from a range of adaptation strategies to climate change by integrating the outputs from GCMs and various modeling efforts in agriculture. The purpose of this work was to develop a GIS - based risk assessment tool to utilize the generic output from the GCMs and apply them, through a modeling framework, to assess the specific responses required by each of the major agriculture sectors. As a case study, the impact of climate change on wheat flowering and its implications in term of adaptation strategy are outlined in this communication.

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8

Atmospheric Aerosol Optical Properties and Climate Change in Arid and Semi-Arid Regions

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1. Introduction

In recent years, there has been much attention to the study of atmospheric aerosols in Asia as aerosols generated in this region has significant direct and indirect effect on changing the Earth's climate on a global scale. Aerosols are small particles in the air that originate from a number of different natural and human activities such as ocean spray, dust storms, fires and pollution from fossil fuel combustion. Aerosol particles may be solid or liquid and their sizes range from 0.01 microns to several tens of microns. Scientists have much to learn about how aerosols affect regional and global climate and the direct and indirect radiative forcing of aerosols are still not understood well. In the last decade, scientists from East Asian countries and the world's science communities have organized and conducted many international and regional experiments and projects on aerosol optical properties and the measurement of radiation , for example: NASA AERONET (Aerosol Robotic Network), East Asian Regional Experiment 2005 (EAREX 2005) of the United Nations Environmental Program (UNEP), Atmospheric Brown Cloud (ABC) project, ABC Maldives Monsoon Experiment (APMEX), SKYNET (MEXT Sky Radiometer Network), ADEC (Japan-Sino Joint Aeolian Dust Experiment), ABC-EAREX (ABC East Asian Regional Experiment) and EAST-AIRE (East Asian Study of Tropospheric Aerosols, International Regional Experiment). Figure 1 shows sites of above mentioned networks in East Asia.

The AERONET provides quality-assured data for aerosol optical properties measured by the Sun/sky multi wavelength radiometer over the World. AERONET facility processes and archives these data according to a standardized procedure for the retrieval of aerosol properties. One of the AERONET site at Dalanzadgad of arid region of Mongolia has been operated continuously since 1999 (Tugjsuren N, 2010). Recently, studies on the aerosol monitoring over Eastern Asia using AERONET Sun-photometer acquired aerosol optical thickness and Angstrom exponent measurement have been conducted in the research on Aerosol properties in a Chinese semiarid region (Xia Xiango at al., 2004).

Seasonal and monthly variations of columnar aerosol optical properties over east Asia determined from multi-year MODIS, LIDAR, and AERONET Sun/sky radiometer measurements, (Sang-woo Kim at al., 2006)

The East Asian regional Experiment 2005 (FAREX 2005) project was organized and conducted from March to April 2005 by researches from east Asian countries and others. The regional experiment preceding to FAREX 2005 was the ABC Maldives Monsoon Experiment (ARMEX) conducted from 1 October to 15 November 2004 in the south Asian region with another ABC supersite at Hanimaadhoo , Maldives. These two regions have large emission sources of anthropogenic aerosols and gases with largely different climates and weather conditions. ARMEX and EAREX targeted detailed study of aerosol characterization in Monsoon transition periods in fall and spring seasons in these regions.

SKYNET is an observation network to understand aerosol-cloud-radiation interaction in the atmosphere. The SKYNET project aims at a better understanding of long-term variability in the radiation budget and atmospheric parameters over the eastern Asia and its attributes based on the analysis of ground-network data. As for this objective, both regional and local analyses are needed to investigate the aerosol effects on climate change. The main instruments consist of a sky radiometer and radiation instruments such as pyronomter and pyrgeometer as a basic site, and a super site has more instruments extended for analyzing atmospheric parameters of aerosol, cloud and radiation. SKYNET has maintained Sky radiometer observation site since 1997 at Mandalgobi of semiarid region of Mongolia, in collaboration with the Chiba University, Japan (Tugjsuren N, 2010).

Fig. 1. Site map for projects studying aerosol and radiation measurement in Asia

2. Direct and indirect aerosol radiative effects

Aerosols play dominant role in affecting the energy budget of the Earth climate system by interacting with solar and terrestrial radiation. Aerosols can affect solar radiation budget in two ways; by directly scattering and absorbing solar radiation (this is known as the direct radiative forcing), and also by acting as cloud condensation nuclei thereby influencing the optical properties and life-time of clouds (this is known as the indirect radiative forcing). Aerosols tend to cool the Earth's surface directly beneath them. As most aerosols reflect sunlight back into space, they have a "direct" cooling effect by reducing the amount of solar radiation reaching the Earth’s surface. The magnitude of this cooling effect depends on the size and composition of the aerosol particles, as well as the reflective properties of the underlying surface. Aerosols are also believed to have an "indirect" effect on climate by changing the properties of clouds. Clouds with low aerosol concentration and few large water droplets do not scatter light well, and allow much of the sun's light to pass through and reach the Earth’s surface. Whereas high aerosol concentrations in clouds creates nucleation points necessary for the formation of many small water droplets. A well known Twomey effect (Twomey et al., 1984) that causes an increase in the cloud optical thickness when aerosols act as cloud condensation nuclei to increase the cloud droplet number and hence to increase the effective cloud droplet radius when the total liquid water path of the cloud does not change. The decrease of cloud optical thickness and water path partially reduces cloud cooling effect.

Up to 90% of visible light is reflected back to space by such clouds without reaching the Earth's surface. Indeed, if there were no aerosols in the atmosphere, there would be no clouds. It is very difficult to form clouds without aerosol particles acting as "seeds" for the formation of clouds. As aerosol concentration increases within a cloud, the water in the cloud gets spread over many more particles, each of which is correspondingly smaller. We have yet to accurately appraise the respective impacts of naturally caused aerosols and those caused by human activities on the climate. Aerosols are produced naturally, from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray. Human activities, such as the burning of fossil fuels and the alteration of natural surface cover, also generate aerosols. Moreover, we do not precisely know in which regions the amount of atmospheric aerosol is increasing, diminishing, and remaining constant. The emission of anthropogenic aerosol is usually based on conversions of government statistics of energy used by various industries (Streets D.G et al., 2009). Aerosols are continuously transported by atmospheric motions and are largely removed by cloud and precipitation processes thus the amount of aerosols in a unit volume of atmosphere is frequently changing. Aerosol particles larger than 1 micrometer in size are produced by windblown dust and sea salt from sea spray and bursting bubbles. Aerosols smaller than 1 micrometer are formed mostly from condensation processes such as conversion of sulfur dioxide (SO_2) gas to sulfate particles and from formation of soot and smoke during combustion. As volcanoes erupt, they blast huge smoke clouds into the atmosphere. These clouds are made up of particles and gases, including sulfur dioxide. Millions of tons of sulfur dioxide gas from a major volcanic eruption can reach the stratosphere. There, with the help of water vapor, sulfur dioxide converts to tiny persistent sulfuric acid (H_2SO_4) aerosols. These aerosols reflect radiation from the sun, thereby preventing the sun's rays from heating the Earth's surface. Aerosols play dominant role in affecting the energy budget of the Earth climate system by interacting with solar and terrestrial radiation. Aerosols tend to cool the Earth's surface directly beneath them. As most aerosols reflect sunlight back into space, they have a "direct" cooling effect by reducing the amount of solar radiation reaching the Earth's surface. The magnitude of this cooling effect depends on the size and composition of the aerosol particles, as well as the reflective properties of the underlying surface. Global dimming and brightening phenomena have been studied using data of surface radiation networks.

Wild et al. (2005) found that surface solar radiation in most parts of the world experienced a reversal trend from "dimming" to "brightening" in early 1990s. Also, Shi et al. (2008) observed similar situation in China in the beginning of 1990s. These studies showed that the surface solar solar radiation is increasing in the European region , while the Asian region still suffers a decrease in the surface solar radiation due to increasing anthropogenic aerosols.

Rei Kudo et al. (2010) measured surface solar radiation under the clear sky conditions from 1975 to 2008 by measuring optical thickness and single scattering albedo. Their findings show that surface solar radiation at numerous locations decreased until the mid-1980s (global dimming), and increased after the decline (global brightening). During this study, they observed that optical thickness increased until the mid-1998s, then decreased until the late 1990s, and was almost constant in the 2000s. Single scattering albedo was low until the late 1990s, then increased, and was almost constant in the 2000s. The magnitude of the brightening was 12.7 Wm^{-2}, of this, 8.3 Wm^{-2} was due to a decrease of optical thickness, and the remaining 4.4 Wm^{-2} was due to an increase of single scattering albedo.

Volcanic eruptions are thought to be responsible for global cooling as it has been observed that there is cooling for a few years after a major eruption As volcanoes erupt, they blast huge smoke clouds into the atmosphere. These clouds are made up of particles and gases, including sulfur dioxide. Millions of tonnes of sulfur dioxide gas from a major volcanic eruption can reach the stratosphere. There, with the help of water vapor, the sulfur dioxide converts to tiny persistent sulfuric acid (H_2SO_4) aerosols. These aerosols reflect radiation from the sun, thereby preventing the sun's rays from heating the Earth's surface. In the case of major eruptions, injection of volcanic dust into the stratosphere may affect the climate globally as well as regionally due to the large amount of volcanic aerosols that remain in the stratosphere for years. The extent of the cooling depends on the force of the eruption and, possibly, on its location relative to prevailing wind patterns. After formation, the aerosols are mixed and transported by atmospheric motions (Budyko et al., 1986). In the Northern Hemisphere, a quick change in monthly average surface air temperatures has been observed after major volcanic eruptions and the effects last a few years. The average temperature decrease over the first year is about 0.3-0.4 ^{0}C. Short term surface temperature effects were observed over the northern United States after Mt. St. Helen erupted. The importance of sulfuric aerosol which is formed by the conversion of sulfur dioxide in volcanic gas to sulfuric acid in evaluating the stratosphere was first established in the 1980-1990’s. During the last 100 years, many volcanoes erupted on the planet Earth. The eruption of Mt. Pinatubo in Philippines on 15 June 1991 was regarded as an extraordinary activity in the 20th century. Disk-shaped ash clouds with diameters of up to 600 km were observed by GMS-4 at one hour intervals, as they dispersed at altitudes of 20-30 km in the stratosphere, which were above dense typhoon clouds. The amount of sulfur dioxide injected into the stratosphere was about 15 to 30 MT by the 1991 eruption of Mt. Pinatubo, compared with 7 to 20 MT of sulphur dioxide by the 1982 El Chichon eruption (in southern Mexico) and about 50 MT by the 1883 Krakatoa eruption. The potential effect of volcanic eruptions on global climate may be huge, but careful studies are required to determine the exact impact as the climatic dynamics are complicated by the greenhouse effect due to the increases of carbon dioxide in the air.

Asian dust particles have significant effect on the radiative budget of the earth-atmosphere system through the scattering and absorption of solar and long wave radiation and acting as condensation nuclei to form cloud. During the past thirty years, the physical, chemical and optical properties, as well transport mechanism of the Asian dust have been intensively investigated. Recently, a number of lidar groups in East Asia have coordinated a lidar network for the observation of dust during Spring in order to understand their three-dimensional spatial distribution and temporal variation in Asia. Dust storms can also generate large amounts of aerosol in the troposphere. Usually, dust aerosols are produced in arid and semi-arid areas on Earth and transported by the atmosphere to be later deposited over land or ocean and influence the primary formation and deep ocean sediments. The radiative effect of the dust layer still remains to be assessed. Every year during spring, a number of dust storms occur in the Gobi desert in southern and western Mongolia and northern or northwestern China. Large amounts of soil and sand particles uplifted from this area are transported to Japan, Korea and the North Pacific region by prevailing westerly wind. Dust storms may have contributed to the desertification of the southern and western Mongolia and northwestern China during recent decades. Due to the large spatial and temporal extent of desert dust in the atmosphere, interactions of desert dust with clouds and land surface can have substantial climatic impacts. The absorption or diabatic heating of Asian dusts can cause the evaporation of cloud droplets and reduce cloud water path.

Clearly desertification is a historical phenomenon, and not a phenomenon of present times. Desertification is a global problem, not only because of the vast areas of drylands, which occupy about one third of the earth's surface. The deserts of central Asia are located in the temporal belt of the continental climate (Fig.2).

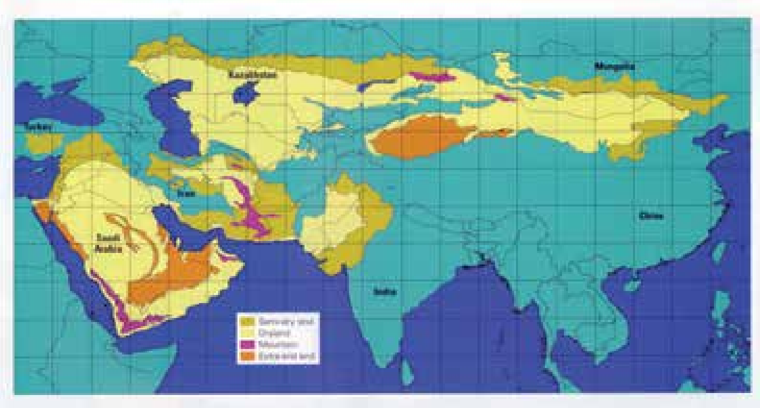


Fig. 2. Regional map of semiarid lands and drylands of Asia (Source: Nikolai Kharin and Ryutaro Tateishi and Hussein Harahsheh)

The main cause of desertification is the diminishing state of vegetation and plant coverage and increase in bare land, which in its turn elevates the air temperature, and affects biodiversity and ecological sustainability negatively. Presently 10-20 % of world dry lands is affected by desertification (Millenium Ecosystem Assessment, 2005). Desertification assessment must take into consideration the local conditions of the study area. These conditions should be investigated through field observations, with the help of remote sensing tools. The type and degree of desertification can be interpreted from the results of such investigations. Vegetation cover degradation is considered to be the main form of desertification. The soils of deserted lands are particularly sensitive to changes in the physical environment and in vegetative cover. Crop cultivation is one of the important factors contributing to soil erosion. The total land area of Mongolia is 156.5 million hectares and cultivated land occupies 1.35 million hectares of the total land area. Our calculations show that over the past 30 years, an average of 35-50 tons of soils have been lost from each hectare of cultivated land due to erosion (Tugjsuren N., Takamura T., 2003). Destruction of vegetation in sandy desert contributes to the development of wind. As known, the velocity of wind and the wind regime determines the intensity of wind erosion. For wind velocity v>6 m/s, sand particles can be blown aloft, and clay particles are moved by v>10 m/s. The significantly dry climate, low soil fertility and sparse vegetation cover of arid and semi-arid regions, make desertification a key issue of environmental concern. As a result of Mongolian desertification researches have concluded that 77.2 % of total territory was affected by desertification at low, medium and strong levels (Tugjsuren N., Enkhjargal G., 2010).

3. Climate change trends in arid and semi-arid region (on the example of Mongolia)

Arid and semi-arid areas comprise about 30% of earth surface. Changes in climate and climate variability will likely have a significant impact on these regions. Worldwide climate change and global warming have affected the humidity and warmth, circulation and balance of matters in the troposphere, causing significant changes in the climate, strength, frequency of occurrences, thus has become one of the challenges faced by humanity. Current features of the climatic changes differ from fluctuations that took place over few hundred thousand years in the world history by its frequency, and have significantly changed in the last few hundred years, raising issues of capacity to adapt to such changes. Researchers have warned that more than 2.0 ^{0}C change in the world's outer surface mean air temperature would bring serious damages to the world ecosystem. However, in the last 100 years (from 1906 to 2006) the air temperature has increased by 0.74 ^{0}C , thus reaching one third of the peak change, and their studies over many years have determined that such increase in temperature will accelerate in the future. The April 2007 report, produced by the Intergovernmental Professional Committee on Climate Change, concludes that 90% of climate changes are caused by negative human activities. The climate is extremely continental with low precipitation in arid and semi-arid regions in southern and western Mongolia and northern and northwestern China. Summer is hot, dry and cloudless. Average summer temperature is +20^{0}C, average winter temperature is -26^{0}C and average rainfall is between 200-220 mm in arid and semi-arid regions of Mongolia. Winter lasts from November to late April. Although winter is cold with lot of snowfalls, it also has many sunny days. Studies show that the climate of arid and semi-arid regions has been significantly changing in the past 70 years (Report on the state of the environment of Mongolia , 2008).

Trends in temperature changes. The results of continuous study on Mongolia's climate reveal that on average the air temperature on surface from 1940 to 2009 has become warmer by 2.1^{0}C throughout the whole territory (Figure 3); by 1.9-2.3^{0}C in mountainous regions; and 1.6^0-1.7^{0}C in Gobi and steppe regions. The warmer climate was observed in all seasons; however, the colder seasons had temperature increases of 3.6^{0}C and spring and fall seasons had temperature increases of 1.8^0-1.9^{0}C. In the summer season, the temperature increase was 1.1^{0}C (Report on the state of the environment of Mongolia, 2008). Rapid increases in the air temperature in warmer seasons and no significant increases in the level of precipitation are the main reasons for dryness in arid and semi-arid regions of Mongolia.

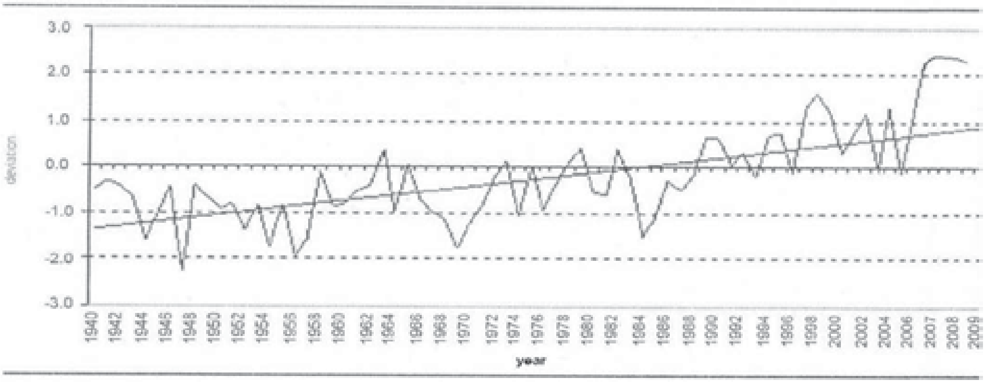


Fig. 3. Annual mean air temperature trend during 1940-2009 in Mongolia

For instance, Mongolia's mean air temperature is expected to increase on average by 1.4-1.5^{0}C in the years 2010-2039, and the total annual precipitation is estimated to be reduced by 4.0% in the years 2010-2039 (Report on the state of the environment of Mongolia, 2008). One of the important effects is an indirect effect through change in the earth's surface temperature and general circulation. The large scale general circulation is changed when the surface of the region is cooled by aerosols through direct and indirect surface forcing.

Trends in precipitation changes. The changes and trends in the precipitation throughout Mongolian territory were determined by seasons, and by period from 1940 to 2009. The annual precipitation of Mongolia is determined by warmer seasons level of precipitation, which makes up about 70% of the total precipitation. For instance, 92% of the annual precipitation falls in warmer seasons and less than 3% falls in winter season. Besides precipitation, changes in the features of summer time rain has also occurred. The percentage of mild rain has reduced and from 1980s, the percentage of thunderstorms has increased by 20% in arid and semi-arid regions. Changes in the climate has caused changes in the total transpiration, balance in the soil humidity and land ecosystem, thus leading to increase in transpiration speed of 2-3 mms/per annum in arid regions. In other words, in 50 years the total transpiration will be increased by 100 mms and the transpiration in arid regions will be most accelerated. In the past 70 years, annual total precipitation has dropped by 7% or 16 mms in arid and semi-arid regions of Mongolia. Precipitation has dropped by 8.7-12.5% in the central and Gobi regions, and rose by 3.5-9.3% in the eastern and western regions; while precipitation has increased by 5.2-10.7% in fall and winter, and dropped by 9.1-3.0% in spring and summer (Report on the state of the environment of Mongolia, 2008). The drop in annual and summer season precipitation was observed mainly in the central region, eastern side of the western region, in the middle of the Gobi region, and center of the eastern region (Figure 4).

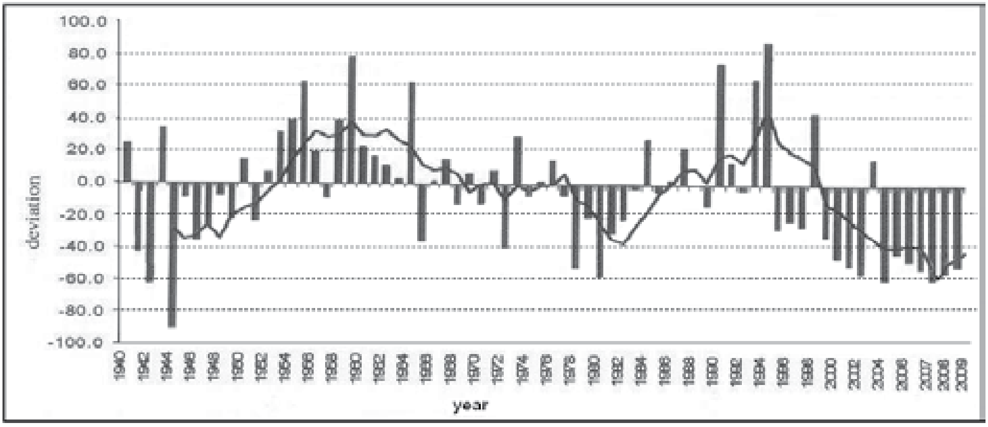


Fig. 4. Annual total precipitation in Mongolian territory

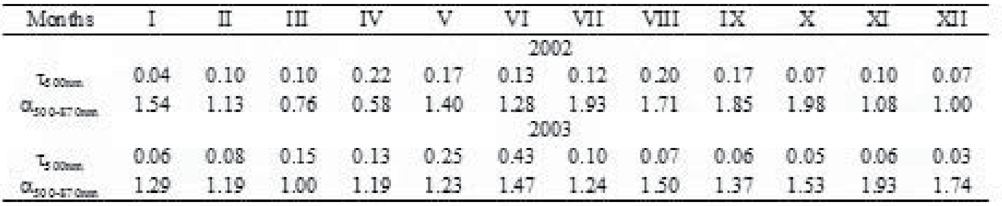
This trend of precipitation in arid and semi-arid regions can be explained by competing effects of natural and anthropogenic aerosols. By some researcher (Jianping Huang., 2008), a semi-direct effect may be the dominating factor of dust aerosol-cloud interaction over arid and semi-arid areas in East Asia, and contribute to the reduction of precipitation via a significantly different mechanism as compared to that in Africa. Certainly, further research is needed to verify it.

4. Aerosol optical properties in arid and semi-arid regions

To accurately study aerosol distribution and composition, continuous observations are required through satellites, networks of ground-based instruments and dedicated field experiments. The AERONET is global ground-based network of Sun/sky automated radiometers supported by NASA's Earth Observing System (EOS) and other international research institutions. AERONET Sun-photometer has been used to measure solar radiation and aerosol properties in the arid Gobi desert region of Mongolia, Dalanzadgad (43.57722°N, 104.41917°E and 1470m above the sea level) since February 1997. We have analyzed Aerosol Optical Thickness (AOT), and derived Angstrom exponent acquired by an AERONET Sun-photometer at Dalanzadgad (Tugjsuren N., Batbayar J., 2008). Monthly means computed from quality-assured daily means, seasonal trends were presented and discussed. Spring and early summer has the maximum seasonal average AOT and minimum seasonal average appears in winter of 2002-2003. Average monthly Angstrom exponents indicates that aerosol mixtures of both coarse and fine mode particles, and especially dust aerosols were dominant in spring in Dalanzadgad. One of the main problems of the regional climate understanding is atmospheric aerosol variability. The atmospheric aerosols have a complicated non-uniform structure, characterization and optical properties. Thus ground based continuous monitoring of their physical and optical properties are necessary. The AERONET provides quality-assured data for aerosol optical properties measured by the Sun/sky multiwavelength radiometer over the World. AERONET facility processes and archives these data according to a standardized procedure for the retrieval of aerosol properties. This chapter addresses the aerosol optical properties over arid and semi-arid regions of Mongolia using data obtained from representative sites of the Global AERONET Sun-photometer and SKYNET Sky radiometer measurements (Tugjsuren N., Batbayar J., 2008, 2010).

SKYNET is an observation network to understand aerosol-cloud-radiation interaction in the atmosphere. SKYNET has maintained Sky radiometer observation site since 1997 at Mandalgobi (45.711°N, 106.265°E and 1393 m above the sea level) of semi-arid region of Mongolia, in collaboration with the Chiba University. This site has been equipped mainly with a sky radiometer and radiation instruments for continuous measurements of atmospheric parameters such as aerosol, cloud and radiation. The SKYNET project aims at a better understanding of long-term variability in the radiation budget and atmospheric parameters over eastern Asia and its attributes based on the analysis of ground-network data. As for this objective, both regional and local analyses are needed to investigate the aerosol effects on climate change. SKYNET data at Mandalgobi site provide us with valuable information of the Earth's and atmospheric parameters. The data are also important for extracting precise knowledge on the Earth's atmosphere, as well as on physical processes of aerosol-cloud-radiation interactions. Accurate information of aerosol optical properties determined by analyses using data collected by the sky radiometer of SKYNET network has been involved research activities in the semi-arid region of Mongolia. These efforts have allowed an opportunity to obtain comprehensive information of aerosol optical properties that will be helpful to recognize the aerosol effects on regional climate change and future climate scenarios. The data used in the present study are from the Sky radiometer observations at Mandalgobi for spring, 2007. The data observed at Mandalgobi site are compiled and archived in the SKYNET server in Chiba University. The data provided from SKYNET server of Chiba University have been treated with data quality control procedure. We used Level 2.0 data including retrieved parameters such as Aerosol optical thickness (τ), Angstrom Exponent (α) and Single scattering albedo (ω) at wavelengths of 500nm from SKYNET archives at Chiba University (http://atmos.cr.chiba-u.jp).The results of the analysis for monthly and seasonal mean AOT and Angstrom exponent and size distribution over Mongolian arid and semi-arid regions are presented in the research Tugjsuren N., Batbayar J, 2005, 2006, 2008, 2010.

Annual variations of aerosol optical properties. The AERONET retrieval for AOT (τ) is performed at four wavelengths (λ) 340, 500, 870 and 1020nm, and the Angstrom exponent ($\alpha_{500\text{-}870}$) is evaluated at 500 and 870nm for the Dalanzadgad site in Mongolia. The monthly averages of aerosol optical thickness at 500nm(τ_{500}), and Angstrom exponent ($\alpha_{500\text{-}870}$) are summarized in Table 1 (Tugjsuren N., Batbayar J, 2008).



Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
						2002						
τ_{500nm}	0.04	0.10	0.10	0.22	0.17	0.13	0.12	0.20	0.17	0.07	0.10	0.07
$\alpha_{500\text{-}870nm}$	1.54	1.13	0.76	0.58	1.40	1.28	1.93	1.71	1.85	1.98	1.08	1.00
						2003						
τ_{500nm}	0.06	0.08	0.15	0.13	0.25	0.43	0.10	0.07	0.06	0.05	0.06	0.03
$\alpha_{500\text{-}870nm}$	1.29	1.19	1.00	1.19	1.23	1.47	1.24	1.50	1.37	1.53	1.93	1.74

Table 1. The monthly averages of Aerosol optical thickness, τ_{500nm}, and Angstrom exponent, $\alpha_{500\text{-}870nm}$

Average monthly value of AOT at 500 nm greater than 0.15 was in April-May and August-September of 2002 and in March, May-June of 2003. The maximum values observed were 0.22 in April 2002 and 0.43 in June 2003. Furthermore, highest values of average monthly AOT were 0.22 and 0.20 in April and August 2002 respectively and 0.25 and 0.43 in May and June 2003 respectively. The Angstrom exponent provides a rough measure of aerosol particle size. In general, the small values of Angstrom exponent (α) indicate the large particles, and the large values represent small particles. The mean monthly Angstrom exponents values observed were mostly in the range 1.0-1.93 during 2002-2003. However, low values in the range 0.58-0.76 were in March and April of 2002 which indicates that dust aerosol were dominant in Dalanzadgad in spring (March-April). The mean monthly AOT at four wavelengths (λ) 340, 500, 870 and 1020nm for 2002-2003 are illustrated in Figure 5. According to spectral dependence for annual variation of AOT (τ) in the ultraviolet and visible wavelengths (λ_{340}, λ_{500}) have maximum values in spring (April-May), late summer and early autumn (August-September) and minimum values in the middle of winter (January) of 2002 and maximum values in late spring, early summer and minimum values in winter of 2003. At the near infrared wavelengths (λ_{870} and λ_{1020}) 870, 1020nm, AOT maximum values was in middle spring (April) and minimum in middle winter (January) of 2002. AOT annual variation trend of near infrared wavelengths (λ_{870} and λ_{1020}) showed similar trend with AOT of ultraviolet and visible wavelengths (λ_{340}, λ_{500}) during 2003. Indeed, AOT maximum value at ultraviolet and visible wavelength (λ_{340} and λ_{500}) appears 0.43 and 0.61 respectively, in early summer (June) and decreases to a minimum in the winter (December) then increases again to spring and early summer in the all visible and near infrared wavelengths.

The Angstrom exponent (evaluated at 500 and 870nm) variation during 2002-2003 is presented in Fig. 6. The mean monthly minimum value of Angstrom exponent ($\alpha_{500\text{-}870}$) within the range 0.58-0.76 appears in spring (March and April) of 2002, it indicates background conditions dominated by coarse mode (dust aerosols) aerosols. Moreover, mostly fine aerosol particles except spring season in 2002-2003.

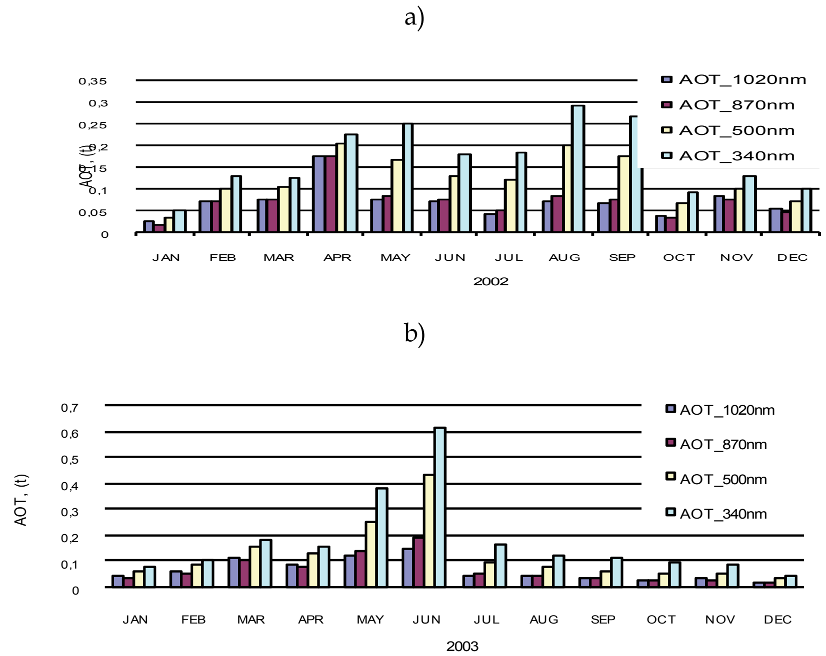


Fig. 5. Monthly mean aerosol optical thickness (AOT) at 440nm, 500nm, 870nm, 1020nm for the 2002 (a) and 2003 (b) at Dalanzadgad AERONET site.

AOT and Angstrom exponent dependence. The scatter plots of Angstrom exponent $\alpha_{500-870}$ versus aerosol optical thickness, τ_{500} for each season are shown in Figure 7. As shown on these scatter plots, there seems similar corelation between Angstrom exponents, $\alpha_{500-870}$ and AOT, τ_{500} for range 0.0-0.3 of AOT for four seasons. Particularly, the Angstrom exponent ranges 0.1- 3.6 for $\tau_{500}< 0.3$. Mostly broad spread observed of Angstrom exponent for 0.0-3.2 to 0.6 of AOT in spring and summer season. Moreover, narrow spread of Angstrom exponent for 1.0-2.0 appears in range 0.5-1.5 of AOT in summer and autumn.

Aerosol size distributions. Seasonal averages of aerosol volume size distribution parameters at Dalanzadgad AERONET Sun-photometer site are summarized in Table 2. The second and forth columns represents effective radius, R_{eff}, third, fifth columns are columnar volume, C_v for fine and course mode particles respectively, and sixth is total columnar volume of particles, C_v. As shown in this table aerosol effective radius, R_{eff} (in μm) and columnar volume of particles per unit section of atmospheric column, C_v ($\mu m^3/\mu m^2$) by two aerosol fine and course modes.

From Table 2, we have seen that aerosol volume size distribution in seasonal pattern at Dalanzadgad has effective radius (R_{eff}) in the range 0.141-0.154 for fine mode and 1.506-2.268 for course mode during 2002-2003. The columnar volume of particles (C_v) ranges from 0.005 to 0.030 and 0.014-0.111 for fine and course mode respectively. Hence, in this table, larger effective radius (1.918-2.268) of course mode occurred in summer and autumn seasons, while large columnar volume (0.111) observed in spring season of this period. The large columnar volume in spring associated with strong wind occurrence season and dry period over this arid region.

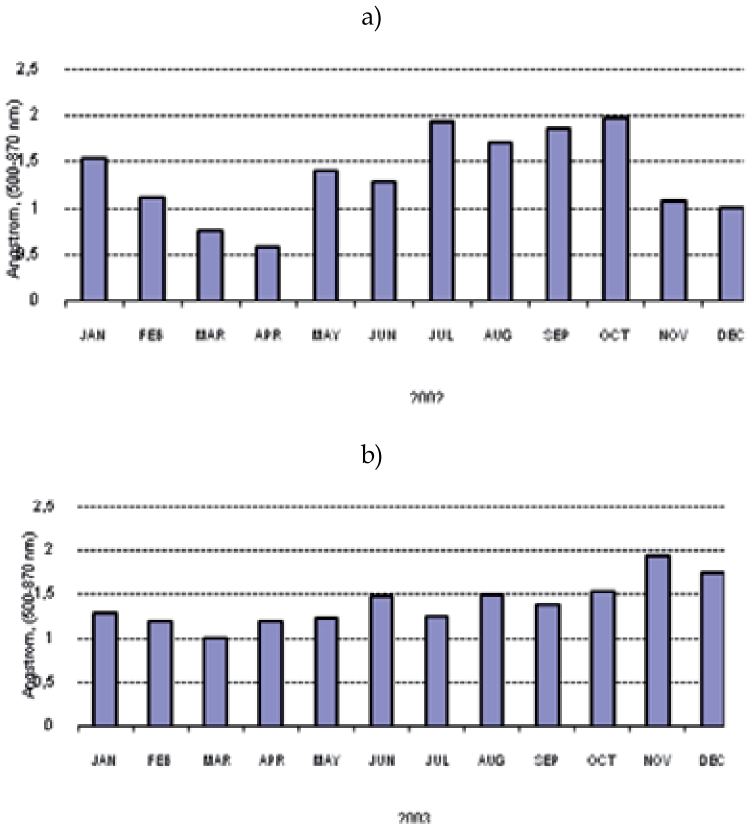
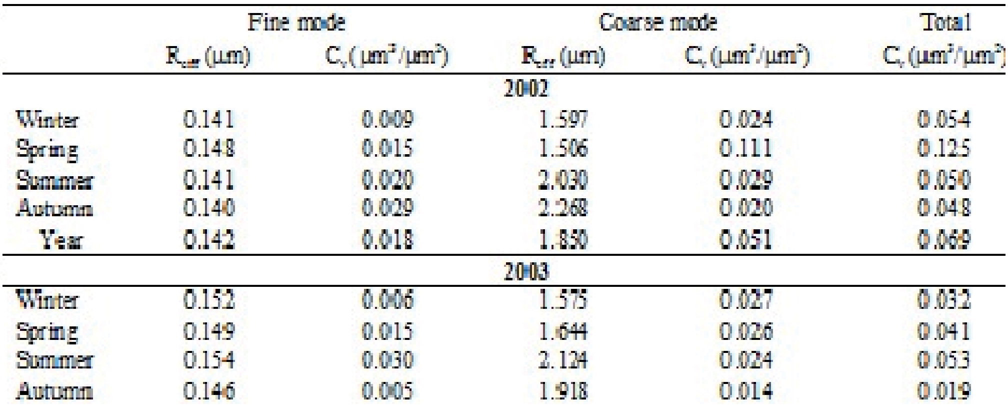


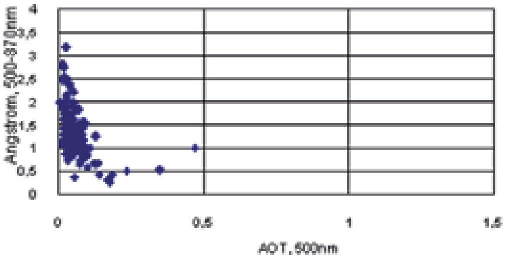
Fig. 6. Monthly mean Angstrom exponent at 500-870 nm for the 2002 (a) and 2003 (b) at Dalanzadgad AERONET site.



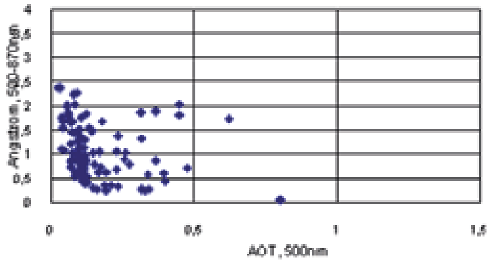
	Fine mode		Coarse mode		Total
	R_{eff} (µm)	C_v ($\mu m^3/\mu m^2$)	R_{eff} (µm)	C_v ($\mu m^3/\mu m^2$)	C_v ($\mu m^3/\mu m^2$)
			2002		
Winter	0.141	0.009	1.597	0.024	0.054
Spring	0.148	0.015	1.506	0.111	0.125
Summer	0.141	0.020	2.030	0.029	0.050
Autumn	0.140	0.029	2.268	0.020	0.048
Year	0.142	0.018	1.850	0.051	0.069
			2003		
Winter	0.152	0.006	1.575	0.027	0.032
Spring	0.149	0.015	1.644	0.026	0.041
Summer	0.154	0.030	2.124	0.024	0.053
Autumn	0.146	0.005	1.918	0.014	0.019

Table 2. Seasonal averages of aerosol volume size distribution parameters at Dalanzadgad AERONET Sun-photometer site; Reff is the effective radius (in µm) and Cv is the columnar volume of particles per unit cross section of atmospheric column

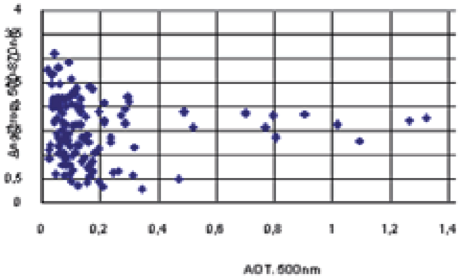
Winter



Spring



Summer



Autumn

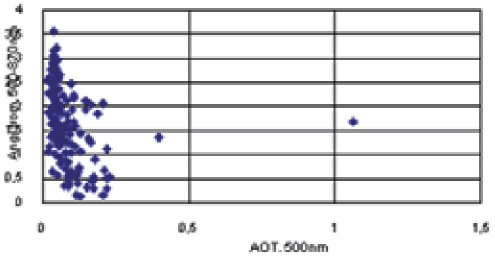
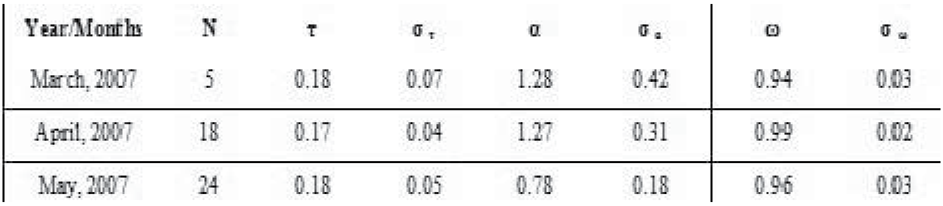


Fig. 7. Scatterplots of daily mean Angstrom exponent, $\alpha_{500\text{-}870}$ versus aerosol optical thickness, τ_{500} for each season at Dalanzadgad AERONET site.

Table 3. below summarizes statistical characteristics of the aerosol optical properties in Mandalgobi semi-arid region. It gives us the opportunity to evaluate the background characteristics of aerosol optical thickness (τ), Angstrom exponent (α) and Single scattering albedo (ω) in semi-arid region of Mongolia.The optical thickness is of mean values of τ (500nm) around 0.17-0.18 and standard deviation of 0.04 to 0.07. The Angstrom exponent ranges 0.78 to 1.28 with standard deviation 0.18- 0.42 and single scattering albedos are around 0.94-0.99 at 500nm with standard deviation 0.02-0.03 (Tugjsuren N., Batbayar J, 2008, 2010).



Year/Months	N	τ	σ_τ	α	σ_α	ω	σ_ω
March, 2007	5	0.18	0.07	1.28	0.42	0.94	0.03
April, 2007	18	0.17	0.04	1.27	0.31	0.99	0.02
May, 2007	24	0.18	0.05	0.78	0.18	0.96	0.03

Table 3. Statistical characteristics of aerosol optical properties at Mandalgobi semi-arid region, Mongolia

Figure 8. illustrates the daily average aerosol optical thickness (a), Angstrom exponent (b), single scattering albedo (c) and standard deviations of daily τ_a(500nm) (d) for the period from March to May in 2007 at Mandalgobi

SKYNET site. From Figure 8a the daily average aerosol optical thickness values at 500 nm are higher in the second half of the spring season than first half. The aerosol optical thickness values are generally, between 0.05 and 0.20, however in some cases this values has been exceed. The monthly variation of the daily average aerosol thickness showed a maximum value of 0.53 in the first decade of May. Thus, daily mean values of τ_a(500nm) over Mandalgobi show the spring seasonal peaks in May 2007. In the majority of cases the computed standard deviations of daily τ_a(500nm) range below 0.07, however, occasionally this value is exceeded (Figure 8d).

Figure 7b presents the daily average values of Angstrom exponent, α for Mandalgobi site. The Angstrom exponent values showed significant variability with values from 0.13 to 1.89 while AOT values are between 0.05 and 0.60 and large day to day variation in the study period can be observed.

Furthermore, the optical observation data collected in Mandalgobi SKYNET site provides single scattering albedo data for this study. Daily average single scattering albedo ω, at 500nm, range from 0.87 to 0.99 (Figure 8c). However, values of single scattering albedo in the range between 0.95 and 0.99 are observed mostly. These values are close to values in a clean region. The single scattering albedo obtained in this region at 500nm is similar to 0.95 in Nagasaki (Nakajima et al., 1989). But some values of single scattering albedo as well as 0.87 and 0.89 obtained sometime during this period are similar to 0.89 in Dunhuang (Kim, D.H. et al., 2005). The frequency of occurrence distributions for aerosol optical thickness τ, and Angstrom exponent α are presented in Figure 8. The frequency histograms of τ (500nm) for Mandalgobi site demonstrate the majority of values (75%) are less than 0.20 (Figure 8a) and other values (25%) are around 0.30-0.60. The most frequently occurring values of aerosol optical thickness τ (500nm) are about 0.20 for this site in spring 2007.The Angstrom exponent frequency for Mandalgobi site shows relatively broader distributions. The frequency histogram has higher Angstrom exponent's peak frequency around between 0.7 and 1.3 (Tugjsuren N., Batbayar J, 2006, 2008, 2010)

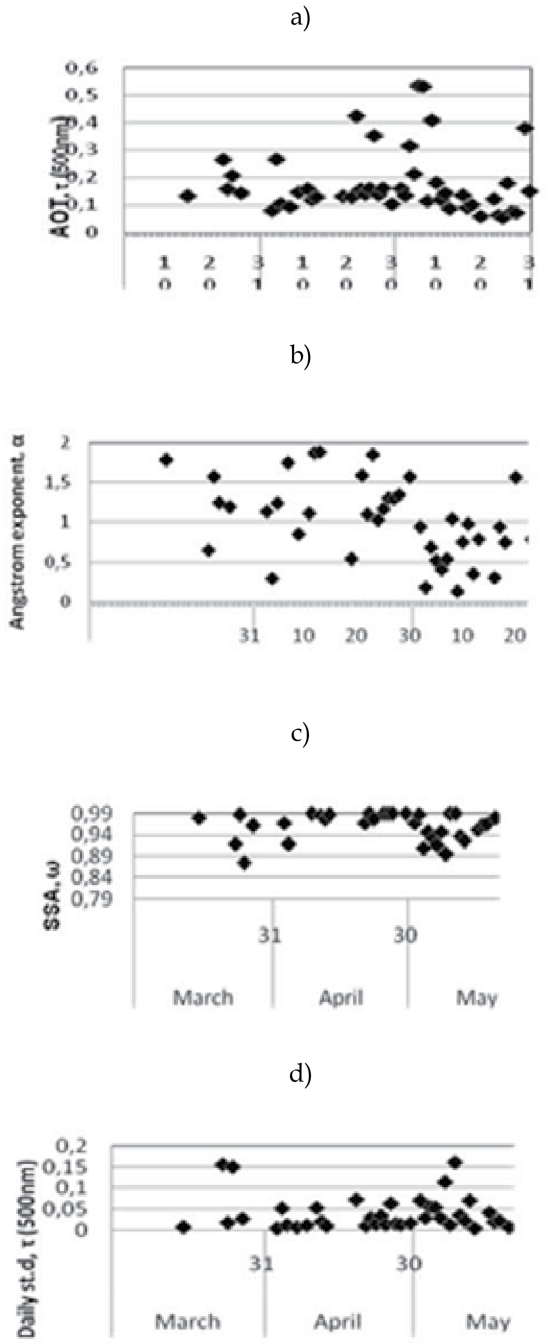
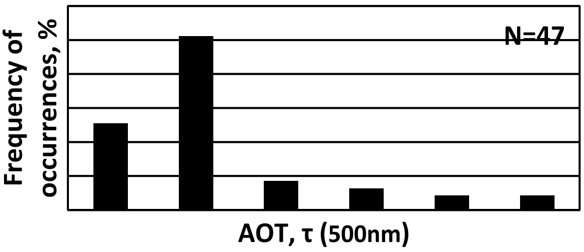


Fig. 8. Daily mean values of aerosol thickness at 500nm (a), Daily mean values of Angstrom exponent (b), Daily mean values of single scattering albedo (c), Daily standard deviations of τ (500nm) (d) for Mandalgobi site (45.711°N, 106.265°E).

a)



b)

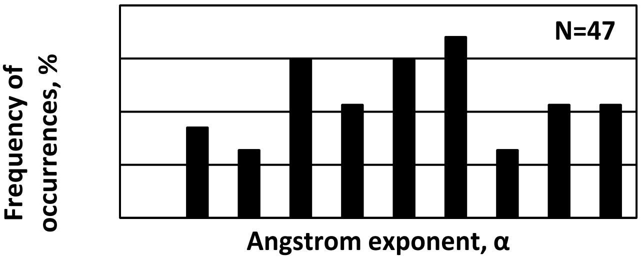


Fig. 9. Frequency of occurrences of aerosol optical thickness at500nm (a) and Angstrom exponent, α (b) for Mandalgobi site.

The scattergrams of Angstrom exponent, αversus aerosol optical thickness, τ (500nm) for spring, 2007 are shown in Figure 9.

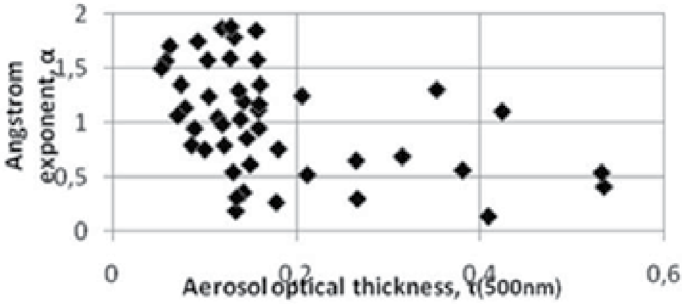


Fig. 10. Scattergram of Angstrom exponent versus and aerosol optical thickness in spring, 2007 for Mandalgobi site.

As shown on these scattergrams, semi-arid region has a wide range of Angstrom exponent values (0.13-1.89) at low aerosol optical thickness (0.05-0.20). It shows a reasonable trend of increasing values of Angstrom exponent, α as τ (500nm) decreases over study site. There is most large variation in aerosol optical thickness values when Angstrom exponent values are smaller than about 0.8 in spring season. Lastly, the analysis of the aerosol optical properties should be continued with more continuous observational data and to elaborate and improve the analyses for different seasons and more optical and physical parameters such as volume size distributions and refractive index.

5. Concluding remarks and discussions

Aerosols have many ways to change the regional climate. Observed long term trends of temperature, cloud properties, precipitation and so on important to be interpreted as the direct and indirect aerosol radiative effects. In order to characterize aerosol optical properties in arid region, we analyzed ground measured aerosol optical thickness, Angstrom exponent and size distribution data obtained from AERONET Sun-photometer site at arid region of Mongolia. As a result, spring and early summer has the highest seasonal average AOT and minimum seasonal average appears in winter and mean monthly Angstrom exponent values occurred mostly in the range 1.0-1.93. However, low values of Angstrom exponent appears within the range 0.58-0.76 in spring. Hence, average monthly Angstrom exponents indicates that aerosol mixtures of both coarse and fine mode particles, especially dust aerosols are dominant in spring (March, April).According to spectral dependence of annual variation of AOT in the ultraviolet and visible wavelengths (λ_{340}, λ_{500}) have maximum values occurred in spring, late summer and early autumn and minimum values in winter. At the near infrared wavelengths (λ_{870} and λ_{1020}) 870, 1020 nm showed similar trend with AOT of ultraviolet and visible wavelengths (λ_{340}, λ_{500}). AOT maximum value at ultraviolet and visible wavelengths (λ_{340}, λ_{500}) appears 0.43 and 0.61 respectively, in early summer and decreases to a minimum in the winter then increases again to spring and early summer in the all ultraviolet, visible and near infrared wavelengths. The aerosol volume size distribution in seasonal pattern at arid region is that the effective radius (R_{eff}), ranges 0.141-0.154 for fine mode and 1.506-2.268 for course mode. Also the result showed that larger effective radius (1.918-2.268) with course mode occurred in summer and autumn seasons, while large columnar volume (0.111) was observed in spring season. The large columnar volume in spring is associated with strong wind occurrence season and dry period over this arid region. Aerosol optical properties (aerosol optical thickness, Angstrom exponent, and single scattering albedo) over semi-arid region were analyzed for spring season, using measurements of the Skyradiometer Network (SKYNET). The aerosol optical thickness values are generally, between 0.05 and 0.20, however some cases has reached up to 0.73 in spring. Mandalgobi site has large Angstrom exponent ranging between 0.13 and 1.89 due to fine particles. And there also exist dust particles with Angstrom exponent values around 0.13-1.00. The single scattering albedo values mostly range from 0.95 to 0.99. But dust concentration in the atmosphere is mostly very high during spring season in arid and semi-arid regions.

The Asian dust particles produce significant perturbation on the earth surface. We found that during normal daytime the direct solar radiation was much larger than diffused sky radiation, except during sunrise and sunset, and at noontime the direct solar radiation flux was 3.5-4.0 time larger than diffused sky radiation in arid and semi-arid regions. But, for dust day of spring, the diffuse sky radiation always appeared larger than the direct solar radiation. Because there was no cloud during that time, this solar radiation perturbation certainly was due radiation by the large amounts of dust particles suspended in the troposphere. Smaller particles fall more slowly in the atmosphere and decrease the amount of rainfall. In this way, changing aerosols in the atmosphere can change the frequency of cloud occurrence, cloud thickness, and rainfall amounts. If there are more aerosols, scientists expect more cloud drops to form. Since the total amount of condensed water in the cloud is not expected to change much, the average drop must become smaller. This has two consequences - clouds with smaller drops reflect more sunlight and such clouds last longer, because it takes more time for small drops to coalesce into drops that are large enough to fall to the ground. Both effects increase the amount of sunlight that is reflected to space without reaching the surface. It is thought that aerosol cooling may partially offset expected global warming that is attributed to increases in the amount of carbon dioxide from human activities. Cloud radiative properties are strongly affected by the relative contributions, which are dependent on wavelength, of in-cloud aerosols, water vapor, cloud droplets as well as ice particles. The probable adverse impact on humanity due to aerosol cooling effect from increased dust particles in the atmosphere will be recognized when greenhouse effect decreases as a result of the concerted effort by countries around the world. There is probability that in the near 5-8 years, decreasing greenhouse effect will be felt as a result of the measures undertaken by the international communities. Aerosols have many pathways to change the regional climate. For one of the main cause of warming in arid and semi-arid regions, may be, related to the dust aerosol warming effect through the absorbing of solar radiation. Certainly, further research is needed to verify it. For further detailed studies of the radiative effects by real aerosols, the importance of closure experiments is highly suggested. Furthermore, for prediction of feature climate changes, it is needed to evaluate the direct and indirect radiative forcing by anthropogenic aerosols.

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Part 2

Reducing Greenhouse Gases Emissions

9

Reduced Emissions from Deforestation and Forest Degradation (REDD): Why a Robust and Transparent Monitoring, Reporting and Verification (MRV) System is Mandatory

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1. Introduction

The reduction of emissions from deforestation and forest degradation (REDD) was approved at the 16th session of the Conference of the Parties of the UNFCCC in Cancún in 2010 as an eligible action to prevent climate change and global warming in post-2012 commitment periods.

REDD assigns a financial value to the carbon stored in forests. In order to generate benefits from REDD countries need to implement sound systems for monitoring, reporting and verification (MRV) of carbon stocks. The mere reporting of point estimates such as carbon stocks or carbon stock changes is not sufficient, unless the associated uncertainties are specified. Sampling and non-sampling errors influence the reliability of estimated activity data and emission factors, and thus affect the potential to generate benefits from implementing a REDD-regime. Uncertainties are addressed by the principle of conservativeness that requests the reporting of the reliable minimum estimate (RME). The RME constructs a reliability interval around a carbon stock estimate and utilizes the lower bound for reporting and the calculation of benefits.

In this chapter, a framework for calculating accountable emission reductions including assessment errors is developed. Theoretical considerations as well as a simulation study for four selected countries with low to high deforestation and forest degradation rates show that even small assessment errors (5% and less) may offset successful efforts in the reduction of emissions from deforestation and forest degradation. The generation of benefits from REDD renders possible only in situations where a robust and transparent MRV-system is applied that provides a sound approach for the calculation of RMEs.

2. Background

According to the United Nations Food and Agricultural Organisation (FAO) forests cover 31% of the global land area. FAO estimates that the world's forests store 289 gigatonnes (Gt) of carbon in their biomass alone (FAO, 2010b). Whilst sustainable forest management, planting or rehabilitation of forests can positively affect forest carbon stocks, deforestation, forest degradation and poor forest management have a negative effect on them. Due to the conversion to other uses or loss through natural causes approximately 13 million hectares of forest disappeared annually in the last decade.

In this context deforestation is generally understood as the direct human-induced conversion of forest land to non-forest land, while forest degradation is according to the Intergovernmental Panel on Climate Change (IPCC) "the direct human-induced long-term loss" of forest carbon stocks in areas which remain forest land (IPCC, 2003).

In 2005 Papua New Guinea together with 8 other developing countries proposed the new agenda item "reducing emissions from deforestation in developing countries" at a national level at the 11th Session of the Conference of Parties (COP 11) to the United Framework Convention on Climate Change (UNFCCC). The proposal aimed at the acknowledgement of reducing emissions from deforestation and forest degradation in developing countries (REDD) as a mitigation option for those countries. The idea of REDD was later on extended beyond the mere conservation of forests in order to include additional aspects of biodiversity, sustainable management of forests and enhancement of forest carbon stocks, called REDD+[1]. At the 16th session of the Conference of the Parties of the UNFCCC in Cancún in 2010 the REDD mechanism was approved as an eligible action to prevent climate changes and global warming in post-2012 commitment periods (UNFCCC, 2011).

A country participating in the REDD mechanism of the UNFCCC has to demonstrate substantial capacities for monitoring and accounting emissions from forest carbon stocks. Thus a reliable framework for MRV is vitally required to ensure the integrity and credibility of possible REDD efforts in general. Approaches for MRV as well as potential financing mechanisms for the set-up of appropriate incentives have been widely discussed (Eliasch, 2008; GOFC-GOLD, 2010). IPCC requests the use of the reliable minimum estimate (RME) to address uncertainties associated with the estimation of forest area and carbon stock changes. Even though these uncertainties have a fundamental impact on accountable carbon credits and the cost-benefit ratio, they play only a minor role in the discussions both on political, scientific and operational level.

2.1 Assessment of emissions from deforestation and forest degradation

There are five major carbon pools in forests (IPCC, 2003): (1) above-ground biomass, (2) below-ground biomass, (3) dead wood, (4) litter, and (5) soil organic matter. The reduction of emissions from deforestation and forest degradation renders the maintenance of carbon in the living biomass essential. For this reason the most pragmatic monitoring approach is to concentrate efforts on the assessment of the carbon pool "above-ground biomass".

To monitor and report deforestation and forest degradation the assessment of two components is required (IPCC, 2003):

- changes in forest area over time (activity data), and
- changes in the average carbon stock per unit area over time (emission factors).

Assessments at successive occasions or the availability of models that extrapolate data from one point in time to another, allow the estimation of changes. To assess the total loss of forest carbon stock in a given period and area two components have to be considered:

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[1] The terms REDD and REDD+ are used synonymously in this text.

(1) the carbon stock loss on areas that changed from forest land to other land uses in the respective period, and (2) the reduction of average carbon stock in areas that remain forest land. Aiming at the enhancement of the reliability of estimates, the forest area can be subdivided in several categories showing distinct levels of carbon stock changes.

Changes in forest area can be estimated by in-situ surveys or remote sensing techniques. Remote sensing techniques are more cost efficient and result in spatially explicit data. Furthermore, remote sensing data allow for the separation of the total forest area into different homogeneous sub-groups or strata, such as forest types (e.g. broadleaf, tropical moist or tropical dry). The classification of forest areas can be complemented by risk factors that utilize probabilistic approaches for describing the likelihood of changes. Proxies for risk factors can be accessibility, population density or previous intensities of human impacts. In extensive surveys of large areas the use of remote sensing techniques are capable of detecting deforestation patterns. In contrast to deforestation forest degradation does not necessarily lead to an obvious reduction of canopy cover, even under substantial removals of biomass. The detection of forest degradation by remote sensing techniques is far more difficult than the detection of deforestation and provides reliable results only for advanced stages of forest degradation.

Changes in carbon stock can be quantified by various methods. Among others IPCC provides a set of default values for carbon stocks per unit area (IPCC, 2003). However, these may not reflect the true country specific values. Using these default values can result in substantial uncertainties. Country specific data on degradation of distinct forest types or risk classes reduce uncertainties. The most reliable estimates of carbon stock changes are provided by sample based field assessments on successive occasions. Individual trees are measured, and biomass and carbon stock are calculated on plot level. Upscaling procedures are applied to expand plot level data to area related estimates (Köhl et al., 2006; Plugge et al., 2010), resulting in sound and sensitive estimates of changes in forest biomass and degradation activities.

The IPCC Good Practice Guidance (IPCC, 2003) and Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) include recommendations on methods and default values for assessing carbon stocks and emissions. Two approaches for the calculation of changes in average carbon stock per unit area are proposed (IPCC, 2003, 2006):

1. the *stock difference method* makes reference to traditional forest resource assessments and calculates changes in average carbon stock per unit area as the difference between carbon stock at time 2 and time 1, and
2. the *gain-loss method* builds on the understanding of carbon uptake by forests (tree growth) and carbon release by anthropogenic activities such as timber removals, fuelwood gathering, sub-canopy fires or grazing.

The IPCC-guidelines provide three tiers of detail for reporting in order to consider the substantial differences between countries regarding the capacities and implemented MRV-systems for carbon stock changes. Moving to higher tiers increases the complexity and cost of the utilized MRV-systems but results in a higher reliability of estimates.

2.2 Uncertainties

The Subsidiary Body for Scientific and Technological Advice (SBSTA) is concerned with methodological issues with reference to the implementation of REDD as a mitigation option in the context of UNFCCC and stated in its 28th session that "means to deal with uncertainties in estimates aiming to ensure that reductions in emissions or increases in removals are not overestimated" need to be further considered (UNFCCC, 2008), to ensure the credibility of estimated emissions and removals from deforestation and forest degradation. In general any assessment and estimation methodology is intrinsically associated with uncertainties. In REDD those are mainly linked to the assessment of deforestation and forest degradation areas (activity data, AD) and the carbon stock changes in those areas (emission factors, EF).

Two major error types exist regarding the estimation of AD and EF: sampling errors and non-sampling errors (Lessler & Kalsbeek, 1992). The former arise from inferring from a subset (i.e. the sample) of the population to the whole population. The size of the sample and the survey design can be used to control the size of sampling errors. The latter encompass all other sources of errors involved in a survey. This can be measurement errors, calculation errors, classification errors, incorrect application of definitions, errors arising from the application of functions and models, or frame errors (i.e. the sample population is different from the target population). Precision, accuracy, and bias are means to quantify different types of errors (Köhl et al., 2006).

To quantify the uncertainty of estimates the IPCC suggests the 95%-confidence interval (IPCC, 2003, 2006). In statistical terminology the confidence interval is related to sampling errors only. A useful measure is the Mean Square Error (MSE), that combines sampling errors with the square of the bias. For unbiased estimators MSE and precision are asymptotically identical. In order to quantify all error sources associated with an estimate the total survey error (Kish, 1965) or error budgets (Gertner & Köhl, 1992) can be applied.

2.3 Monitoring changes over time

Quantifying AD requires estimates of forest area changes over time. The use of remote sensing techniques implicates that the uncertainty related to the estimation of changes between two points in time is strongly affected by classification accuracies at both occasions and the magnitude of the respective changes. Fuller et al. (2003) discuss the measurement of land-cover change over time and present a statistical approach to quantify the reliability of change estimates. They show that for 10-class maps the accuracy at both times needs to be 99% to detect a smaller than 20% change with a 90% reliability. Fuller et al. (2003) conclude that the "measurement of small to medium scale changes over large areas requires levels of precision in mapping which are near impossible to achieve with satellite image classification alone".

Another critical issue is the ability to detect forest degradation by remote sensing data. Especially in heterogenic vertical stand structures and contiguous canopy covers, e.g. in natural forests in the tropics and subtropics, forest degradation can only be detected, when the formerly closed canopy cover is dissolved (Fig. 1).

Quantifying EFs is realized by in-situ assessments in forest stands, following the rules of probabilistic sampling theory. Above-ground volume or biomass figures are used to estimate the carbon stock of trees. However, these figures cannot be directly assessed on standing trees and have to be estimated via volume or biomass functions, which utilize tree measurements such as diameters, tree heights or crown parameters as independent variables. Biomass expansion factors (BEF) expand volume estimates to biomass estimates, while biomass estimates are transferred into carbon stock estimates by applying biomass-carbon conversion factors. The conversion factors depend on the wood density of the respective tree species and tree components.

Fig. 1. Different status of forest degradation and potential of detection by passive remote sensing techniques (Baldauf et al., 2009)

Including measurement errors and function errors, the EF-estimates are subject to multiple error sources. Highly problematic are frame errors, as assessments of a limited set of field plots (i.e. the sample population) may not be representative for the entire domain of tree species, forest types, ecosystem regions and disturbance levels within a country (i.e. the target population) (Houghton et al., 2001; Nogueira et al., 2008). Figures for above-ground biomass, which show a large range of variability, are presented by IPCC (IPCC, 2003). For example, the possible range of values in wet tropical forests covers 34% to 248% of the average, showing that currently a high level of uncertainty is associated with the quantification of above-ground biomass stock.

2.4 The principle of conservativeness

In order to “address the potential incompleteness and high uncertainties of REDD estimates” the principle of conservativeness was proposed by Grassi et al. (2008). UNFCCC has already included this principle in several documents, e.g. for afforestation and reforestation activities under the Clean Development Mechanism (CDM) (UNFCCC, 2006a, 2006b).

The completeness principle depends on “the processes, pools and gases that need to be reported and on the forest-related definitions” (Grassi et al., 2008). In REDD the quantification of carbon stock changes needs to consider both, uncertainties and incompleteness. To address uncertainties the Reliable Minimum Estimate (RME) is suggested by the IPCC-Good Practice Guidance in the context of the assessment of changes in soil carbon. The RME serves as a surrogate for the lower bound of a confidence interval and is the minimum quantity to be expected with a given probability (Dawkins, 1957).

In the context of carbon stock change assessments the principle of the RME has to be expanded from a sole sampling error perspective to the concept of total survey errors. A conservative RME qualifying for accounting can be calculated as the difference between the lower bound of the error interval at the reference period (time 1) and the upper bound of the error interval at the assessment period (time 2). While error intervals take into account the total survey error, confidence intervals include only sampling errors. Thus error intervals are wider than confidence intervals and result in notably smaller accountable emission reduction.

For countries that are still in the readiness phase and have not implemented a sound REDD inventory concept so far, the principle of conservativeness is a wise recommendation. However, in a situation where a country is maintaining or only slightly decreasing its forest area, the principle of conservativeness might lead to counterproductive results. The RME of the estimated forest area at time 1 would be (considerably) lower as the higher RME of the estimated (unchanged) forest area at time 2, thus a forest area loss would need to be reported. Or, in other words, if the area of afforestation activities has the same size as the difference between the RMEs at time 1 and time 2, a country without any deforestation activities would be able to report only an unchanged forest area under the principle of conservativeness. Introducing a REDD-regime under these conditions would not be beneficial for such a country.

3. Data and methods

3.1 Global Forest Resources Assessment

For more than five decades the state of the world's forests has been monitored by FAO, with the intention to provide information "to policy-makers, to international negotiations, arrangements and organizations related to forests and to the general public" on a global scale (FAO, 2010b).

Earlier forest resources assessments focused mainly on the provision of information on the productive forest functions (i.e. attributes such as basal area, timber volume, wood assortments, timber value or increment). Nowadays FAOs forest resources assessments have a much wider scope and cover the rising demand for more detailed information. The Global Forest Resources Assessment 2010 (FAO, 2010a) is the most comprehensive assessment to date, incorporating the seven thematic elements of sustainable forest management:

- extent of forest resources;
- forest biological diversity;
- forest health and vitality;
- productive functions of forest resources;
- protective functions of forest resources;
- socio-economic functions of forests;
- legal, policy and institutional framework. (FAO, 2010b)

The Global Forest Resources Assessment 2010 (FRA 2010) provides information for four points in time, i.e. 1990, 2000, 2005 and 2010, and the respective trends (FAO, 2010b). In the scope of this study we decided to analyze FRA data from the years 1990, 2000 and 2010. Data from the year 2005 were omitted in order to simulate a reference period from 1990 to 2000 and an assessment period from 2000 to 2010, both of equal length (10 years).

Information needs for REDD on forest area changes (AD) and carbon stock changes in those areas (EF) can be satisfied by focusing on the FRA's first thematic element. Table 1 shows country specific data on forest resources for four countries that hold small to large forest areas and show low to high deforestation rates.

Activity data for these countries can be calculated as the difference in forest area between two successive points in time. The ratio of total forest carbon stock and total forest area gives information on the emission factors. Table 2 presents the annual mean values of activity data for the anticipated reference (1990 to 2000) and assessment period (2000 to 2010) and the per hectare carbon stock for each point in time.

		Forest area (1000 ha)			Carbon stock (Mt)		
Country/Year	Category *	1990	2000	2010	1990	2000	2010
Costa Rica	LFLD	2,564	2,376	2,605	233	217	238
Indonesia	HFHD	11,8545	99,409	94,432	16,335	15,182	13,017
Malaysia	HFMD	22,376	21,591	20,456	2,822	3,558	3,212
Madagascar	LFLD	13,692	13,122	12,553	1,778	1,691	1,626

Table 1. Country specific data on forest resources (from FRA 2010) (FAO, 2010a); HF = high forest area, LF = low forest area, HD = high deforestation rate, MD = medium deforestation rate, LD = low deforestation rate, * according to Griscom et al. (2009)

		Forest area change (1000 ha/y)		Carbon stock (t/ha)		
Country/Year	Category*	1990 - 2000	2000 - 2010	1990	2000	2010
Costa Rica	LFLD	-19	23	90.87	91.33	91.36
Indonesia	HFHD	-1,914	-498	137.80	152.72	137.85
Malaysia	HFMD	-79	-114	126.12	164.79	157.02
Madagascar	LFLD	-57	-57	129.86	128.87	129.53

Table 2. Country specific data on annual forest area change and per hectare carbon stock; HF = high forest area, LF = low forest area, HD = high deforestation, rate MD = medium deforestation rate, LD = low deforestation rate, * according to Griscom et al. (2009)

The data given in Table 1 and Table 2 are used as the input data for the simulation study described below. The layout of the simulation study follows the principles described in Köhl et al. (2009).

3.2 Accountable emission reductions

For the generation of benefits from a REDD regime possible reductions of emission from deforestation and forest degradation must be identified. Therefore a reference must be defined, against which the actual emissions from deforestation and forest degradation are set off. In the nomenclature of REDD this reference emission level is called baseline. Different types of baselines are still subject to political and scientific discussions (Griscom et al., 2009) as the choice for a specific baseline may be of advantage or disadvantage to a single country. There are simple baseline approaches like historical baselines, based on annual deforestation areas in past periods, to more complex approaches that project a future deforestation scenario by integrating numerous variables, including key socioeconomic, technological, and political factors that drive deforestation (Eliasch, 2008).

The data on carbon stock in forests in the Global Forest Resources Assessment (FAO, 2010a) appears to be distorted by inconsistent estimation approaches for different points in time, which add an unknown amount of uncertainty to the values presented. For example, the carbon stocks presented for Malaysia increase by 30 percent between 1990 (126.12 t/ha) and 2000 (164.79 t/ha), while showing a more reasonable decrease by 5 percent between 2000 and 2010 (157.02 t/ha). The values for carbon stock development in forests shown in Table 2 do not include the underlying level of reliability which needs to be taken into account in the development of baselines. Therefore, we decided to use a business-as-usual scenario for the construction of the baseline that takes into account the forest area development only. The reference period for this scenario is defined as the period 1990 – 2000.

$$\Delta_{REF} = (A_{t1} - A_{t0}) / A_{t1} \tag{1}$$

where
Δ_{REF} = proportional change of forest area between t_0 and t_1, Δ_{REF} = {-1.1}, where negative values indicate a decrease of the forest area, and positive values an increase, e.g. by afforestation or forest growth.
t_0 = time 0 (i.e. 1990)
t_1 = time 1 (i.e. 2000)
A_{t0} = Forest area at t_0
A_{t1} = Forest area at t_1
The baseline itself is a mere proportional prolongation of the development of the carbon stocks from the reference period to the assessment period. Therefore we anticipate that the same proportional change holds for forest area and for carbon stock.

$$\Delta_{REF} = \Delta_{BL} \tag{2}$$

where
Δ_{BL} = proportional area change between t_0 and t_1 according to the baseline, Δ_{BL} = {-1.1}, where negative values indicate a decrease of the forest area and positive values an increase of the forest area.
The assessment period is defined as the period between 2000 and 2010. Although REDD-incentives have not been implemented, we assume that initiatives and measures other than REDD led to a reduction of deforestation in this period. The carbon stock at the end of the assessment period (i.e. 2010), C_{t2real}, has to be compared to the expected carbon stock according to the baseline scenario, C_{t2BL}. This results in the change of carbon stock, C_{t2REDD}.

$$C_{t2REDD} = C_{t2real} - C_{t2BL} \tag{3}$$

where
C_{t2REDD} = difference between expected carbon stock according to the baseline and the real carbon stock at time 2
C_{t2BL} = expected carbon stock at t_2 according to the baseline
C_{t2real} = real carbon stock at t_2
Emission reductions are accountable as long as C_{t2REDD} has a value > 0. Whenever C_{t2REDD} is ≤ 0 no emission reductions qualify for accounting. C_{t2REDD} can also be given as a function of C_{t1} and its proportional change indicated by the baseline, Δ_{BL}, on the one hand and C_{t2real} on the other hand.

$$\begin{aligned} C_{t2REDD} &= C_{t2real} - C_{t2BL} \\ &= C_{t2real} - C_{t1} + (C_{t1}\Delta_{BL}) \\ &= C_{t2real} - C_{t1}(1 + \Delta_{BL}) \end{aligned} \tag{4}$$

The amount of accountable emission reductions is not only subject to the realized reduction of emissions from deforestation and forest degradation at time 2, but depends on the respective total error (E_{t2}) associated with the estimation of C_{t2real} as well. Equations (3) and (4) do not incorporate E_{t2}. C_{t2RME} is taking into account the total error at the end of the assessment period (E_{t2}) and relates it to C_{t2real}.

$$C_{t2RME} = C_{t2real}(1 - E_{t2}) \tag{5}$$

where

C_{t2RME} = carbon stock at t_2 constrained by the total error

E_{t2} = error of the estimated carbon stock at t_2, C_{t2real}

To adhere to the principle of conservativeness, C_{t2real} has to be replaced by C_{t2RME} in equation (4) resulting in a new estimate for the accountable emission reductions, $\hat{C}_{t2REDD}$, that incorporates the total error at the end of the assessment period.

$$\begin{aligned} \hat{C}_{t2REDD} &= C_{t2RME} - C_{t2BL} \\ &= C_{t2real}(1 - E_{t2}) - C_{t1}(1 + \Delta_{BL}) \end{aligned} \tag{6}$$

where

$\hat{C}_{t2REDD}$ = accountable emission reductions at t_2

In equation (6) all components that affect the amount of accountable emission reductions are included. While Δ_{BL} shows the business-as-usual scenario for the carbon stock development in a situation where no incentives to reduce deforestation and forest degradation have been applied, C_{t2real} assumes that such incentives have been successfully applied. The total error affecting the accountable emission reductions (E_{t2}) is directly linked to the implemented MRV-system.

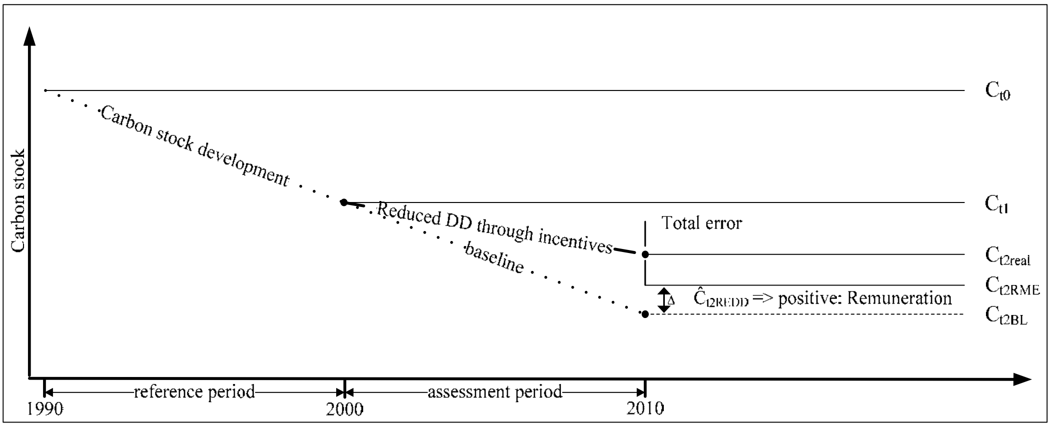

Fig. 2. Reference period (1990 to 2000) and respective carbon stock development for baseline deduction (i.e. difference of carbon stock at t_1, C_{t1}, and carbon stock at t_0, C_{t0}) and relationship of the reduction of deforestation and forest degradation (DD) during the assessment period (2000 to 2010), total error and the respective reliable minimum estimate (RME), and their contribution to the values of the expected carbon stock at time 2 according to the baseline scenario (C_{t2BL}), real carbon stock at time 2 (C_{t2real}), carbon stock at time 2 qualifying for accounting (C_{t2RME}) and difference of C_{t2BL} and C_{t2RME} ($\hat{C}_{t2REDD}$)

Fig. 2 illustrates the influence of E_{t2} on the accountable emission reductions under a REDD regime. The business-as-usual baseline scenario is derived based on the carbon stock development of the reference period. In this figure the carbon stock resulting from the application of incentives to reduce emissions from deforestation and forest degradation (C_{t2real}) without error components and its associated RME (C_{t2RME}) including the error components exceed the baseline scenario (C_{t2BL}). In this situation a country would be able to transform the accountable emission reductions ($\hat{C}_{t2REDD}$) into benefits from emission reductions.

As shown in Fig. 2 accountable emission reductions can only be generated where the real carbon stock in 2010, C_{t2real}, is larger than the carbon stock according to the baseline, C_{t2BL}. In this case $\hat{C}_{t2REDD}$ becomes positive. However, the amount of the accountable emission reductions generated depends on the error associated with the carbon stock estimates, E_{t2}. The functional relationship between C_{t2BL}, C_{t2real} and E_{t2} indicates that the smaller the difference between C_{t2BL} and C_{t2real}, the smaller E_{t2} has to be in order to generate accountable emission reductions.

4. Results

A country that intends to benefit from the adoption of a REDD-regime, needs to proof that deforestation and forest degradation in a current commitment period is smaller than it was in the periods before. Accountable carbon credits, $\hat{C}_{t2REDD}$, are obtained by subtracting the real carbon stock at t_2, C_{t2real}, from the carbon stock expected under the baseline scenario, C_{t2BL}, which is derived from past deforestation and forest degradation rates. The larger the difference the more carbon credits are generated.

The approach presented above was utilized for a simulation study that links the calculation of accountable emission reductions with assessment errors. Results are presented for four selected countries with low to high deforestation and forest degradation rates and illustrate the effect of the inclusion of uncertainties in REDD estimates.

Based on the input data taken from FRA 2010 (FAO, 2010a) Table 3 shows country specific data on the proportional development of the forest area, Δ_{BL}, and the expected carbon stocks in 2010, C_{t2real}. These are used to offset them against C_{t2BL} in order to achieve the value of the respective emission reductions, C_{t2REDD}.

Country	Δ_{BL} (%)	C_{t2BL} (Mt C)	C_{t2real} (Mt C)	C_{t2REDD} (Mt C)
Costa Rica	-7.91	199.83	236.08	38.17
Indonesia	-19.25	12,259.50	14,381.84	757.50
Malaysia	-3.64	3,428.64	3,360.58	-216.64
Madagascar	-4.34	1,617.55	1,614.35	8.45

Table 3. Country specific data on Δ_{BL} (%), C_{t2BL} (Mt C), C_{t2real} (Mt C), C_{t2REDD} (Mt C)

Among the selected countries Malaysia shows the lowest deforestation rate for the reference period (-3.64%), while Indonesia's rate is rather high (-19.25%). The combination of these proportional figures with the absolute carbon stocks lead to distinct values for the emission reductions. Whereas Madagascar and Costa Rica reached only marginal absolute values of emission reductions (i.e. 8.45 Mt C and 38.17 Mt C), the data by FRA 2010 indicate that

Indonesia's efforts to reduce deforestation are obviously performing well. The negative value of C_{t2REDD} for Malaysia suggests that inconsistent data on carbon stocks in forests have a major influence on the values of emission reductions, and potential activities to reduce deforestation do not result in accountable carbon credits.

Fig. 3 shows the carbon stock development of Costa Rica over time (i.e. 1990, 2000 and 2010) according to the data of the FRA 2010. For the year 2010 the difference of C_{t2real} and C_{t2BL}, i.e. C_{t2REDD}, is shown in red colour.

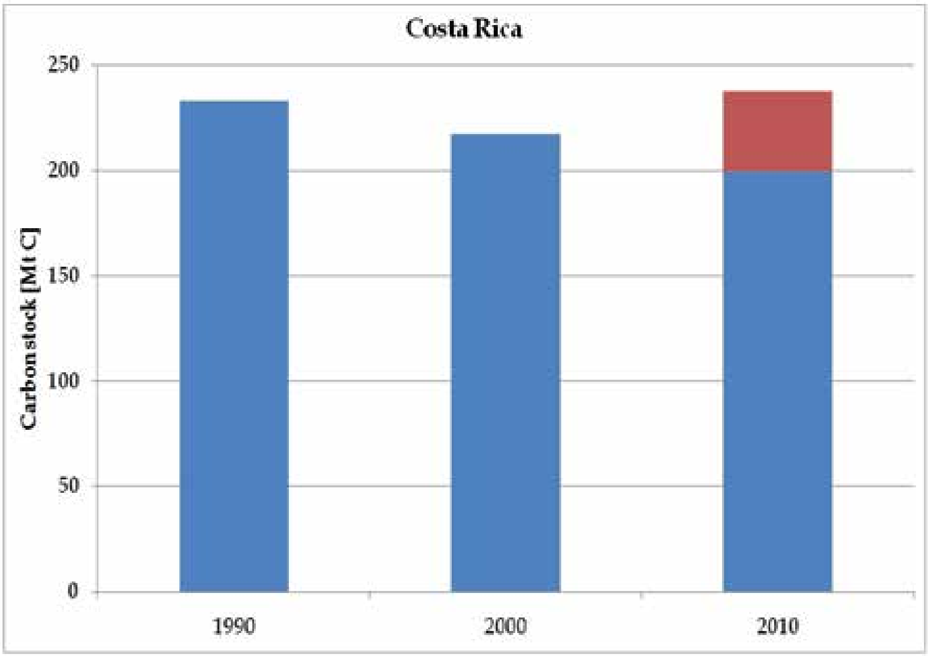

Fig. 3. Carbon stock development over time (i.e. 1990, 2000 and 2010) for Costa Rica; for the year 2010 the difference of C_{t2real} and C_{t2BL}, i.e. C_{t2REDD}, is shown in red colour

For calculating the accountable carbon credits generated by a REDD regime the RME of C_{t2real} is used in order to illustrate the effect of uncertainties. Including errors generally reduces the amount of accountable emission reductions. To show the effect of errors, the reliable minimum estimates (RME) of C_{t2real} for the four countries were calculated for 0 to 20% total error. The country specific data on C_{t2RME} are shown in Table 4.

	C_{t2RME} (Mt C)				
Country / E_{t2}	0%	2%	5%	10%	20%
Costa Rica	238.00	233.24	226.10	214.20	190.40
Indonesia	13,017.00	12,756.66	12,366.15	11,715.30	10,413.60
Malaysia	3,212.00	3,147.76	3,051.40	2,890.80	2,569.60
Madagascar	1,626.00	1,593.48	1,544.70	1,463.40	1,300.80

Table 4. Country specific data on C_{t2RME} (Mt C)

The decrease of the RME of C_{t2real} for higher errors in MRV-systems is obvious for all four countries. While an idealistic total error of 0% would lead to a C_{t2RME} of 13,017 Mt C for Indonesia, a total error of 20% would result in about 10,414 Mt C. The respective values were used as reference for calculating the resulting accountable emission reductions, $\hat{C}_{t2REDD}$ (Table 5).

	$\hat{C}_{t2REDD}$ (Mt C)				
Country / E_{t2}	0%	2%	5%	10%	20%
Costa Rica	38.17	33.41	26.27	14.37	-9.43
Indonesia	757.50	497.16	106.65	-544.20	-1,845.90
Malaysia	-216.64	-280.88	-377.24	-537.84	-859.04
Madagascar	8.45	-24.07	-72.85	-154.15	-316.75

Table 5. Country specific data on $\hat{C}_{t2REDD}$ (Mt C)

Correspondingly, increasing errors decrease the accountable emission reductions, $\hat{C}_{t2REDD}$, for all countries. Negative numbers in Table 5 display an increase of CO_2 emissions to the atmosphere, positive numbers display CO_2 emission reductions. Only the latter would lead to the generation of carbon benefits.

In Fig. 4 the accountable emission reductions are plotted for the four countries over different levels of total error (0 to 20%).

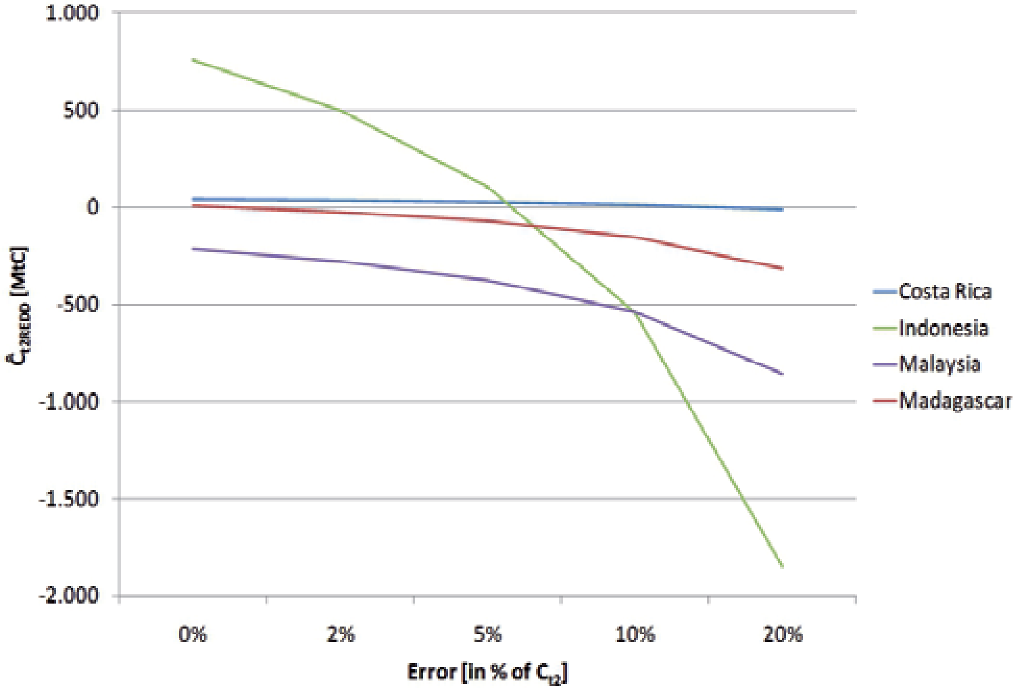

Fig. 4. Influence of total error of a MRV-system on accountable emission reductions

As large errors jeopardize the generation of accountable carbon credits by REDD, the implementation of a sound MRV-system is decisive for the generation of benefits by the adoption of a REDD regime.

On closer inspection, Fig. 3 shows that even small assessment errors (7% and less) confound the successful efforts in the reduction of emissions from deforestation and forest degradation. The generation of benefits from REDD is possible only in situations where a robust and transparent MRV-system is applied that results in low total errors associated to carbon estimates. According to studies from Fuller et al. (2003), Gertner and Köhl (1992) or Waggoner (2009) total errors larger than 5% are most likely to occur.

5. Conclusion

In the Eliasch-Review in 2008 it was stated that "Emissions reduction targets can only be monitored effectively if carbon emissions are estimated robustly and uncertainties are managed and quantified." (Eliasch, 2008)

Accordingly, Fig. 5 exemplarily shows the effect of a large total error as a result of a poor MRV-system. The inclusion of the principle of conservativeness through the RME leads to a situation where the carbon stock qualifying for accountable emission reductions is well below the assumed baseline scenario. Under these conditions no credits would be generated, because the country could not prove that it successfully reduced its deforestation and forest degradation rates.

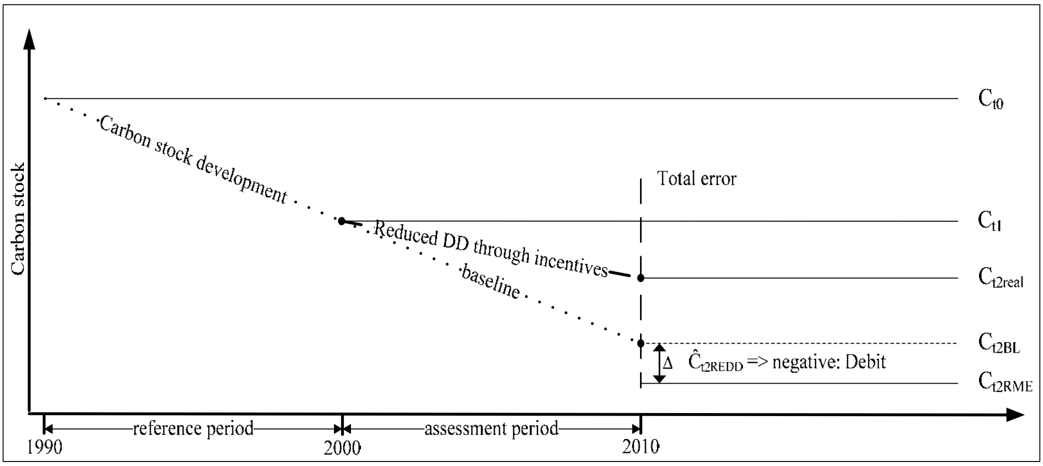

Fig. 5. Reference period (1990 to 2000) and respective carbon stock development for baseline deduction (i.e. difference of carbon stock at t_1, C_{t1}, and carbon stock at t_0, C_{t0}) and relationship of the reduction of deforestation and forest degradation (DD) during the assessment period (2000 to 2010), total error and the respective reliable minimum estimate (RME), and their contribution to the values of the expected carbon stock at t_2 according to the baseline scenario (C_{t2BL}), real carbon stock at t_2 (C_{t2real}), carbon stock at t_2 qualifying for accounting (C_{t2RME}) and difference of C_{t2BL} and C_{t2RME} ($\hat{C}_{t2REDD}$). A large total error for the MRV-system can result in a negative $\hat{C}_{t2REDD}$

The results of the simulation study show that even small errors result in situations where no carbon credits can be generated (Fig. 4). Total errors larger than 7%, which are realistic in extensive forest carbon surveys (Fuller et al., 2003; Gertner & Köhl; 1992, Waggoner, 2009), may exclude national REDD-regimes from generating benefits.

As shown by theoretical considerations the total error associated with carbon estimates can outweigh efforts to reduce deforestation and forest degradation. This was verified in the simulation study indicating that countries with medium or low deforestation and forest degradation rates are not in a position to generate carbon credits from REDD when the uncertainties of carbon stock estimates are included in calculations as requested in a REDD certification process. Even when a country was successful in reducing carbon losses from deforestation and forest degradation, only a minor amount of carbon credits could be generated or – even worse – emissions from forestry might have to be reported.

A prerequisite for any successful implementation of a REDD regime is the estimation of activity data and emission factors with high reliability, which can be achieved by a robust and transparent MRV-system using appropriate techniques, and comprehensive and internationally consistent approaches (Eliasch, 2008). Special attention needs to be taken to the quantification of the total survey error. A sound assessment and quantification of non-sampling and sampling errors is essential for any REDD inventory concept. We recommend that especially countries in the readiness phase, which have not yet developed appropriate capacities, carefully study the effects of the principle of conservativeness in preparing for REDD. For those countries capacity building for implementing a robust, cost-efficient and transparent MRV-system is urgently needed in order to turn efforts in reducing deforestation and forest degradation into benefits generated by REDD.

6. Authors' contributions

Daniel Plugge and Thomas Baldauf equally conceived of the study, performed the statistical analysis, and drafted the manuscript. Michael Köhl participated in the study's design and coordination. This chapter is a revised and updated version of a paper published in 2009 (Köhl et al., 2009).

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10

Addressing Carbon Leakage by Border Adjustment Measures

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1. Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change calls for industrialized countries and economies in transition (listed in the Annex B) to reduce their aggregate carbon equivalent emissions of greenhouse gases by 5.5 percent of their 1990 levels. To fulfil domestic mitigation targets efficiently, policymakers have typically focused on two market-based regulatory mechanisms: taxes and caps with trading. Both policy measures will create a similar carbon price on the combustion of fossil fuels and therefore increase the domestic production costs of energy-intensive industries. Because the Kyoto Protocol does not require mitigation from developing countries, such asymmetric climate policies will lead to changes in terms of trade. Firms located in countries which implement carbon pricing policies will bear an additional production cost and are placed at a disadvantageous position comparing with their competitors in countries which do not internalise the carbon costs in production.

Facing an increase in production cost, firms can choose to pass carbon related costs onto their downstream consumers or to cut their profit margins in order to keep the market share. Both options will however lead to losses in both international competitiveness and employment. An alternative way of produce domestically is to relocate production to countries with less stringent climate policies. Relocation may help to address losses in competitiveness but in employment.

Another concern closely related to the competitiveness losses and relocation is "carbon leakage", which generally refers to an increase of emissions in countries without climate policies that are attributable to emission reductions in countries with climate policies. The effectiveness of climate polices on reducing global emissions will be undermined if the leakage is high.

The competitiveness and leakage concerns have centred in the climate policy debates first in EU when EU Emissions Trading System was introduced and implemented, then in US and Australia when a cap-and-trade system is being considered (Houser et al., 2008; Reinaud, 2008; Carbon Trust 2010; van Asselt & Brewer, 2010). The best way to address these concerns in implementing carbon pricing policies would be the completion of a harmonized international climate policy (Stern, 2006; Manders & Veenendaal, 2008). However differences between countries in the level of economic development, political conditions, obligations stemming from historic emissions, and responsibilities arising from current and future emissions mean that harmonization is still a long way off. Among other policy alternatives, the use of offsetting measures at the border to level the playing field is getting popular in policy proposals.

Climate change related border adjustment measures (BAMs) are aimed at restoring international competitiveness through internalising the carbon cost globally, combating carbon leakage, enabling wider and deeper emission cuts domestically and incentivising other countries to join international efforts to cut emissions. Except for the good will of using a BAM, however BAMs implemented unilaterally may invoke political repercussions, harm trade relations and international relations in future climate negotiations and are likely to be challenged by the World Trade Organization (WTO) law. Taking account of the risks and costs of applying strong trade measures in climate policies, it is therefore very important to demonstrate that whether BAMs at issue can effectively deliver the expected economic and environmental benefits and overweight the potential risks and costs.

Although there is little empirical analysis to date, many economic analyses focusing on the economic and environmental effectiveness of different border measures (such as the inclusion of importers to surrender carbon allowances in a cap-and-trade system, import tariffs, and export rebates) have been conducted since last decade (e.g., Babiker et al., 2000; Babiker & Rutherford, 2005; Peterson & Schleich, 2007; Manders & Veenendaal, 2008; Fischer & Fox, 2009; McKibbin & Wilcoxen, 2009; Monjon & Quirion, 2010; Takeda et al., 2010, 2011; Winchester et al., 2010). By conducting a comprehensive literature review, we found that there is disagreement among researchers on both the quantitative importance of leakage and the effectiveness of policy instruments proposed to limit leakage and competitiveness impacts. Many studies indicated that how effective the various options will be in reducing competitiveness and leakage impacts depends, among others, on the differences in GHG emissions among like products from different origins. In turn, measuring the carbon content of imported goods is critical in assessing policy effectiveness. However calculating embodied emissions by tracing the origin of production at product or firm level is a challenge in both technical and practical terms.

Based on these observations, this chapter aims at assessing the economic and environmental effectiveness of selected BAMs, in particular import tariffs. We focus on a carbon tax system in Japan. Based on the Kyoto Protocol, Japan committed to reduce GHG emissions by 6 percent below the base year 1990, during the period of 2008-2012. In 1998, Japan promulgated the Law Concerning the Promotion of the Measures to Cope with Global Warming to determine the national framework to cope with global warming (Ministry of the Environment of Japan, 1998). In 2005, the Kyoto Protocol Target Achievement Plan was formulated (Government of Japan, 2005). More recently the government of Japan announced a plan to impose carbon tax from 2011 (Ministry of the Environment of Japan, 2010). The implementation of the carbon tax system has caused political and business concerns on domestic competitiveness and carbon leakage. For this analysis, a recursive dynamic global computable general equilibrium (CGE) model is employed. Not just adding one more similar economic analysis to current CGE literature on border adjustment, we take account of the nationally appropriate mitigation actions (NAMAs), of which implementation in the selected developing countries could shorten the gap in the production costs of carbon-intensive industries between countries which implement carbon pricing policies and developing countries. These two points has yet been well addressed in the existing literature.

The rest of this chapter consists of four sections. Section 2 explains the model and data. Section 3 presents simulation results. Section 4 provides conclusions. Section 5 (the Appendix) discusses the WTO compatibility of BAMs.

2. The framework

2.1 The model

The model employed in this chapter is a multi-region CGE model which is based on the GTAP6inGAMS (Rutherford, 2005). In the model, a representative firm produces goods by using intermediate goods and production factors (skilled labour, unskilled labour, capital stock, land and natural resources). Inputs of intermediate goods and composite factors are described by the Leontief formulation while composite factors are formed by the constant-elasticity-of-substitution (CES) function. Household behaviour is modelled by employing the Cobb-Douglas utility maximisation. Allocation of demands (for both firms and household) between domestic goods and imported goods is formulated by the Armington approach (Armington, 1969). Sectoral investment is treated as an exogenous variable: hence, savings are not formulated in this model.

In order to do post-sample simulation, a recursive dynamics is introduced. Specifically, given the growth rates of population, skilled labour input, unskilled labour input and capital stock, we derive the future paths (from the year 2004 to 2020) of these three inputs.

Moreover, we add an embodied emission module to the original GTAP6inGAMS model by using the emission coefficients computed in Zhou et al. (2010).

2.2 Data

The main dataset of this analysis is GTAP Database version 7 (base year is 2004). Since the embodied emission coefficients in Zhou et al. (2010) are obtained by using the Asian International Input-Output (AIIO) Table 2000 (Institute of Developing Economies, 2006), the sector aggregation of our dataset basically follows the 24-sector-classification in the AIIO Table. Sector classification and matching between the AIIO Table and GTAP Database are presented in Table 1. The world economy is divided into thirteen regions in this model. The regional classification is described in Table 2.

As shown in Table 1, the chemical products and rubber products sectors are separated in the AIIO Table whereas they are aggregated in the GTAP Database. In this analysis, we disaggregate the chemical and rubber products sector in the GTAP Database by using sectoral output shares in India's 2004 input-output table (for India), EU KLEMS gross output data (for EU) and the AIIO Table 2000 (for the other ten economies) with the program SplitCom[1].

For constructing their future paths until 2020, the growth rates of population, skilled labour input, unskilled labour input and capital stock are taken from Dimaranan et al. (2007).

3. Simulation analysis

Applying the model described in the previous section, we analyse the economic and environmental effects of BAMs. Particularly, we focus on changes in international carbon leakage, global embodied emissions, output in energy-intensive sectors and GDP towards the year 2020. All results from 2011 are presented in this section since Japan's carbon tax will be put into practice from the year 2011.

3.1 Simulation analysis and results

In order to quantify the effects of BAMs and NAMAs, we prepare the following four simulation scenarios: BAU, Cases 1, 2 and 3. The BAU scenario is the baseline scenario of

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[1] Regarding SplitCom, see http://www.monash.edu.au/policy/splitcom.htm.

2004 without the introduction of carbon tax. In Case 1 scenario, carbon tax is levied on Japan's imports of fossil fuels. According to the Ministry of the Environment of Japan (2010), the carbon tax levied on fossil fuels (coal, crude oil, petroleum products and natural gas) will be JPY289/t-CO_2, which is equivalent to US$2.671/t-$CO_2$[3]. Although the Government of Japan will levy the carbon tax from 2011 and increase the rate gradually to the level of US$2.671/t-$CO_2$, we assume that Japan will implement a carbon tax of US$2.671/t-$CO_2$ from 2011 in our analysis. The carbon tax will be introduced as an additional tax to the current Petroleum and Coal Tax. Since most of fossil fuels used in Japan are imported, we assume that the carbon tax is levied on the imports of fossil fuels to Japan[2]. In addition to carbon tax

	AIIO 24 sector classification		GTAP 57 sector classification
	Symbol	Description	Code
1	PDR	Paddy	pdr
2	XAG	Other agricultural products	wht, gro, v_f, osd, c_b, pfb, ocr
3	LSP	Livestock and poultry	ctl, oap, rmk, wol
4	FRS	Forestry	frs
5	FSH	Fishery	fsh
6	CPG	Crude petroleum and natural gas	oil, gas
7	XMN	Other mining	coa, omn
8	FBT	Food, beverage and tobacco	cmt, omt, vol, mil, pcr, sgr, ofd, b_t
9	TEX	Textile, leather and the their products	tex, wap, lea
10	WDP	Timber and wooden products	lum
11	PPP	Pulp, paper and printing	ppp
12	CHM	Chemical products	crp
13	PTR	Petroleum and petro products	p_c
14	RBP	Rubber products	crp
15	NMM	Non-metallic mineral products	nmm
16	XMP	Metal products	i_s, nfm, fmp
17	MCN	Machinery	ele, ome
18	TRE	Transport equipment	mvh, otn
19	XMF	Other manufacturing products	omf
20	EGW	Electricity, gas, and water supply	ely, gdt, wtr
21	CNS	Construction	cns
22	TRT	Trade and transport	trd, otp, wtp, atp
23	SRV	Services	cmn, ofi, isr, obs, ros, dwe
24	PBA	Public administration	osg

Table 1. Sector classification

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[2] Based on the energy balance table for Japan (Energy Data and Modelling Centre, Institute of Energy Economics, 2011), Japan's imports of coal, crude oil, petroleum products and natural gas in 2009 accounted for 99.4 percent, 99.6 percent, 100 percent and 96.0 percent of primary supply, respectively.

in Japan, the Case 2 scenario includes import tariff levied on all imports of Japan from other economies[3]. This border adjustment tariff rate is computed by embodied emission coefficients (carbon contents) of exporting countries. Emissions embodied in imports include emissions emitted from all upstream production stages wherever they are in order to produce the goods. Embodied emission coefficients for imports are emissions embodied in per unit imports, which are calculated at sectoral level using the multi-region input-output model. The formulation of the tariff rate basically follows that in Winchester et al. (2010). The Case 3 scenario consists of the Case 2 scenario and NAMAs for China and India. Based on the Copenhagen Accord, China and India proposed to decrease CO_2 emissions per GDP in the year 2020 by 40-45 percent and 20-25 percent from the 2005 levels, respectively. In this scenario, we introduce linear-cuts of embodied emission coefficients in China and India which satisfy the corresponding reduction targets in 2020.

1	Indonesia (IDN)
2	Malaysia (MYS)
3	Philippines (PHL)
4	Singapore (SGP)
5	Thailand (THA)
6	China (CHN)
7	Taiwan (TWN)
8	South Korea (KOR)
9	Japan (JPN)
10	United States (USA)
11	India (IND)
12	European Union (EU)
13	Rest of the world (ROW)

Table 2. Regional classification

Case 1	Carbon tax in Japan
Case 2	Carbon tax and import-tariff-based border adjustments in Japan
Case 3	Carbon tax and import-tariff-based border adjustments in Japan plus nationally appropriate mitigation actions in China and India

Table 3. Simulation scenarios

3.2 Global emissions

Percentage changes in global emissions from BAU are shown in Table 4. By introducing carbon tax in Japan, global emissions rise slightly. In contrast, emissions decrease by the

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[3] Since Japan will levy carbon tax on the imports of fossil fuels, it is reasonable to apply border adjustment to the carbon contents of energy in other countries. Since Japan's carbon tax on fossil fuels will influence all downstream stages which use energy, we assume that border adjustment will be applied to all imported goods to Japan in this analysis.

application of Japan's border adjustment. Shifts of production between Japan and other economies result in these outcomes. Energy efficiency of Japan is one of the highest in the world. Due to the carbon tax, imports of Japan from other countries, which are usually less energy efficient, increase and substitute part of Japan's domestic production. This will contribute to an increase in global emissions. For Case 2, the reverse results occur because border adjustments will help resume Japan's domestic production and constrain carbon-intensive imports to Japan which will contribute to the decrease in global emissions. In Case 3, global emissions decline substantially. This result indicates that NAMAs of China and India have great potential impacts on the generation of global emissions[4].

	Case 1	Case 2	Case 3
2011	0.00001	-0.00122	-6.69720
2012	0.00001	-0.00112	-7.65082
2013	0.00002	-0.00103	-8.60368
2014	0.00002	-0.00092	-9.55537
2015	0.00003	-0.00082	-10.50530
2016	0.00003	-0.00071	-11.45266
2017	0.00004	-0.00060	-12.39637
2018	0.00004	-0.00051	-13.33499
2019	0.00004	-0.00042	-14.26663
2020	0.00005	-0.00036	-15.18883

Table 4. Percentage change of global emissions from BAU

3.3 Carbon leakage

The impacts of BAMs on international carbon leakage are the main concern of this analysis. Deviations of national emissions from BAU are illustrated in Table 5. For Case 1, Japan's national emissions decline while emissions from other countries' increase. From these results, we can observe carbon leakage from Japan to other countries due to the carbon tax system. Also, the effect of carbon tax on emission reduction is quite limited because the proposed carbon tax rate is not enough to make it an effective incentive. In order to satisfy its own emission reduction target, Japan might need other effective abatement policies.

In contrast to Case 1, we can find that national emissions in Japan will increase while emissions from other countries will decrease for Case 2. Due to the introduction of BAMs, imports of Japan from other countries are expected to decrease.

For Case 3, we can see similar results as Case 2 although the magnitude for other countries is different. By decreases in embodied emission coefficients in China and India, we can expect that Japan's national emissions will also decline due to global supply chains and international trade of intermediate goods. Because we fix the emission coefficients for Japan, the propaganda effects of changes in the emission coefficients of China and India are not taken into account in this analysis. The increase of Japan's national emissions indicated by Case 3 is mainly the effect of BAMs, which contributes to resuming domestic production

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[4] Changes of embodied emission coefficients in other countries due to less carbon intensity in China and India attributable to their NAMAs is not considered in the analysis. If this propaganda effect is included, we could expect more reductions in global emissions.

and substituting carbon-intensive imports. If we update Japan's embodied emission coefficients based on the changes in the emissions coefficients in China and India, we can see both the effect of BAMs and the effect of NAMAs implemented by China and India. Two effects will impact Japan's national emissions in two opposite directions.

	Japan			Other countries		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
2011	-0.000004	0.000129	0.000112	0.000011	-0.000900	-4.234302
2012	-0.000004	0.000125	0.000106	0.000013	-0.000852	-4.944332
2013	-0.000004	0.000120	0.000100	0.000016	-0.000797	-5.682395
2014	-0.000004	0.000114	0.000093	0.000019	-0.000737	-6.448525
2015	-0.000005	0.000108	0.000085	0.000023	-0.000670	-7.242434
2016	-0.000005	0.000100	0.000077	0.000027	-0.000599	-8.063437
2017	-0.000005	0.000092	0.000067	0.000031	-0.000525	-8.910348
2018	-0.000006	0.000081	0.000057	0.000036	-0.000452	-9.781361
2019	-0.000006	0.000070	0.000045	0.000040	-0.000386	-10.673914
2020	-0.000007	0.000057	0.000033	0.000042	-0.000332	-11.584544

Table 5. Deviation of national emissions from BAU (Billion ton-CO_2)

3.4 Output effects

In this chapter, changes in output are examined for the following energy-intensive sectors which are usually considered more vulnerable to the competitiveness effects: the pulp, paper and printing, chemical products and metal products sectors. Although the magnitudes differ, Japan's output in the selected sectors declines for Case 1 (the introduction of carbon tax in Japan) throughout the simulation period. From the results for output changes in the chemical products sector, border adjustments do not necessarily improve the output. It depends on input-output and trade structure of an industrial sector.

3.4.1 Pulp, paper and printing sector

Percentage changes in output for the pulp, paper and printing sector are presented in Table 6. For this sector, border adjustments greatly improve its output. Despite an increase of price due to border adjustments, China and India also experience an output increase. By contrast, output in the rest of the countries declines. It can be considered that Japan's output increase will stimulate output increase in both China and India through trade.

	Case	2011	2015	2016	2017	2018	2019	2020
JPN	1	-0.00019	-0.00022	-0.00023	-0.00023	-0.00024	-0.00025	-0.00025
	2	0.01389	0.01370	0.01366	0.01363	0.01362	0.01361	0.01362
	3	0.01306	0.01234	0.01215	0.01196	0.01177	0.01158	0.01140
CHN	1	-0.00003	-0.00004	-0.00004	-0.00004	-0.00004	-0.00004	-0.00004
	2	0.01440	0.01224	0.01164	0.01101	0.01036	0.00968	0.00897
	3	0.01035	0.00721	0.00651	0.00584	0.00520	0.00458	0.00399
IND	1	0.00003	0.00004	0.00004	0.00005	0.00005	0.00005	0.00005
	2	0.00389	0.00441	0.00459	0.00479	0.00502	0.00525	0.00551
	3	0.00309	0.00325	0.00334	0.00345	0.00358	0.00372	0.00388
The rest	1	0.00001	0.00001	0.00002	0.00002	0.00002	0.00002	0.00002
	2	-0.00207	-0.00211	-0.00213	-0.00214	-0.00215	-0.00217	-0.00219
	3	-0.00180	-0.00171	-0.00169	-0.00167	-0.00166	-0.00165	-0.00165

Table 6. Percentage change of output in the pulp, paper and printing sector from BAU

3.4.2 Chemical products sector

Table 7 shows percentage change of output in the chemical products sector from BAU. Contrary to the results for the pulp, paper and printing sector, border adjustments will not have the expected effects. For all three cases, Japan's chemical output declines. We find more output decrease in Cases 2 and 3 for Japan. In contrast, outputs for the rest of the twelve regions rise. Particularly, outputs of countries other than China increase. To explain the reasons, we need to conduct a decomposition analysis which is beyond the scope of this work.

	Case	2011	2015	2016	2017	2018	2019	2020
JPN	1	-0.00135	-0.00139	-0.00141	-0.00143	-0.00145	-0.00147	-0.00149
	2	-0.02825	-0.04574	-0.05138	-0.05761	-0.06448	-0.07202	-0.08025
	3	-0.03058	-0.04838	-0.05389	-0.05989	-0.06641	-0.07347	-0.08109
CHN	1	0.00007	0.00012	0.00014	0.00016	0.00018	0.00020	0.00021
	2	0.00066	0.00015	0.00015	0.00023	0.00037	0.00058	0.00086
	3	0.00182	0.00256	0.00290	0.00331	0.00376	0.00424	0.00474
IND	1	-0.00002	-0.00005	-0.00006	-0.00006	-0.00007	-0.00008	-0.00009
	2	0.00424	0.00648	0.00711	0.00775	0.00841	0.00908	0.00978
	3	0.00444	0.00676	0.00739	0.00803	0.00869	0.00935	0.01002
The rest	1	0.00016	0.00017	0.00017	0.00017	0.00017	0.00017	0.00018
	2	0.00290	0.00498	0.00564	0.00637	0.00716	0.00802	0.00895
	3	0.00295	0.00488	0.00547	0.00611	0.00681	0.00758	0.00841

Table 7. Percentage change of output in the chemical products sector from BAU

3.4.3 Metal products sector

As illustrated in Table 8, Japan's output changes in the metal products sector have the same trend as for the pulp, paper and printing sector (i.e. decrease in the case of carbon tax and increase in the case of border adjustments). As a consequence of border adjustments, we find a decrease in output for China and countries other than Japan, China and India. By contrast, India's output rises. Interestingly, the sign of output changes for China under Case 3 turns into positive from 2019. NAMAs are included in Case 3 and the level of border adjustments depend on carbon price and the embodied emission coefficients of exporting countries. Thus, we can observe that NAMAs enable China to lower its export price of metal products gradually and increase its output as a consequence.

	Case	2011	2015	2016	2017	2018	2019	2020
JPN	1	-0.00228	-0.00251	-0.00259	-0.00267	-0.00277	-0.00288	-0.00301
	2	0.10326	0.09094	0.08654	0.08154	0.07593	0.06971	0.06292
	3	0.09445	0.07974	0.07529	0.07052	0.06541	0.05998	0.05425
CHN	1	0.00032	0.00046	0.00051	0.00056	0.00060	0.00064	0.00066
	2	-0.01117	-0.00862	-0.00762	-0.00648	-0.00523	-0.00389	-0.00253
	3	-0.00632	-0.00281	-0.00191	-0.00103	-0.00021	0.00051	0.00109
IND	1	0.00016	0.00019	0.00021	0.00022	0.00024	0.00026	0.00028
	2	0.00100	0.00281	0.00352	0.00435	0.00530	0.00639	0.00760
	3	0.00025	0.00156	0.00211	0.00277	0.00353	0.00439	0.00535
The rest	1	0.00033	0.00034	0.00035	0.00036	0.00037	0.00038	0.00040
	2	-0.01075	-0.00981	-0.00955	-0.00929	-0.00903	-0.00878	-0.00854
	3	-0.01048	-0.00943	-0.00914	-0.00885	-0.00853	-0.00821	-0.00787

Table 8. Percentage change of output in the metal products sector from BAU

3.5 Welfare effects

Table 9 demonstrates percentage change of welfare from BAU. Although carbon tax is a factor for price increase, Japan's welfare rises from BAU for Case 1. It can be explained that a price increase is limited because the carbon tax rate is quite limited and is applied only to energy products. Also, the introduction of carbon tax contributes to government revenue. Thus, it is considered that the positive effects through government behaviour are greater than the negative impacts of carbon tax on national welfare. In contrast, Japan's welfare declines for Cases 2 and 3. Import prices go up by border adjustments and these negative effects are substantial for these cases. According to the results of Japan, border adjustments would not help to improve welfare. In this model, tax revenue from border adjustments is not transferred to household and does not have direct positive impacts on household consumption. This may be a reason for these unexpected results.

Similar changes can be found for China. Welfare changes of China are negative for Cases 2 and 3. This shows that the adoption of border adjustments in Japan may have negative impacts on Chinese economy, particularly on the exports because of higher tariffs. Contrarily, signs of welfare changes for India are opposite to those of Japan and China. Even though India faces border adjustments, its welfare is improved. To explain the reasons, we need decomposition analysis which is not considered in the current analysis. The introduction of NAMAs affects China negatively and India positively compared with BAU. However, compared with Case 2, welfare deterioration will be less for China and India's welfare will improve more.

	Case	2011	2015	2016	2017	2018	2019	2020
JPN	1	0.00124	0.00135	0.00140	0.00145	0.00151	0.00159	0.00168
	2	-0.05537	-0.06042	-0.06213	-0.06407	-0.06627	-0.06876	-0.07157
	3	-0.05166	-0.05473	-0.05595	-0.05739	-0.05909	-0.06107	-0.06336
CHN	1	0.00000	0.00004	0.00006	0.00007	0.00009	0.00010	0.00012
	2	-0.03426	-0.03011	-0.02953	-0.02913	-0.02895	-0.02902	-0.02937
	3	-0.02528	-0.01837	-0.01713	-0.01606	-0.01517	-0.01445	-0.01392
IND	1	-0.00004	-0.00004	-0.00004	-0.00004	-0.00004	-0.00004	-0.00004
	2	0.00146	0.00218	0.00240	0.00265	0.00291	0.00319	0.00350
	3	0.00176	0.00263	0.00288	0.00316	0.00346	0.00379	0.00414

Table 9. Percentage change of welfare from BAU

4. Conclusions

In this chapter, we quantified the economic and environmental effects of CO_2 abatement policy as well as border adjustments by applying a global CGE model with 13 regions and 24 sectors. In particular, we focused on Japan's proposed carbon tax and border adjustments in the form of import tariffs. Major findings are as follows:

- Due to the implementation of carbon tax in Japan, international carbon leakage will occur.
- Border adjustments (e.g. by Japan in this analysis) can help mitigate international carbon leakage and global emissions.
- However, border adjustments do not necessarily contribute to output increase of energy-intensive sectors, which is related to the concern on industrial competitiveness of the implementing country. In addition, BAMs may have negative impacts on the national welfare of the implementing country.
- Nationally appropriate mitigation actions (NAMAs) have great potential impacts to reduce global emissions and to improve national welfare in both the implementing country of a BAM and its target countries.

Although we analysed the impacts of Japan's carbon tax and import-tariff-based border adjustments, several improvements can be expected. First, the embodied emission coefficients are calculated based on the data of 2000. Updating the data is necessary. Second, the embodied emission coefficients for all selected countries should be re-calculated based on the changes of emission intensities in China and India. Third, we showed some positive and substantial impacts of NAMAs on both economy and the environment. However, specific approaches and policies to implement NAMAs in China and India are not reflected and should be examined further. Finally, we only analysed Japan's climate policy and BAMs. The inclusion of EU Emissions Trading System (EU-ETS) and US cap-and-trade system will provide more comprehensive insights.

5. Appendix: WTO compatibility of border adjustments

Any BAM with a serious trade impact may be challenged before the WTO. Given the vague nature of WTO law in this respect, the WTO may either uphold or strike down the BAM provision. In principle, a trade measure needs to be justified by the non-discrimination principle, i.e. national treatment and the most-favoured nation clauses, provided under GATT (Articles I, II, and III). Therefore, a climate change-related trade provision that applies only to imports is suspect to be protectionist. A measure that applies to both imports and domestic products is accepted as long as it does not discriminate against imports from domestic products or against imports from particular countries. In addition, under trade law, price-based measures such as taxes are regarded as more transparent and economically more efficient than regulations. Hence, generally speaking, WTO rules push countries to adopt price-based measures such as tariffs or taxies, rather than quantitative import restrictions or trade restrictive regulations.

Depending on the form they take, trade measures to address competitiveness and carbon leakage concerns associated with the implementation of unilateral climate policy may be very different in both economic terms and legal terms. The choice of instrument is therefore crucial to their fate of WTO compatibility. As indicated by some legal analyses (e.g., Pauwelyn, 2007), an import restriction provision in the form of an import ban or punitive tariffs on imports from free-riding countries, anti-dumping duties against "environmental dumping", or counterveiling duties offset the "subsidy" of not imposing carbon restrictions would have little chance of survival before the WTO challenge. While border tax adjustment based on a domestic carbon tax or a cap-and-trade system would have better chance to survive WTO scrutiny.

5.1 Border tax adjustments on imported products

In its examination of BTAs, the 1970 GATT Working Party distinguished that taxes directly levied on products, the so-called indirect taxes (such as excise duties, sales taxes and the tax on value added), were eligible for adjustment, while certain taxes that were levied on producers, the so-called direct taxes (such as payroll, taxes on income, property and profits, social security charges, or interests), were normally not eligible for adjustment.

Pursuant to GATT Article II.2 (a) allows WTO members to impose a charge equivalent to an internal tax on the importation of i) products that are like domestic products; or ii) articles from which the imported product has been manufactured or produced in whole or in part.

Based on these rules, however there is long-standing legal debate focusing on i) the eligibility of domestic carbon/energy taxes as indirect taxes for border adjustment; ii) the qualification of the allowance price under a cap-and trade system as an "internal tax"; and iii) the extent to which the energy inputs and fossil fuels could be considered to be articles from which the imported product has been manufactured or produced in whole or in part, related to the requirement of physically incorporated into the final product and the explanation of "direct" and "indirect" physical incorporation (Biermann & Brohm, 2005; Pauwelyn, 2007).

If the price-based climate policy takes the form of a carbon tax, it needs to pass two critical eligibility tests for being adjustable under GATT: (i) carbon/energy taxes are indirect taxes; and (ii) energy/carbon emissions are articles incorporated in whole or in part of imported product. On the one hand, following the definitions of "direct" versus "indirect" taxes in the WTO Agreement on Subsidies and Countervailing Measures (SCM), a carbon tax can be justified as an "indirect tax" and thus eligible for adjustment (Pauwelyn, 2007). On the other hand, it remains unclear whether input or process-related taxes on physical inputs (such as energy or carbon emissions), the so-called "taxes occultes", can be adjusted at the border. Therefore energy/carbon taxes to be defined as "indirect taxes" that are "indirectly" applied to products lacks clear legal basis for justification (Biermann & Brohm, 2005).

If the climate policy takes the form of a cap-and-trade system, in general, its qualification for adjustment is more complicated than the policy designed in the form of a carbon tax. The fundamental concern is whether the obligation to hold emission allowances can be qualified as an "internal tax or other internal charge of any kind". In addition, the complication is further under the situations: (i) when all or part of the allowances is allocated for free; and

(ii) when the adjustment also takes the form, not of a tax, but of a requirement to importers to surrender emission allowances.

Even if border adjustment were permitted for a carbon tax or a cap-and-trade system, one more critical question is the definition of "likeness" of domestic and imported products in its relations to the non-discrimination principle. The WTO Appellate Body in the EC-Asbestos case provided four "characteristics" for assessing the "likeness" including: (i) the physical properties of the products; (ii) the extent to which the products are capable of serving the same or similar end-uses: (iii) the extent to which consumers perceive and treat the products as alternative means of performing particular functions in order to satisfy a particular want or demand; and (iv) the international classification of the products for tariff purposes. However whether steel from China made with coal (high carbon-intensity), for example, is "like" steel from US using natural gas (low carbon-intensity) may remain unclear.

5.2 Border tax adjustments on exported products

GATT (Article XVI on Subsidies and Ad Article XVI, 1994) and WTO SCM Annex I Item (g) permit, under certain conditions, the use of border tax adjustments on exported products. However, export Border Tax Adjustment (BTA) cannot be subject to anti-dumping duties aimed at exports at less than domestic market price, nor to countervailing duties aimed at offsetting certain subsidies provided in the exporting country. In addition, the rebate should not be larger than the actual indirect tax levied on "like" products "when sold for domestic consumption".

5.3 GATT Article XX on the general exceptions clause

More related to climate change measures is GATT Article XX, which provides a number of specific exemptions from GATT rules, in particular related to the protection of human, animal and plant life or health (paragraph (b)) and the conservation of exhaustible natural resources (paragraph (g)). However, there are many debates on its application to climate-oriented trade measures. Several case laws (US-Shrimp case, Brazil-Retreaded Tyres case, EC-Asbestos case, etc.) indicated the importance for the trade measure at issue to show (i) the satisfaction in the requirements of the "chapeau" of Article XX on the manner in which trade measures are applied; (ii) the necessity of the trade measure and the availability of alternative options in achieving the environmental objective related to Article XX (b) and (g); and (iii) substantial link between the trade measure and the stated climate change policy objective (means and ends relationship).

On the one hand, the opponent to the justifiability of BAMs by WTO law must prove that the policy is not worthy of an exception under Article XX and show that a less trade-restrictive policy option is available and effective (related to (ii)), or that the policy does not contribute toward achieving a reasonable climate goal at all (related to (iii)). In this regard, Manders & Veenendaal (2008) reveal that alternative measures, in particular recycling part of permit auction revenues to exposed ETS-sectors and greater reliance on the Clean Development Mechanism, could be more effective than a border measure. In addition, several economic analyses (e.g. Babiker & Rutherford, 2005; Fischer & Fox, 2009) reveal that BAMs' contribution to the conservation of the climate is not assured. On the other hand, the proponent to a trade measure needs to demonstrate that it has been well tailored to achieve a legitimate environmental objective in a least trade restrictive manner. Protecting domestic producers from foreign competition may therefore not be recognized as a legitimate policy objective under WTO law (Houser et al, 2008).

5.4 Practical challenges

Once border adjustments were permitted by the WTO, collecting the relevant data for the process-based calculation of a border adjustment, that is, tracing the proper amount of taxed input in the production process in the respective country of origin is still difficult. There are several proposals to reducing complexity. One is to limit the number of products subject to BAMs to a manageable level. As for exports, an energy-added tax method, similar to invoice methods for value-added tax can be used. In the case of imports where the necessary information on the production process is limited or not provided by the exporter, the use of a benchmark of "the best available technology" seems to be a feasible approach compatible with world trade law (Pauwelyn, 2007; Ismer & Neuhoff, 2004), however is weaker adjustment factor and would therefore be less effective (Takeda et al., 2010).

Another challenge is permit allocation. Auctioning may be a prerequisite for border adjustment, since the free allocation of permits through grandfathering might be an unfair subsidy (Pauwelyn, 2007).

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11

The Climate Change and the Power Industry

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1. Introduction

Electricity generation is responsible to a large extent for the climate change all over the world. To reach the sustainable power supply the RENewable ratio should be raised and the CO_2 emission technologies should be rolled back. The indirect cost of the climate changes appearing later, the harmful effects and the irreversible environment change are expressed by the externality cost. This paper shows a linear programming optimization technique how one can define the optimal portfolio having clear data and targets. The key of the problem is to find approved initial data and objectives accepted by the society that we want to reach. In practice there are dozens of real and lobby tasks, so it is really hard to judge what is the multi-compound-objective function what we optimize for.

We introduce the trends of energy needs and emission and the basic power generation technologies. We define the notion of externalities and power mix. A method is shown how the ideal generation mix can be defined by linear programming tools. The result shows that the renewable sources mean cheap solution for long term. We show the different ways how to decrease the CO_2emission of the power technologies. These are the decrease of the amount of the used electricity; changing the generation portfolio; raising the electrical efficiency of the generation and trapping the exhausted CO_2. Finally we discuss the difficulties of the decision making regarding the power plant constructions.

2. GHG and the energy industry

The green house gases (GHG) create a special heat trap around the Earth globe and this phenomenon is considered one of the causes of the global climate change, the raise of the yearly average temperature. There are many GHGs, the two most important are the CO_2 and methane. Although at each technology the structure and ratio of the emission could be measured or counted, the CO_2 emission is the most simple and characteristic component that is why it is used as indicator of the mischievousness of a technology. The direct CO_2 emission origins from the combustion technology of the fossil fuel (oil, gas or coal) the indirect CO_2 production must be taking into account what is produced during the whole life cycle of the power plant construction and decommissioning and also during mining and processing the fuel.

In spite of all the efforts of the global CO_2 emission, the exertion of the fossil materials increases sharply. The exploited primary energy sources after some delay are transformed into CO_2. The main emitters are the power, metal, construction and transportation industries (see fig.1.).

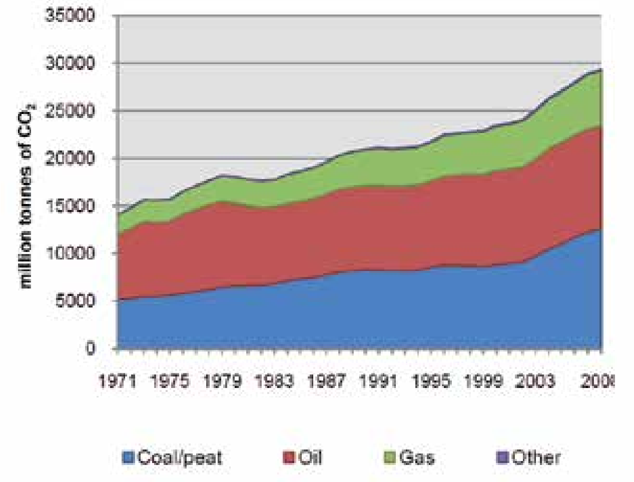

Fig. 1. CO_2 emission by fossil fuels[1]

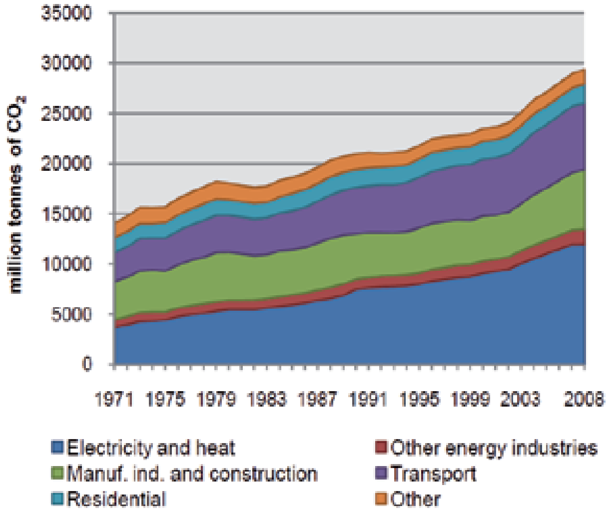

Fig. 2. CO_2 emission by sector[1]

As one can see the power sector (electricity and heat) is responsible for more than one third of the total CO_2 emission (see fig.2.). If we look for the primary source of the electricity generation, we can see that almost 60 % is fossil fuel (see fig.3.). Having known this fact it is hard to fight against the CO_2 emission.

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[1] CO_2 Emissions from fuel combustion *Highlights* (2010 Edition);
http://www.iea.org/co2highlights/co2highlights.pdf

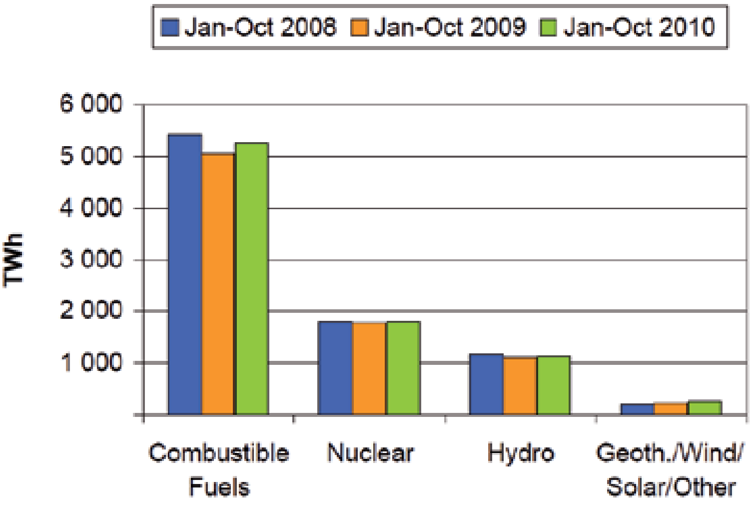

Fig. 3. Monthly worldwide electrical energy generation by primary sources[2]

This global ratio differs in certain countries. E.g. in Hungary is only 0,5% the hydro and 4% the other renewable generation for the lack of these type of sources and plants (see fig.4.).

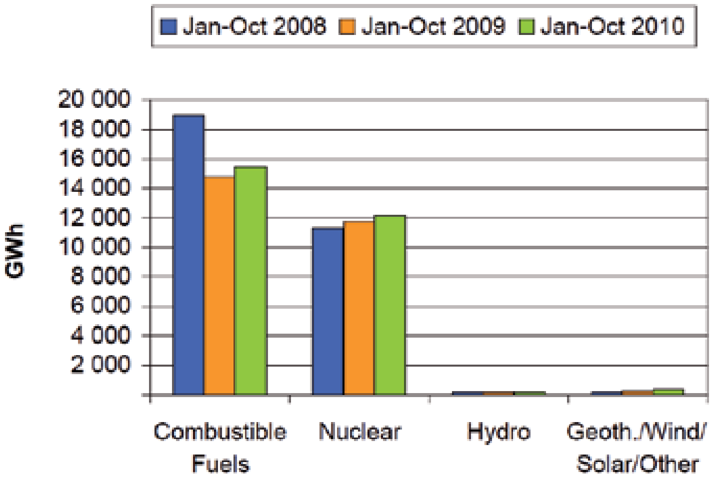

Fig. 4. Monthly electrical energy generation by primary sources in Hungary[2]

More frightening is that the emission growth of the electricity industry is among the highest (is not kept on a level or decreases – see fig.5.). The global growths of the emission and the high fossil ratio seem to be constant in spite of CO_2 reduction efforts, directives and conferences. And the energy starve do not stops in the near future (see fig.6.).

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[2] Monthly Electricity Statistics November 2010; 'Year to Date' Comparison of Production by Fuel Type; http://www.iea.org/stats/surveys/mes.pdf

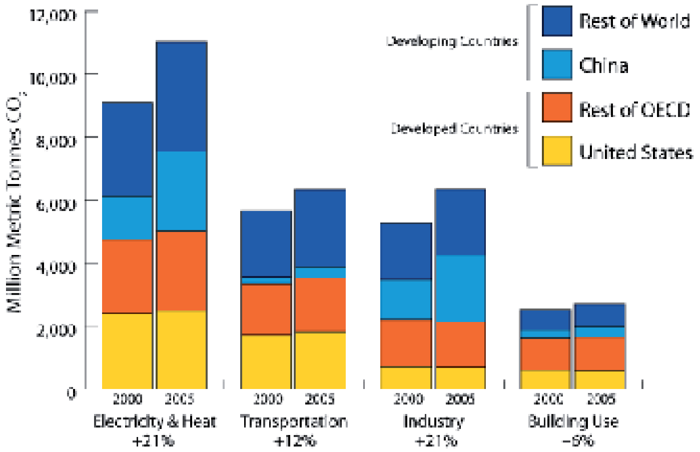

Fig. 5. Global CO_2 emission growth in selected sectors 2000-2005[3]

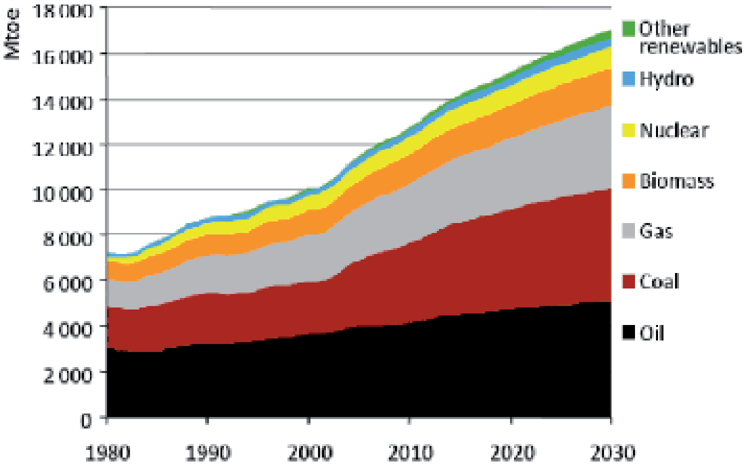

Fig. 6. Primary energy need outlook till 2030[4]

3. Basic power generation technologies

In this subchapter the traditional and renewable power (heat and electricity) generation technologies, their operation, measures and effects are enumerated.

In the industrialized world the primary energy sources (coal, oil, natural gas) are transformed into secondary energy forms, such as heat and electricity, that can be easily handled at end-user technology. This transformation is performed in power plants. Figure 7. shows this general transformation scheme.

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[3] http://www.usablemarkets.com/2010/06/13/world-greenhouse-gas-emissions

[4] http://www.energy4me.org/energy-facts/energy-sustainability

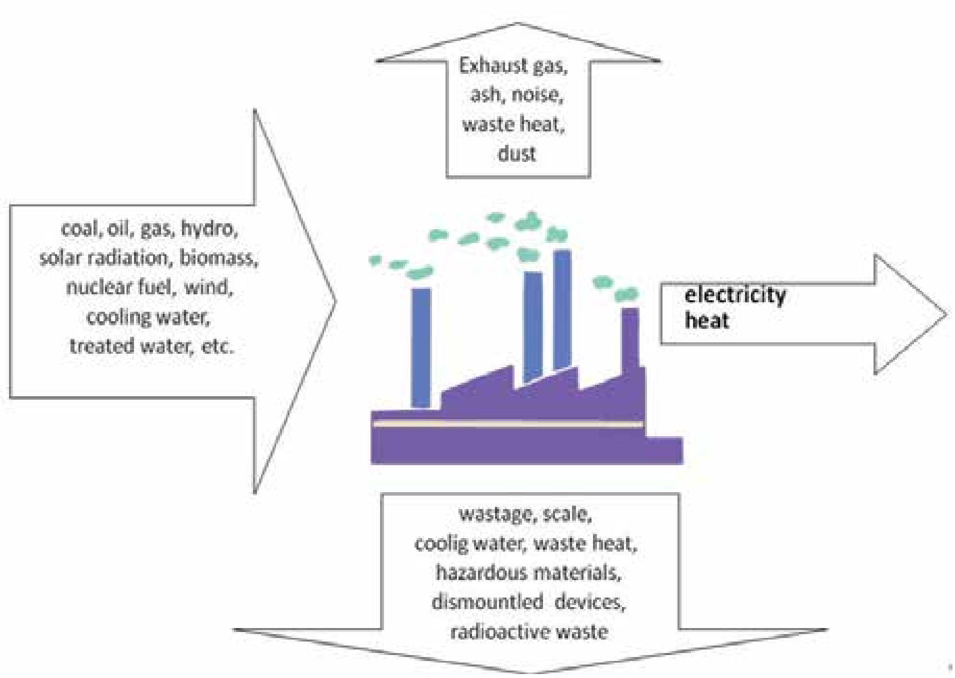

Fig. 7. Energy transformation in power plant

3.1 Coal fired power plant

Up to the middle of the 20th century the coal fired plants had hegemony. It has a new renaissance typically in China.

The powdered coal boils the treated water into steam in furnaces. The steam turbines run generators. The dead steam is condensed into liquid form by condenser in cooling towers (or other cooler solution).

- Fuel: coal (from the stone coal to the lignite)
- Typical electrical efficiency: 30 – 45%
- Measure: 200 – 800 MW/ unit; 1000 – 2000 MW/ plant

3.2 Oil/gas fired power plant

The strong development of oil based plants dates back to the middle of the 20th century. The technology is relatively simple and clean, no special solid rest or refuse handling technology is required. The power output of these plants can be controlled in wide range between 30-100%.

In the traditional technology the gas or oil boils the treated water into steam in furnaces. The steam turbines run generators. The dead steam is condensed in liquid form by condenser in cooling towers.

- Fuel: wide variety of oil and gas
- Typical electrical efficiency: 30 – 45%
- Measure, bulk plant: 200 – 400 MW/ unit; 1000 – 2000 MW/ plant

The gas turbine technology origins from the aircraft engine industry. The machine has three sections:

- a compressor section for the raise of the temperature and pressure of the air
- a second stage, where fuel (natural gas or oil vapour) is burning producing high pressure and temperature exhaust gas.
- the third section (in case of heavy duty power generation turbines), where a turbine is driven by the exhaust gas providing torque for electric generator.

The gas turbines work by open Carnot-cycle, the hot and expanded burned oil or gas (exhaust gas) turns directly the turbine.

- Fuel: fuel oil or gas
- Typical electrical efficiency: 45 - 60%
- Measure, bulk plant: 130 – 250 MW/ unit; 400- 1000 MW/ plant

3.3 Nuclear power plant

The nuclear plants are based on radioactive fission. These plants produce relatively cheap bulk base energy in spite of the high investment cost. There are more than 400 units in operation all over the world.

The fission produces heat in the fuel cassettes and this is cooled by water that turns into steam in the Boiled Water Reactor (BWR). The steam turbines run generators. The dead steam is condensed in liquid form by condenser. In the Pressurized Water Reactor (PWR) in the primary circle the water do not boils, the heat transferred through heat exchanger into the secondary, boiled water circle. The nuclear fission has no direct CO_2 emission. The construction process, the steel and cement production and fuel processing have remarkable emission. Eventually there is unwanted radioactive emission.

- Fuel: enriched uranium
- Typical electrical efficiency: 30 %
- Measure: 300 – 1500 MW/ unit; 1000 – 4000 MW/ plant

3.4 Hydro power plant

The hydropower is one of the oldest energy technologies, e.g. it is enough to think of the watermills. The level of the natural water flow is raised by a dam, and the potential energy of the water turned into kinetic – mechanical energy. The hydro plants can have low (till 15m), medium (till 50m) and high headings. The turbines are built in the dam, in underground cave or at the end of the artificial open air channel far from the reservoir. The main turbine types are the Banki, Francis, Kaplan and Pelton. During its operation there is no CO_2 emission. The construction process, the cement production and the decay of the organic materials in the reservoirs have remarkable emission.

- "Fuel": water flow
- Typical electrical efficiency: 85-93 %
- Measure: 0,01 MW – 800 MW/ unit; : 0,01 MW – 20 000 MW / plant

4. Emissions and externalities

The energy production must be investigated in a longer time scale and in a wider context. Externality means an external economic impact that is not taken into consideration in a present transaction, e.g. in the energy generation process: now we produce cheap electricity, but no one calculates the huge future costs of the nuclear waste bury or the costs of the CO_2 caused climate change. These costs must be paid by the future economy, by the future society. We talk about internalization of the externality if we assign these costs to the present transactions. In the price of the electricity over the fuel, maintenance and operation costs we should separate funds to avoid these harmful effects. The private cost is the present 'market price'. It is only a part of the total social cost (see fig.8.).

private cost + external cost = social cost

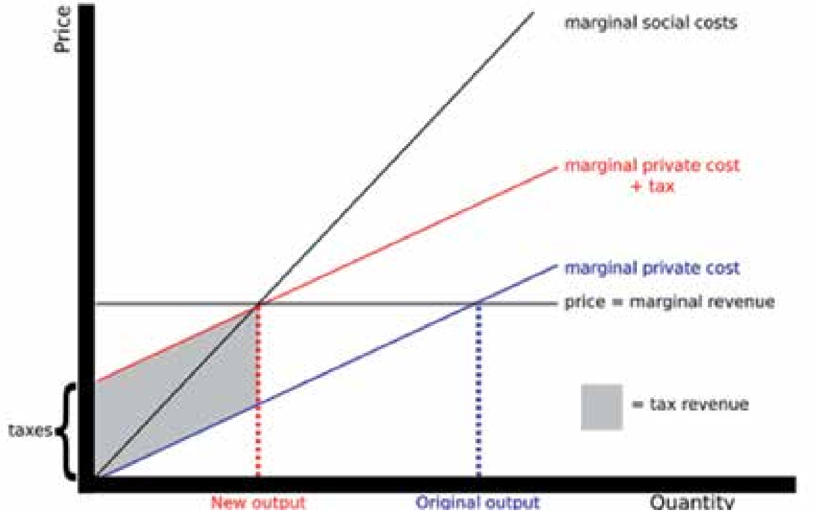

Fig. 8. The difference between the private and society costs[5]

The external cost calculation can deal with the green house gas emission, natural resource and area usage, health damage and landscape changes, too. It is a really complex process but several projects dealt with it already:

- EU ExternE project
- NEEDS consortia (New Energy Externalities Development for Sustainability)
- USA NSA project „Hidden Cost of Energy" project
- German BMU project „Externe Kosten der Stromerzeugung" project, etc.

Figure 9. shows a typical range of the externality cost that should be paid (virtually) in the future for each kWh of electricity produced and consumed today. The values depend on the investigated technology. Figure 10 refers to the Hungarian externalities.

The external cost is a greater set that contains the estimated cost of the GHG emission. Typically a greater emission technology has greater external cost but the relation is not linear. The external cost calculation is far less exact, that is why the emission measurement/calculation/estimation/trade is prevailing.

The exact external cost and the emission are valid always for a specific technology, a certain power plant. That is why the externality and emission used to given by from–to range, as an average value. This is a specific value, related to the production of 1 kWh or 1 MWh of energy. E.g. the CO_2 emission by coal fired plants can be approx. 700 g/kWh in case of high calorie coal and new combustion technology but it can be also 1200 g/kWh in case of lignite

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[5] United World College Mostar: Blue Books Economic Notes
http://www.scribd.com/doc/20735011/Economics-book-United-World-college-Mostar

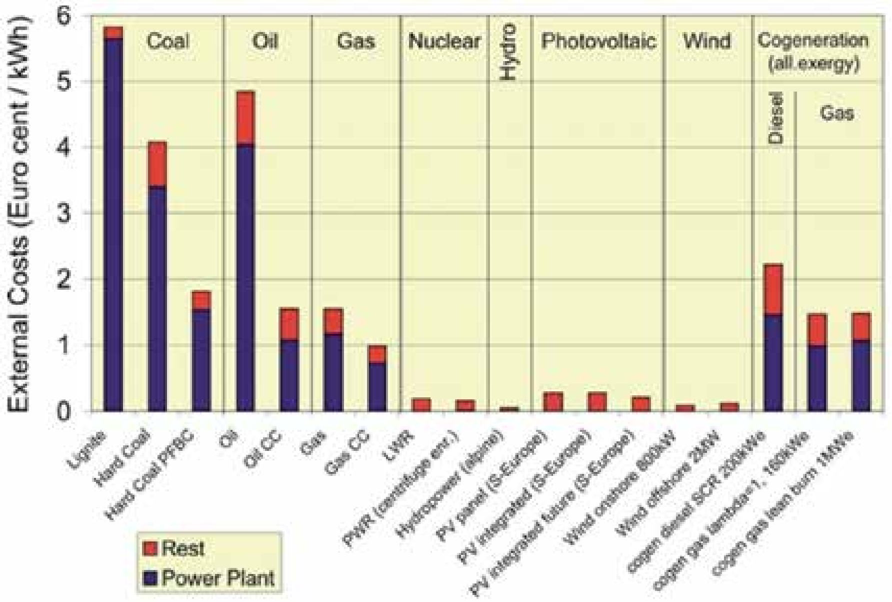

Fig. 9. External costs of current and advanced electricity systems, associated with emissions from the operation of power plant and with the rest of energy chain [6]

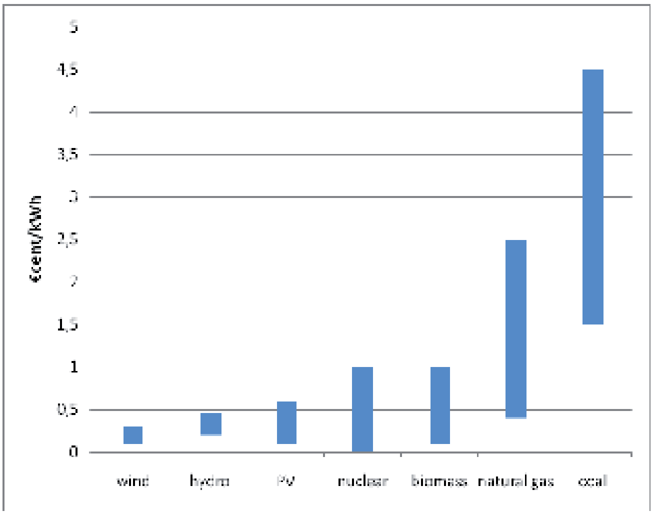

Fig. 10. External cost of electricity generation technologies in Hungary[7]

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[6] Dones R., Heck T., Bauer C., Hirschberg S., Bickel P., Preiss P., Panis L., De Vlieger I., New Energy Technologies – Final Report on Work Package 6 – Release 2, July 2005. ExternE-Pol Project 'Externalities of Energy: Extension of Accounting Framework and Policy Applications', European Commission (2005). Retrieved from http://www.externe.info/expolwp6.pdf

fired plant. Figure 11. shows these ranges, and Figure 12. shows the typical values for the Hungarian emission.

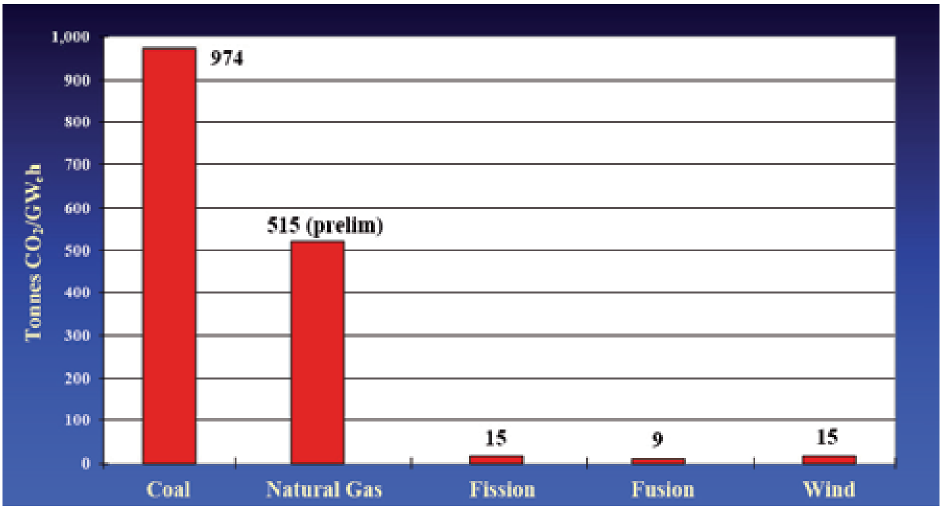

Fig. 11. A set of CO_2 emission data of electricity generation technologies[8]

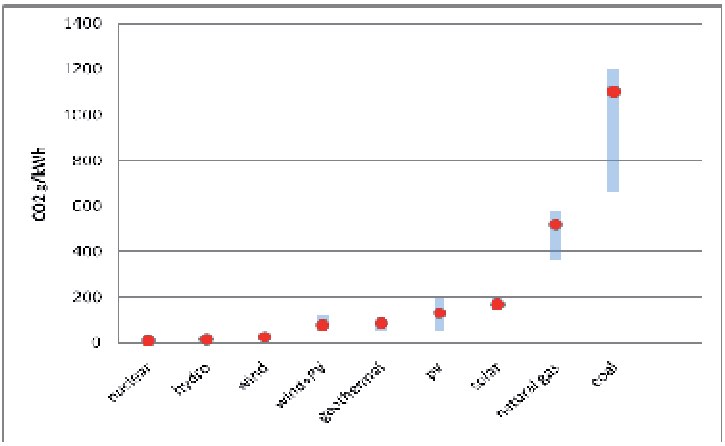

Fig. 12. CO_2 emission of electricity generation technologies in Hungary[7]

5. The ideal power mix

The country/area electric (and heat) demand is easy to forecast. This demand is fulfilled by electricity power generation in the same minutes of the need because the large electricity power is not storable in large quantity. The energy need (during the day) or the power need in a specific time is provided by a set of generators (thousands) driven by different primary

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[7] Study for the Hungarian energy Authority by the Power Consult Ltd.: The externality cost of the electricity production – special focus on the renewable sources, Budapest, 2010

[8] S.W.White – W.H.Readcliffe-G.L.Kulcinski: Life Cycle Energy Cost of Wind and Gas-Turbine Power

energy sources. The actual ratio of these sources, the actual set is named "power mix". This mix can be fully fossil - based of fully renewable, but the typical ratio is 60-70% fossil fuel, 10-30% of nuclear, 5-20% renewable (see Figure 13. – nuclear – orange, yellow – small CHP, gray – large CHP, small - brown – coal, green – gas, blue - import).

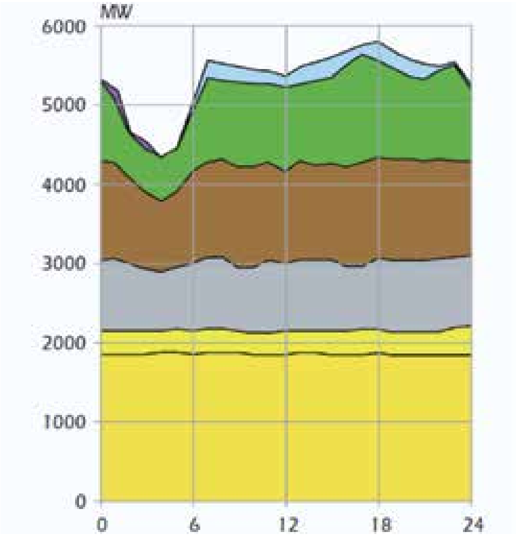

Fig. 13. Daily generation portfolio[9]

Having clear objectives on national or global level the power generation mix should be easily defined by minimizing the harmful effects. The realization is far more difficult. The European Union defined national quotes for the ratio of the renewable energy generation. For Hungary this share is 13% of the total generation for the year 2020. The current share is only 5% that is why new sources must be set up. Each technology has special requirements, effects so it is not easy to say which type must be developed, how the new renewable level should be fulfilled. The Hungarian Energy Authority started a process for the definition of the new generating capacities based on the following criteria:

- definition of the cheapest generation portfolio
- definition of the lowest CO_2 emission portfolio
- definition of the lowest external cost portfolio

The cheapest means that it requires the least financial effort at present but the environmental pollution is not taken into consideration (externality). The CO_2 emission (and other climate changing emissions) can be measured in a relatively exact way. The notion of the external cost is given above. In the following sections we introduce power generation portfolio optimization techniques:

5.1 Optimization

Having known that there are some cloudy targets, that should be reached by constraints and we are going to find the best solution we choose the optimization techniques (Lee & Sharkawi, 2008). There are a lot of optimization applications related to the power industry and power system, as well. (Kádár, 2009 – I, II). In simple cases we seek for Single Objective

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[9] source: MAVIR – Hungarian transmission operator

Optimum (SOO), in other cases we optimize by many aspects (Multi Objective Optimization – MOO). The energy strategy, the definition of the future energy mix is a MOO problem. Nowadays there is a large variety of numerical optimization tools. Further on we demonstrate that the above mentioned data are appropriate for the investigation of the future alternatives. In the demonstration we use SOO. The objectives are in Table 1.

INV	Investment cost minimization
EXT	External cost minimization
CO_2	CO_2 emission minimization

Table 1. Objectives of the optimization

Renewable	**type**	**max. built in cap.**	**max. load factor**	**energy potential**	**energy produced/ built in MW**	**external cost**	**CO_2 emission**
		MW		**TWh**	**TWh/MW**	**MEUR/TWh**	**Mt/TWh**
	nuclear	3500	0,95	29,1	0,008322	2	0,015
	coal	1500	0,75	9,9	0,00657	53	0,8
	CCGT gas	4500	0,8	31,5	0,007008	23	0,5
R	**hydro**	500	0,5	2,2	0,00438	2	0,015
R	**wind**	1500	0,2	2,6	0,001752	1	0,025
R	**biomass (central)**	500	0,5	2,2	0,00438	33	0,4
R	**PV**	200	0,15	0,3	0,001314	2,5	0,13
R	**geothermal**	100	0,5	0,4	0,00438	3	0,086
R	**biogas**	250	0,6	1,3	0,005256	3	0
	total			**79,5**			

Table 2. The data of the power sources

We used the following fixed data in our calculations (see Table 2).

- existing power generation capacities
- enlarging possibilities
- yearly energy demand (today 40 TWh and 50 TWh in 2020)
- load factor
- maximum energy production
- minimal energy production
- external cost/MWh
- CO_2 emission/MWh
- investment cost
- lifetime

Having limited primary energy sources the potential development ranges are limited:

type	**present capacities (MW)**	**potential enlargement in 10 years (MW)**
nuclear	2000	1500
coal	1100	400
CCGT gas	3500	1000
hydro	50	450
wind	300	1200
biomass (centralized)	300	200
PV	1	199
geothermal	5	95
biogas	50	200
total	**7306**	**5244**

Table 3. Power plant development ranges

	investment cost for 1 year for 1 TWh (no fuel and maintenance) **MEUR/TWh**	*externalities (source NEEDS* **MEUR/TWh***)*	*CO_2emission* **Mt/TWh**
hydro	3,42	2	0,015
wind	20,55	1	0,025
central biomass	5,33	33	0,4
PV	30,44	2,5	0,13
geothermal	5,71	3	0,086
biogas	6,34	3	0
nuclear	2,4	2	0,015
coal	1,83	53	0,8
CCGT gas	1,71	23	0,5

Table 4. Technology costs and emissions

The following SOOs were performed:

- CO_2 emission minimization
- CO_2 emission minimization, with 13% renewable share
- Externality minimization
- Externality minimization, with 13% renewable share
- Investment minimization
- Investment minimization, with 13% renewable share

The different technologies have different investment needs (power plant construction), externality cost and CO_2 emission. The common platform is "the cost of a power plant generating 1 TWh electricity". It is calculated from the total cost of the plant, and the total production of its life time (see Table 4.).

The objective function is a mathematical expression that shows the value of the feature to minimize. We have the followings:

1) Investment cost minimization
Minimize value = 3,42 (hydro) + 20,55 (wind) + 5,33 (biomass) + 30,44 (PV) +
5,71 (geo) + 6,34 (biogas) + 2,4 (nuc) + 1,83 (coal) + 1,71 (gas)
2) Externality cost minimization
Minimize value = 2 (hydro) + 1 (wind) + 33 (biomass) + 2,5 (PV) +
3 (geo) + 3 (biogas) + 2 (nuc) + 53 (coal) + 23 (gas)
3) CO_2emission minimization
Minimize value = 0,015 (hydro) + 0,025 (wind) + 0,4 (biomass) + 0,13 (PV) +
0,086 (geo) + 0 (biogas) + 0,015 (nuc) + 0,8 (coal) + 0,5 (gas)

Fig. 14. Objective functions for minimization

All cases take into account the present existing portfolio that is we can only develop (in the green field approach we can stop any plants and we can replace that by wish).

The second step is to set up the different constraints, such as the existing minimum capacities, the possible extension ranges. After having a solution that minimizes our objective function we can calculate e.g. the total CO_2 load, total investment cost necessary, total operation costs. By setting up different constraint sets different alternative development scenarios can be obtained. Regarding the constraints the following limits were built in the model, related to the present situation and the physical possibilities:

- existing power generation capacities (minimum criteria)
- enlarging possibilities (maximum criteria)
- yearly energy demand (today 40 TWh and 50 TWh in 2020) - scenarios
- maximum energy production
- minimal energy production

The constraints are additional inequalities in the equation system that must be solved (see Fig.15.). First we defined an objective function to minimize. This is the total external cost coming from the individual externality of each generation type. The linear programming tool found the solution that meets all the constraints and equation furthermore it produces the minimal externality cost (see Fig 16.).

Table 5. shows the result portfolio of the externality minimization. The total generated energy is 50 TWh, the renewable ratio is 13%. The total external cost is 401 MEUR. Coal and biomass firing is stopped. The CO_2 emission is 7,8 Mt per year. It is almost the half of the present emission.

Setting up different objective functions we get different "optimal" power mixes. All are optimal by a Single Objective (see Table 6.).

The demonstration above shows

- This methodology is appropriate for the qualitative strategy definition
- The energy portfolio definition is a real MOO problem

Externality minimisation
The LP Problem Constraints are:
Maximum quantities in yearly TWh:
1) 1 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) <= 2,2
2) 0 (hydro) + 1 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) <= 2,6
3) 0 (hydro) + 0 (wind) + 1 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) <= 2,2
4) 0 (hydro) + 0 (wind) + 0 (biomass) + 1 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) <= 0,3
5) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 1 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) <= 0,4
6) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 1 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) <= 1,3
7) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 1 (nuc) + 0 (coal) + 0 (gas) <= 29,1
8) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 1 (coal) + 0 (gas) <= 9,9
9) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 1 (gas) <= 31,5
Total energy is 40 TWh
10) 1 (hydro) + 1 (wind) + 1 (biomass) + 1 (PV) + 1 (geo) + 1 (biogas) + 1 (nuc) + 1 (coal) + 1 (gas) <= 40
Minimum quantities in yearly TWh:
11) 1 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) >= 0,22
12) 0 (hydro) + 1 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) >= 0,5
13) 0 (hydro) + 0 (wind) + 1 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 0 (coal) + 0 (gas) >= 1,6
14) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 1 (nuc) + 0 (coal) + 0 (gas) >= 16
15) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 1 (coal) + 0 (gas) >= 5
16) 0 (hydro) + 0 (wind) + 0 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 0 (nuc) + 1 (coal) + 0 (gas) >= 10

Fig. 15. Constraints for the optimization (constraints table)

Externality minimization solution[10]
The optimal externality value is 95,6282 (OBJ FUNCTION)
0,22 (hydro) + 0,5 (wind) + 1,6 (biomass) + 0 (PV) + 0 (geo) + 0 (biogas) + 1,6 (nuc) + 5,0 (coal) + 16,68 (gas)

Fig. 16. The optimized externality result (SOO solution)

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[10] For the demonstration the Archer's Linear Programming Tool was used

hydro	2,2	TWh	biogas	1	TWh
wind	2,6	TWh	nuc	29,1	TWh
biomass	0	TWh	coal	0	TWh
PV	0,3	TWh	gas	14,4	TWh
geo	0,4	TWh	EXT cost	401,35	MEUR

Table 5. Yearly production rate and cost in case of externality optimization

	CO_2 emission minimization	CO_2 emission minimization	EXT cost minimization	EXT cost minimization	INV. cost minimization	INV cost minimization	INV cost minimization	
Total energy	50	50	50	50	40	50	50	TWh
hydro	2,2	2,2	2,2	2,2	0,22	0,22	2,2	TWh
wind	2,6	2,6	2,6	2,6	0,5	0,5	0,5	TWh
biomass	2,2	0	0	0	1,6	1,6	2,2	TWh
PV	0,3	0	0,3	0,3	0	0	0	TWh
geo	0,4	0,4	0,4	0,4	0	0	0,4	TWh
biogas	1,3	1,3	1,3	1	0	0	1,2	TWh
nuc	29,1	29,1	29,1	29,1	16	16	16	TWh
coal	0	0	0	0	5	7	7	TWh
gas	11,9	14,4	14,1	14,4	16,68	24,68	20,5	TWh
REN	18 %	13 %	13,6 %	13 %	5,8 %	4,64 %	13 %	%
CO_2	7,44	7,77	7,65	7,8	13,23,	18,83	17,05	Mt
External cost	**417,35**	**401,5**	**395,35**	**401,35**	**733,94**	**1023,94**	**952,4**	MEUR
Yearly power plant building cost	**182,52**	**165,94**	**174,56**	**173,17**	**95,62**	**112,96**	**125,70**	MEUR
Yearly power plant operation costs	**1304**	**1403**	**1383**	**1401**	**1540**	**2128**	**1882**	MEUR

Table 6. The power generation portfolio development alternatives by different objective functions

- Instead of the politicians the numerical solution provides a good sustainable solution
- The future portfolio is not really sensitive to the amount of energy produced
- It is forbidden to build up an energetic monoculture
- In the current low cost solution the future operation costs are enormous
- The power plant building and operation and externality costs are in the same range

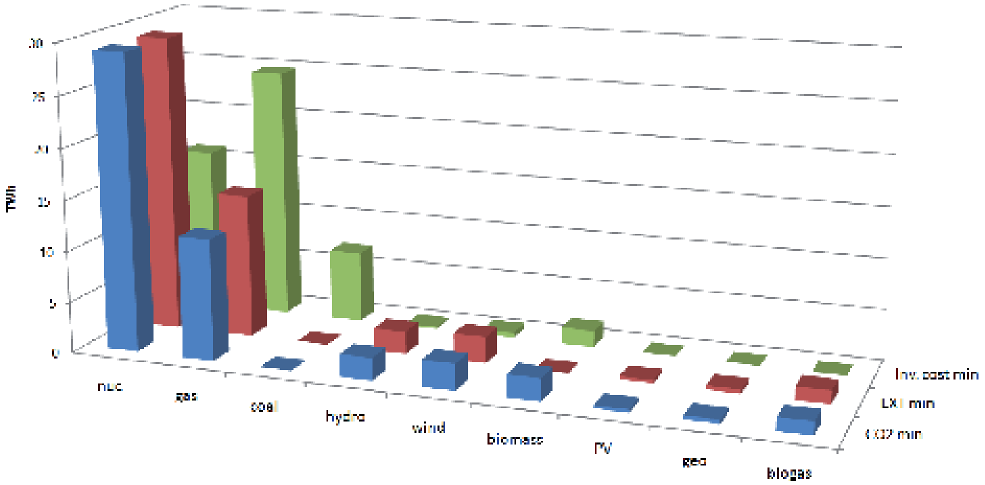

Fig. 17. Visualisation of generation ratios in different optimization alternatives

The optimisation provides the mathematically optimal solution regarding a preference. We always start form the existing situation and take into account the development possibility. Fig. 17. shows e.g. that

- We should not run any coal fired unit if we want to really decrease the CO_2. There is enough non CO_2 emittive capacities (externality and CO_2 minimization)
- On the other side if we want to minimize the investment cost into the power plant (mix) than we must run this type of plants with high load factor, and we can build more gas and coal plant (minimal investment today – maximal external cost in the future).
- The nuclear, wind and hydro capacity plays important role in the externality minimum scenarios.

Fig. 18. shows that the yearly total cost of the fossil based scenario costs more than the renewable generation solution. It comes from the high fuel cost (gas) and externality costs.

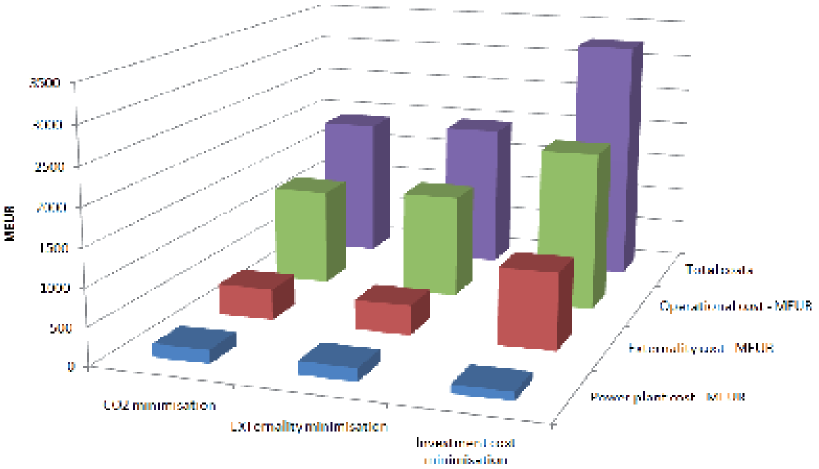

Fig. 18. Yearly costs of the alternatives (MEUR)

From the optimisation we can present other results, too. Figure 19. shows the cost efficiency of the power plant development:
If we had 1 MEUR it is enough to …

- …construct this amount of 'built in power capacity' … – the cheapest is the gas and coal fired plant (green column). If we take into account only the investment only into the construction, we must build more and more gas based plant. But if we count the lifecycle operation (fuel) and externality costs, this is the worst solution!
- … construct and generate this amount of energy (operation cost ~ fuel cost) – (red column) We can generate more energy from hydro, geothermal biogas and nuclear sources. The gas is the most expensive! In the long term planning hydro, geothermal biogas and nuclear (!) solutions are fitting to the relevant criteria.
- …if we pay the externality we get the previous result (blue column)

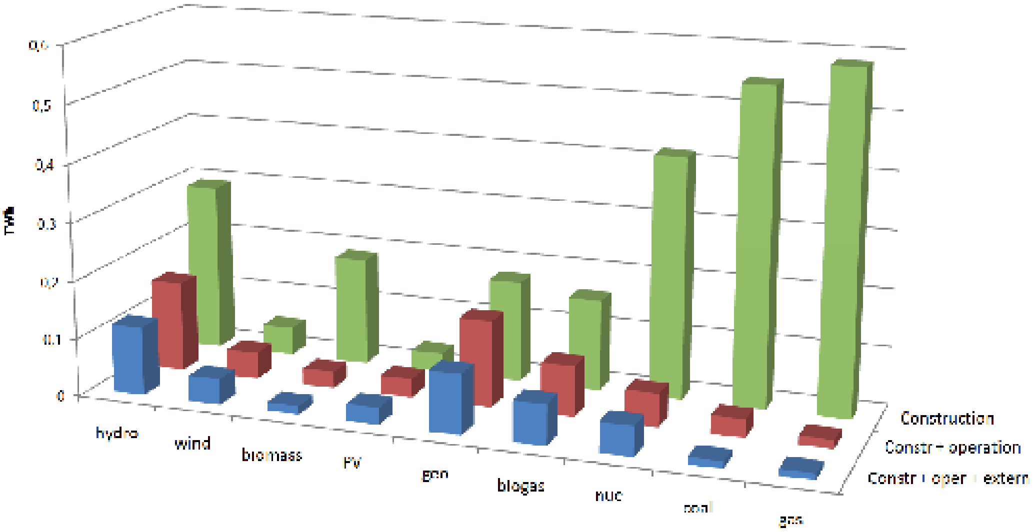

Fig. 19. How much energy can be generated from 1 MEUR?

These calculations demonstrate that the rough SOO produces really distinct scenarios so it is not recommendable to use only the cheapest OR smallest emission version.
As conclusion we can state that

- The CO_2 minimum and external cost minimization produces recommendable scenarios
- The simple cost minimization implies huge CO_2 emission
- The gas (and oil) fired plants are cheap to build but expensive to run for the fuel cost and CO_2 production
- The wind generation is welcome
- All portfolios contain hydro generation
- The bulk central biomass firing is not the part of optimal mix
- All the alternatives contain nuclear generation (do not forget that any other pumped storage plant raises the external costs)

More detailed optimization with exact input data provides real results. We recommend this method for the national planning level too.

6. New technologies

Here we count some novel, but not widely spread - over technologies that can decrease the emission of the energy industry.

There are different ways to decrease the CO_2 emission of the power technologies. These are:

- through the decrease of the amount of the used electricity less generation and less primary source can be enough (raising the energy efficiency, energy thriftiness)
- raising the electrical efficiency of the generation – less primary source must be burned for the same amount of electricity: Combined Heat and Power generation CHP; combined cycle power plant (CCPP); combined cycle gas turbine (CCGT)
- trapping the exhausted CO_2 (Clean Coal Technologies)
- changing the generation portfolio, instead of fossil fuel some CO_2 neutral techniques were used (nuclear, renewable)

6.1 Decreasing the amount of used energy

The efficiency raise helps to use less energy for keeping the same comfort level. The low consumption computer monitors, the energy saving fluorescent lamps and the heat isolation of the buildings foster this objective.

The unlimited following of the energy need requires the usage of peak power plants, too. The passive Demand Side Management (DSM) decreases the total amount of the used electricity through the efficiency raising. The active DSM reschedules the volatile power demand, the peak demand is decreased and pushed into the night time demand valley. Instead of the expensive and fossil peak generators more basic plants, e.g. nuclear plants can operate. To realize powerful demand side management in the deregulated power business environment is a great challenge (Lorrin & Willis, 1999; Shahidehpour, 2001).

The Smart metering and the Home displays can inform the customers about his energy consumption habits, so through the energy consciousness the consumption can be decreased.

The Smart grid technology accepts more renewable sources in the network, the storage technologies helps the balancing the load.

6.2 More energy by the same amount of CO_2

Traditionally electricity was generated in power plants and heat was produced in the heating central. In the co-generation approach useful electricity is also generated when some heat is needed. This is made by "traditional" gas engines (0,5-5 MW) or gas turbines (10-50 MW) with 30-50% electrical efficiency. The exhaust gas heat (mainly gas firing units) is turned into the remote heating system or industry process through heat exchangers. By co-generation almost 80-90 % of the primary energy can be harnessed.

The combined cycle technology uses the heat of the exhaust gas of the gas turbine (CCGT) but by this heat is steam generated that runs a secondary steam turbine and generator. By the utilization of the "second hand" heat the total electrical efficiency of the power plant can hit the 60 %.

6.3 Low emission technologies

The third way to decrease the 'per kWh CO_2' emission is the application of low emission power generation technologies. There are more techniques for heat and electricity generation too:

The combustion of the fossil fuel produces CO_2. By trapping this gas emission the energy production can be almost CO_2 emission free. There are new technologies under development ant test how to catch the gas: pumping it with high pressure underground storages, as depleted gas field, oil reservoirs, saline or deep sea reservoirs (Clean Coal Technologies, Carbon Capture and Storage - CCS). These methodologies decrease the overall electrical efficiency of the plant with 10-15% and require high investment cost. The final result is higher specific production cost that is not always competitive in the market.

Fig. 20. Solar through plant in San Lúcar de Mayor, Spain

6.4 Renewable sources

The renewable production has no CO_2 emission during its operation per definition. By the way in the whole life cycle (construction, maintenance, dismounting) it requires additional energy that has emission. The "during operation CO_2 free" technologies are the wind, PV, geothermal, biomass and the traditional hydro. Most of the renewable sources have relatively small unit power, and places spatially distributed (Lee & Scott, 2000).

Solar irradiation

Most of the renewable sources use the energy of the solar irradiation. The direct solar-heat-trapping heat towers are in experimental phase (see Fig. 21.). The solar trough technology is close to the commercial application (see Fig. 20.). The solar heat collectors are commercially available for decades. The global newly installed solar collector capacity in 2009 registered 48.8 million m^2.[11]

The sun heats the atmosphere to various temperatures, it starts turbulent flows around the globe. The wind turbines catch a part of this motion energy (see Fig. 22.). The world's total wind capacity at the end of 2009 is 150.000 MW.[12] One can't forget that the overall load factor of these plants is around 20% only.

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[11] Bank Sarasin sustainability study on the solar industry: benefiting from rising demand; http://www.sarasin.hk/internet/iesg/index_iesg/about_us_iesg/media_relation_iesg/news_iesg.htm

[12] http://www.windea.org

Fig. 21. Solar tower in San Lúcar de Mayor in Spain and solar collectors in Hungary

The photovoltaic (PV) generation origins from the semiconductor technology. The PV panels transform the solar radiation into Direct Current (DC) electricity with 7-20% efficiency. This is a superb solution for the island mode and hybrid supply (Patel, 2006) but in most cases the PV plants (up to some MW) are connected to the grid (see Fig. 23.). The yearly load factors of the PV systems are between 11-18 %. At the end of 2009 already 22.999 MW [13] PV capacity was installed all over the world. The specific generation cost closes to the traditional technologies.

Fig. 22. Wind turbine in Inota, Hungary. In the background is an old coal fired plant.

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[13] Solar photovoltaic electricity empowering the world; 2011 http://www.epia.org/publications/epia-publications.html

Fig. 23. PV array in Patra, Greece

Biomass

The idea of the biomass based energy production is that the CO_2 produced by the material or gas burning after years will be built in the newly grown forest or plantation. It secure an eternal cycle, the amount of the CO_2 is not increasing in the atmosphere. The problem is the additional emission of the fertilization, cultivation, harvesting, transportation that never pays back. In case of biomasses not only the CO_2 neutrality but for the external energy input and the energy balance must by investigated too.

The primary biomasses as the forest wood (dendromass) or agricultural rests (sugarcane rest – see Fig. 24., wheat stalk, etc.) used to be burned or gasified by pyrolitic technologies. In some countries it makes the base of the renewable electricity production. For the non standardized fuel the flue gas can contain a lot of unwholesome compound. The energy balance fall over if more than 600 km of transportation of the fuel materials is necessary. The typical measure of the biomass units are between 2-30 MW. The perspective way of the biomass based energy generation is the small, distributed CHP plants.

The secondary biomasses as manure or rests of animal processing in the food industry are produced independently from the energy needs. After some months these organic materials for the disorganization turns into methane too that is a really harmful GHG. The idea of the biogas generation is to speed up this decay process by a fermentation process and then to burn the gas arose that contains approx. 70% of methane. This accelerated methane conversion (into CO_2) decreases the greenhouse effect and the climate change. The energy production plays second fiddle.

The metropolitan and urban life produces a large amount of wastewater that contains sludge that is hazardous waste what must be handled. The up-to-date solution is the mezofil or thermofil fermentation by bacteria that produce biogas what contains 70% of methane. This gas can be burned in gas engines (0,1 - 3 MW) producing electricity (see Fig. 25.). The end product of the process is the neutral, solid, savourless material that can be used as fertilizer in the agriculture. By this technology 30-80% of the electrical energy need of the waste water treatment can be generated so this process will not be net electricity producer.

Fig. 24. Sugarcane burning biomass power plant, Mauritius

Fig. 24. Biogas facility in Budapest, Hungary

The situation is similar at the tertiary biomasses. The recent human civilization produces millions of tons garbage, tires, sewage etc. During decades it will become methane partially. The typical handling is the unburdening. The best solution were the total recycling (zero waste city concept), the worst is the littering. A relative good solution is the incineration of the urban garbage where the material is chemically stabilized, energy is produced (heat and electricity – see Fig. 25.), the methane is conversed into CO_2 and the volume is compressed in 23%.

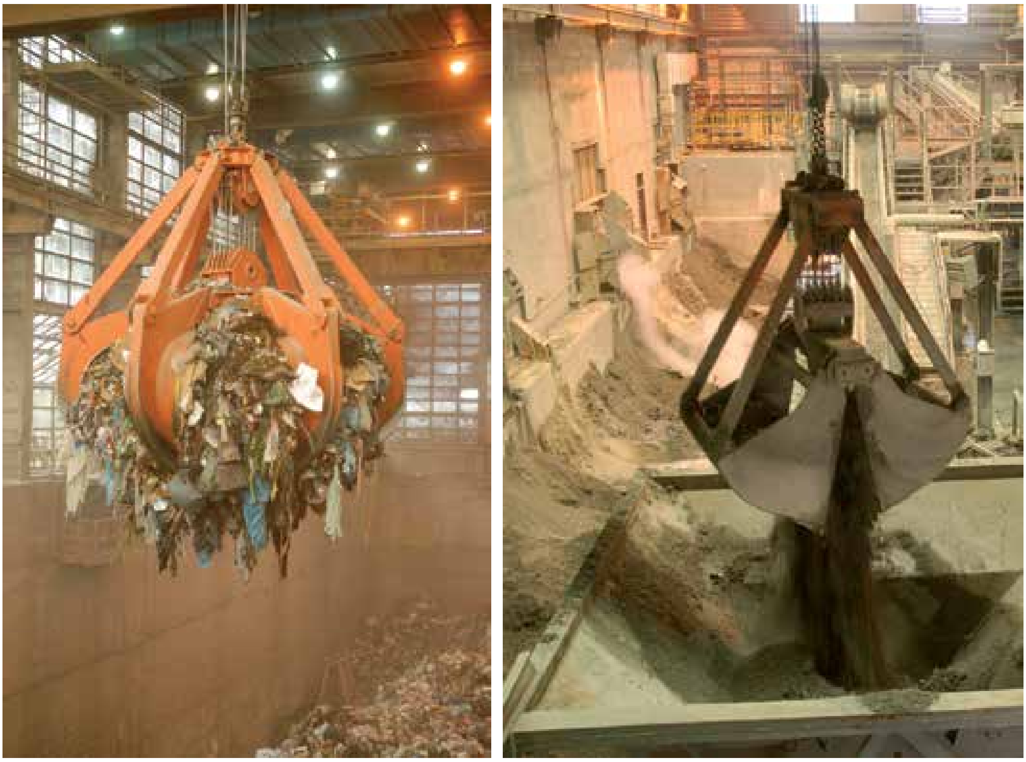

Fig. 24. Garbage before and after the incineration, Budapest, Hungary

Geothermal energy

The interior of the globe consist of a high temperature molten material. Some parts are not too hot, but enough hot to explore heat. The low temperature *geothermal energy* is used as hot water for heating buildings (approx. 80°C – see Fig. 25.). The high temperature water (steam approx. 150°) used directly in steam turbine (free steam emissive system) or with the help of a heat exchanger (binary system). Although the geothermal energy source in our life is unfailing, at the end of 2009 almost 10.500 MW[14] geothermal based electrical plant was installed. The typical unit measure is less than 100 MW. The fuel is priceless, for the high investment cost this type of the generation is not really competitive (expensive drilling, plant devices).

Hydro plants

The traditional hydro plants have the widest measure variability from some kW up to 20 GW (see Figure 26.). The hydro power is free, renewable and CO_2 emission free, but…

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[14] Geothermal Development Expands Globally;
http://www.renewableenergyworld.com/rea/news/article/2009/05/geothermal-development-expands-globally

Fig. 25. Geothermal well in southern Hungary

During the last century, in the thousands of real applications a lot of experiences are gained which harmful effects should be avoided by a new hydro plant construction: water quality, earthquake, drought, agriculture, etc. The value of the water sometimes is higher than the price of the electricity that can be generated by it.
Decisions should be made warily…

Fig. 26. Hydro reservoir in Bihor Mountains, Romania

7. Drivers and barriers

One should ask, if the CO_2 emission has a significant role in the global warming, why we do not switch to low emission technologies? The power plant capacity development is demand driven, the present philosophy is: Generating as much energy as needed. The choice of the power plant type is influenced by not only the price, but the area usage, unit measure, the specific investment cost, the sensibility for the fuel price, the political stability of the fuel producing region, the water usage, the life time, etc. Among the dozens of aspects nowadays the emission is going to get more importance.

The decision about a new power plant construction (yes/no or how large, etc.) is often made in the STEPLE frame:

- **S**ocial (Employment; Right to energy access; Social mission; value of human positions - bureaucracy; etc.)
- **T**echnological (Security of supply; Quality of energy; Efficiency of production and usage; Standardisation; Integration)
- **E**conomic (Costs; End price of the energy; Growth rate of the economy; Profitability, ROI; Accumulation of the investment/development; Lifetime of the assets; etc.)
- **P**olitical (Role of the state decision/subventions; Priority of energy supply; Group interests/lobbying; National interests; etc.)
- **L**egislation (Number of the rules; Strictness of penalties; Controlled competition; Entry barriers; Corruption factor; Cooperative work between the players; etc.)
- **E**nvironmental (Greenhouse effect – EMISSION; Used/wasted materials; Area destruction; Ecological destruction; Energy resources; etc.)

The emission has weak positions nowadays…

8. Conclusion

In the fight for the sustainable industrialized age the energy industry has no good position. It is responsible for one third of the CO_2 emission and we cannot expect any change in the short future (growth of energy need, small unit measure of the renewable generation forms, relatively high direct costs). We have shown that the technologies and its emissions are well known so by a clear mathematical optimisation we could plan the optimal power mix. Also there are many CO_2 decreasing technologies, as the raising the energy usage and generation efficiency, trapping the exhausted CO_2 or changing the generation portfolio to non fossil fuels.

All the energy generation technologies have disadvantages but the decision space is wider than the simple short term profit maximization. The politicians should maximize the long term advantages (or at least to minimize the harmful effects) taking into account the long term external cost.

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12

Alternative Energy: Is a Solution to the Climate Problem?

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1. Introduction

Our position is clearly in favor of alternative energy and they can and must be the solution to fossil fuels, as well as a means of slowing climate change which we are witnessing.

The world is doing many efforts to mitigate climate change, researching and developing various sources of the renewable energy such as wind, photovoltaic, solar, tidal, geothermal, aero thermal, bioenergy, undimotriz or hydropower, They will be overshadowed by the use of some countries like China or India of massive amounts of coal, which generate huge emissions of CO2. This can lead to result in many developed countries resort to the use of coal to be competitive in this field.

As shown in multiple studies, alternative energy may be the weapon of the future in energy production, fossil fuels being relegated to a residual employment. Many countries are turning to so-called intelligent buildings for energy saving, with photovoltaic solar panels that provide electrical energy to the building or buildings with geothermal energy. This is still starting.

Other countries are designing models for efficient energy production from the oceans and seas, tidal energy or undimotriz energy. Although, like other renewable energies are in initial processes.

This leads us to consider for the moment, as it indicates, are alternative energy, namely, they not yet ready to be a substitute for fossil fuels and for the time being complementary energy from fossil fuels. At this time, these energies can not make the various societies to abandon the use of petroleum and its derivatives as energy.

We in this chapter we will try to address not a source of renewable primary energy, but an energy vector, the hydrogen. This, in the future may be the replacement of fossil fuels.

However, despite the efforts of some countries, we are still far from turning the hydrogen energy future, and being the main energy source that solve our energy problems and climate change.

2. Hydrogen and energy

Hydrogen is the most abundant chemical element in the universe and under normal conditions is in a gaseous state. The hydrogen is the most common and ubiquitous of the chemical elements. Hydrogen is an inexhaustible energy. Despite being the most abundant, but he is not pure in the nature, but is present as molecular or ionic.

As noted Jodra Gutierrez (2005:50) the hydrogen reservoir in pure state is found in Jupiter. It is inaccessible for the moment.

Therefore, hydrogen is not a primary source of energy but a vector, and therefore needed to obtain chemical decomposition of the element that he is associated. The most common way to find the hydrogen is in the water, to obtain it must be separated from oxygen by supplying an electric current (electrolysis) on a primary energy source.

A cost effective way to obtain hydrogen is to use renewable energy sources (wind, solar, geothermal, and so on.).

On consideration of hydrogen as an energy vector appropriate to highlight a number of characteristics: 1) low boiling points and proximity to the critical temperature. 2) Low densities of gas and liquid, 3) the content of deuterium, which may be one of the foundations of nuclear fusion (Jodra Gutiérrez, 2005: 50-51).

The most attractive features to hydrogen as a transmitter of energy are in cleaning. In the absence of carbon in the transition process to generate energy that does not produce CO2 emissions. Secondly, it is energy potential (Valero-Matas, 2010:433). Cleaning and energy potential opened up great expectations for climate change advocates, and some car companies saw a new kind of engine with hydrogen fuel. Science and technology have spent decades trying to find or design suitable components to make hybrid vehicles competitive with petrol cars. For now, hybrid cars are powered by so-called fuel cells or fuel cells.

3. The hydrogen economy and social impact

When we refer to the social effects produced by something, it should define what is going to be evaluated, then proceed to the analysis of the facts. This requires a life cycle assessment and impact of technology, becoming part a series of elements such as economic, environmental, social, health, risk, human needs, sensitivity, development objectives of society and political impacts decision making.

Therefore, taking these issues on the horizon, and emphasizing that the implementation of technology can never make the risks significantly outweigh the potential social, as any damage to the citizenship for their implementation, and undermining their quality of life instead of getting beneficial technologies reported. Reflect on the effects of the hydrogen economy.

Depending on what the source of production of hydrogen vary substantially the price. Given this fact we must ask two questions: If the question is to eliminate energy dependence on fossil fuels, or reduce the emission of CO2 into the atmosphere. According to the election, the effects on the social impact vary substantially. If the intention is to reduce emissions of greenhouse gases as stated in previous sections, the current method of producing hydrogen via natural gas is the most profitable. Companies, universities and research centers continue to explore different components to reduce costs, making it competitive and produce fewer emissions of CO2.

Another way is through acquiring hydrogen from biomass. The energetic use of the biomass is the gasification, which allows obtaining gas of synthesis (CO + H2). The synthesis gas obtained can be used as direct fuel, as well as H2 source or chemical feedstock to make other fuels. The production of hydrogen by gasification of biomass is an interesting option, it has the advantage over the conventional (steam methane reforming of water) to use a waste and not a chemical feedstock. It arises as a hope to the energy consumption, though it issues CO2 there diminishes the dependence of the fossil fuels. It has an important disadvantage, his corrosive effect reducing considerably the life of the fuel cells and pipelines of transport.

On the other hand, if you wanted to eliminate the dependence on fossil fuels and emit no CO2, the process is quite different. To achieve carbon-free hydrogen the most common is water, and electrolysis treatment. This method requires a lot of energy to break water molecule and split it into hydrogen and oxygen. The power supply either through renewable energy or nuclear energy is higher than that after the hydrogen is exploited. For example, a kilogram of hydrogen produced through natural gas comes to cost about 2 €, where 45% of its production is due to the cost of natural gas. According to the current price of electricity, a kg of hydrogen produced by electrolysis would cost about 5€, where 85% of product cost is the price of energy. In other ways, depending on a broad range of factors, an estimate would be around roughly between 3.5 € per kg to 8 € per kg of hydrogen.

To this must be added transportation costs, marketing, so on This issue is important to reference when analyzing the economic impact of a product over another. This will appreciate the difference in cost and economic impact on a society.

Another investigation that is under development is the production of hydrogen from green algae. More than 60 years ago it was discovered that a microscopic green algae, -whose scientific name is *Chlamydomonas reinhardtii* and we all know as the ponds scum -, can split water into hydrogen and oxygen in laboratory conditions. The possibility of using algae as microscopic power plants were the brainchild of Hans Gaffron, who observed in 1939, "for reasons unknown at this time, which stopped producing algae began producing oxygen and hydrogen for a short period. Green algae have a hydrogen-producing enzyme known as iron-iron hydrogenase which has evolved a structure that makes its particularly susceptible to attacking oxygen molecules. Green algae can produce hydrogen gas, H2, in a process called "biophotolysis" or "photobiological hydrogen production. This process is carried out by photosynthetic enzymes, which split water to get electrons, photons excite electrons, and finally, use these electrons to reduce 2H + to H2. The scientific challenge associated with this approach to hydrogen production is the enzyme that actually releases the hydrogen, called "reversible hydrogenase, is sensitive to oxygen. The process of photosynthesis, of course, produces oxygen and this normally stops the production of hydrogen very quickly in green algae. A team of biologists led by Raymond Surzycki Jean-David Rochaix and the University of Geneva, and Cournac Laurent and Gilles Peltier, both from the Atomic Energy Commission, National Center for Scientific Research and the University of the Mediterranean, the algae cell research "Chlamydomonas reinhardtii" that through the use of copper in the cells to block the generation of oxygen, it achieves a cycle of hydrogen production.

Algae to produce hydrogen, they must have sunlight and be in an anaerobic environment (without oxygen) to prevent oxygen toxicity to the top eventually responsible for hydrogen production. The alga synthesizes up "hydrogenase" that is ultimately responsible for producing hydrogen by combining with electrons derived from photosynthesis.

Another strategy is to modify the hydrogenase using genetic engineering to be more tolerant of oxygen

One might screen microorganisms in nature for the presence of oxygen-tolerant hydrogenases. The genes of these enzymes could then be introduced into algal cells and tested for hydrogen production under less stringent anaerobic conditions. This is the case of Dr. Melis of the University of Berkeley has managed to "design" a seaweed that contains less chlorophyll density, or that is, is more transparent. This means that sunlight can penetrate deeper into the mass of algae without being stopped by floating on the surface layer, leading to increased production of hydrogen in the amount of algae. Genetic modification of algal chlorophyll density decreases from 600 to 300 in the chloroplasts, the body of the cell where photosynthesis takes place. During normal photosynthesis, the algae use sunlight as energy to convert CO2 in water and glucose, besides providing oxygen to the atmosphere and a small amount of hydrogen.

According to Melis acres of algae could produce about 200 kilograms of hydrogen for day

To realize a balance sheet of the production of hydrogen not only attends to the final values of consumption and money-cost, also involved and the resources needed for production. In this case, tons of water needed to produce hydrogen fuel. Only in the United States was estimated in 2006 (Norskov and Christensen, 2006:1322-1323) about 150 million tons water per year to meet the transportation needs, if this is added, the demand for buildings, business and domestic use, consumption shoots to 500 million tons per year in USA. Does society and water resources and energy are prepared to meet this challenge, the hydrogen economy?

The fuel cells, they are the gadgets needed to transform chemical energy through a substance into electrical energy, and make it work external combustion engine. Currently, there are different types of fuel cells, suitable to various needs and demands. As the alkaline fuel cell (AFCs) that performs better. NASA uses this type of fuel cell in their space activities, but presents a major problem, its high price. Why is this price so high? Basically its components, the catalysts used are platinum / ruthenium, electrodes contain large amounts of noble metals, for example, the anode can be made with platinum and palladium, and gold and platinum cathode, if this is happening worldwide, decreasing costs is impossible, because the demand for gold, platinum, palladium and ruthenium are fired, increasing the value of these metals by the scarcity and the need to use. In the case of reaching the market, would be a matter of asking him, because if the oil runs out, the noble metals also. And on this there is a greater lack of durability. In the immediate future no one can see a drop in prices in the world there are millions upon millions of cars and their production is increasing.

In an attempt to make viable hydrogen-powered vehicles, automotive companies have developed a technology stack PEM (Proton Exchange Membrane) rather the product cheaper. The problem is not solved completely, because the platinum catalyst remains. Returning to the same matter, and if you choose to design all hybrid cars with this type of batteries, the fired platinum price, increasing the cost of the fuel cell. Enter the fray again the question of durability. Platinum is perishable and we are talking about millions of cars and piles of life between 10 and 15 years at best, and do not forget that the noble metal platinum is a finite.

At this point, several developments have occurred in lower prices and fuel cell performance without precious metals from catalysts. The research of Barnett and Zhan (2006) have developed a new fuel cell solid oxide, or SOFC, that converts iso-octane, high-purity compound similar to gasoline, hydrogen, which is used by the cell to energy. Also developed by the team of Michel Lefèvre et al.,which have taken a giant step to reduce costs, using new catalysts that use iron instead of platinum without performance degradation. Iron-based catalysts for the oxygen-reduction reaction in polymer electrolyte membrane fuel cells have been poorly competitive with platinum catalysts, in part because they have a comparatively low number of active sites per unit volume. We produced microporous carbon–supported iron-based catalysts with active sites believed to contain iron cations coordinated by pyridinic nitrogen functionalities in the interstices of graphitic sheets within the micropores (2009: 72).

Store large amounts of hydrogen safely and cheaply, and enable its use (through fuel cells or direct combustion) is another challenge for this product. Hydrogen can be stored in different ways: aerated, high pressure compressed, liquid, by chemical or carbon nanostructures (Fakioglu, Yürüm y Veziroglu, 2004: 1373-1374). Currently, hydrogen is the most used aerated, transported in cylinders and high pressure gas. This form of storage is not optimal if you are used as energy for a vehicle, due to the high volume of these cylinders. If the interest is in providing a group of houses (as they currently do propane tanks) will need a silo which will triple the amount currently used by the propane storage tanks. This is easy to observe, one must look at the main tank (where the liquid hydrogen) of the space shuttle, whose volume is greater than the aircraft itself[1]. Gasified hydrogen tanks must be made with special materials that maintain safety and avoid the risk (Kreith y West, 2004). The chemical composition involves hydrogen use by many transition metals and alloys to store hydrogen in metal hydrides. This process presents a major problem, the heavy weight of the storage system as a result of low levels of hydrogen retention are achieved (Conte, *et al.*, 2004:6).. Finally, carbon nanostructures involve inserting inside a solid material at a temperature and pressure to later extract it with other values of pressure and temperature. This form of storage can accumulate a larger amount of hydrogen in volumes of the above dimensions. It is not the optimal model, although recent research has put a glimmer of hope to the nanoparticles such as hydrogen storage system (Aguey y Ares, 2008). .

The liquid hydrogen and hydrogen gas under pressure are the most widespread in the storage and transportation of hydrogen. In the case of hydrogen gas under pressure for transport, some suggest the network of natural gas pipelines. This is not possible because the natural gas will still be using for many years. In the course of doing so for the same natural gas pipelines, they do not serve as the fragility of the steel in the hydrogen makes the pipes require special insulation, carbon fiber for example. Therefore implies a high cost. The other option corresponds to submit to high pressure and hydrogen storage. For transporting liquid hydrogen needs to be exposed to hydrogen at a temperature of -252 degrees Celsius, that is to say, cryogenic fuel. In the United States, NASA and companies working with liquid hydrogen is transported in cryogenic tanks either truck, rail car or barge specially prepared. Bossel and Eliasson (2003) advise against this practice as domestic consumption for two reasons: 1) The power consumed by a tank of pressurized hydrogen becomes a significant fraction of the energy content of hydrogen consumed. For example, for a supply of 40 kilometers, the energy used in the route of supply is equal to 20% of the hydrogen energy delivered. 2) You need a great transport fleet. As the ratio of 15 trucks of hydrogen for a fuel truck 25 tons. Select this possibility is irrelevant and irrational. First, the truck fleet overflows traffic; its implementation would entail a considerable increase in jobs. Secondly, the hydrogen fuel would shoot.

Safety is another important principle in assessing the impact of technology on society. As announced in its day Beck (1998) we face the risk society, it symbolizes not take more risks than necessary, and many are the result of side effects of technology. Regarding the safety of hydrogen there is no common approach. Some as Braun (2003:114) attest to the high security of hydrogen compared to other fossil fuels, and indicate that the numbers of accidents

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[1] NASA to reduce the weight and volume, special alloy used the product too expensive. The current alloy of aluminum and lithium, which approximate price hydrogen tank is approximately $ 6 million.

resulting from hydrogen are currently about 1%. In contrast, other theorists believe hydrogen more dangerous than gasoline (Hordeski, 2005:25).

Hydrogen cars are the best opportunities in life, certain companies Ford, Toyota, Honda, Volkswagen, Chrysler, and so on. have developed hybrid cars combining petrol and electric power, reducing fuel consumption and therefore CO2 emission. These cars have greatly two problems: 1) the need to introduce two motors inside, increasing the size and reduce the space for passengers or trunk, 2) the price of a hybrid between 12,000 € and 18,000 € more than a petrol or diesel, depending on model and automobile company.

Another idea lies in the use of clean hydrogen, ie 100% hydrogen car, whose impact will be of another magnitude. As happens with vehicles powered by gasoline or diesel fuel will need storage, but in the case of hydrogen as the volume is larger deposit is needed a larger and heavier, added to the engine problem, determine the size of the vehicle. For benefits equal to their gasoline counterparts need more power, resulting in higher consumption and cost. A liquid, the evaporation capacity of hydrogen is very high. A NASA study (Los Alamos) showed that in ten days had evaporated hydrogen from a tank car.

The environmental impact to a hydrogen economy would be the ideal of sustainability, but only when conditions were appropriate. And this is not the case. To stop issuing between 70% and 80% of CO2 into the atmosphere, it would mean the possibility of regeneration in a relatively small space of time, as well as, improve air quality in cities, especially the most polluted as Mexico. Even with only operate worldwide with hydrogen cars, only the issuer would reduce greenhouse gases by 20%. These values refer to hydrogen fuel with no carbon. Not taken into account, the hydrogen obtained from natural gas. If your application is given in optimal conditions, the hydrogen would be a sustainable energy vector.

Political action of this magnitude, in a globalized world where oil is currency, and the big multinationals of oil and oil producing countries are strangling the world economies, it would happen to be a history. The decision would not prevent the various problems announced by Rifkin (2002). Some of them even become worse over. Rifkin declares that with the economy of the hydrogen it was coming near to a social justice, prosperity and equality.

This will not happen; the hydrogen economy requires a very high technological level which lacks the most disadvantaged countries and oil producing countries. The formation of the citizens of these countries is very limited. Therefore continue to rely on the industrialized countries (first world). Second, if the technological and production levels depend on first world countries, how will they be able to produce such materials, wind turbines, photovoltaic systems, water electrolysis, fuel cells, and so on? Especially, when some living on the threshold of subsistence, and even below. How can promise the power of freedom? The incursion of the hydrogen economy in society will produce an unprecedented social change and energy; we might even attend a social revolution. Your application will not only transform the concept of energy also ways of life.

4. Hydrogen economy may be the solution to dependence on fossil fuels?

There is every reason to not consider the economics of hydrogen energy as XXI century, for example

a. The inability to produce hydrogen for all cars in the world. And not just the millions of existing vehicles, but the millions of cars to the growing demand from China and India (remember that these countries are the main cause of increased oil).

b. The necessary water to produce this quantity of hydrogen. We are before a problematic substance since it is the water. His shortage has led to the War to several countries. With the time they will be sharpening before the major shortage of this liquid.

c. The cost to address the need to produce hydrogen through electrolysis. This is not resolved in the same terms as the oil where a plant can refine million tons of crude oil. The hydrogen production plants have less capacity, so it will require thousands.

d. The number of hydro and other tools necessary for citizens to fill up your fuel tank, regardless of the proposal (more media than real), Rifkin (2002) that all citizens have a hydrogen charger at home or with a proximity 10 meters.

e. The costs in their development, production, storage, distribution networks, product modification and furnishings of everyday life (adjustment of housing supply hydrogen, cooker, washing machine, and so on).

Today, most hydrogen is produced from natural gas through steam reforming of methane, and although this can be understood as a first foray into the hydrogen economy, represents only a modest reduction in emissions from automobiles hybrid vehicles. Along with this model also can use the electrolysis of water, heat, wind, geothermal, solar and biomass processing (using a variety of technologies ranging from reforming to fermentation).

The Biomass processing techniques can benefit greatly from the wealth of research carried out over the years in refining and fuel conversion of liquid and gaseous fossil. Biomass can be easily converted into liquid fuels, including methanol, ethanol, biodiesel and pyrolysis oil can be transported easily and generate hydrogen on site. Although biomass is clearly (and necessarily) sustainable, it can be transformed into the hydrogen supply taking into account the amounts required for global hydrogen supply. Fundamentally, the limitation of food as it has been observed with ethanol driving up grain prices. Still, even if they can pay the money, would leave the neediest people without food. On the other hand, continues to emit CO2 to the atmosphere, to a lesser extent. It is clearly not sustainable. Hydrogen energy may not be a substitute for fossil fuels by the huge amount of problems and impossibilities that make it unfeasible

Hydrogen energy may not be a substitute for fossil fuels by the huge amount of problems and impossibilities that make it unfeasible. The hydrogen economy was again a false alarm, before the world need to address energy issues have taken place in the world. This may be another case like cold fusion. Where they had placed many hopes, it did not produce environmental impact of nuclear waste were not hazardous and generated large amounts of energy.

In 1989, Pons and Fleischman scientists announced they had achieved cold fusion production with the corresponding energy release. It was all a hoax. Why?, it is quite clear, when in the 70's of last century opened the door to cold fusion research, scientists, politicians, enterprises, and so on, saw it, the energy solution and began to demand research, funds and materials to address the issue. After much money spent, time and human capital, it has not seen results. To avoid abandonment of the project, the researchers invented the fraud. Hopes were cooled cold fusion. Although there is research but are being developed with less enthusiasm and expectations of previous years. Pass the same to the hydrogen economy, this will not be a hoax but it will be a succession of isolated research and she will not be motivated by a project of general interest. At the bottom of this issue, there is another political reality commercial interests, and do not forget the politics and economics, is that the potential importance of hydrogen as an energy carrier may seem exaggerated, but very significant. The energy value of hydrogen as a substitute for oil is the main objective of the policies of OECD countries, occupying a secondary interest environmental benefit (Andrews, 2005:24). Like there is no economic profitability, the project will suffer a drop, though, this energy carrier is important to keep clean our planet from greenhouse gases.

5. Conclusions

The future of energy is now a major concern in Western societies. The increasing economic development had in the world -especially for industrial development in the India, China and Brazil- as a result of globalization, it has brought an increase of the energy consumption, and with the current model is not able to cope in the next years.

The direct effects have been a progressive rise in energy prices and an increase in CO_2 emissions. Given this reality, there is a consensus on the need to make to develop a new energy map where renewable energize control yourself take the place: solar energy, wind energy, tidal energy, biomass energy, and so on., hydrogen and even nuclear energy, and thus cope to the demand and energy supply care for the environment. For a decade it seems that research on renewable energy is new, It is, as if it was own of the 21st century. But we must not forget that the 1973 oil crisis also entailed to the emergence of many investigations to find one or more energy to help us to leaving from fossil fuels.

The oil crisis in 1973 prompted research on biological hydrogen production, including photosynthetic production, as part of the search for alternative energy technologies. Green algae were known as light-dependent, water-splitting catalysts, but the characteristics of their hydrogen production were not practical for exploitation. A continuous gas flow system designed to maintain low oxygen concentrations within the reaction vessel, was employed in basic studies, but has not been found practically applicable (Greenbaum, 1988).

Based on such research is developing the hydrogen economy is still far from being the energy of the future

The efforts being made by developed countries are inadequate and in our opinion. are more oriented to solve political problems which really become energy, as said Rifkin (2002), freedom.

Obama decided to drop in 2009 to aid the investigation of the hydrogen economy for the electric car, since it perceived as more viable, especially more profitable.

Europe has established in the year 2020, 20% of the energy consumed comes from renewable energy and from 100% in 2050. From the perspective of maintaining a clean environment is good news, but in order to achieve this there must be a common policy designed to achieve sustainable development using renewable energy, and for this it is necessary to provide a large global project, the style of the Manhattan Project, United States. If countries get to work on a large project, possibly within ten years would have a commercially viable hydrogen economy. But today, this seems more like a siren song that a reality.

Not only is the hydrogen energy that we can draw from this dependence on oil, and consequently to reduce CO2 emissions, there are many other alternative energy sources, which were developed in the past, and as of today, research and employment is very low. In 1870, geothermal energy, took a quantum leap, as scientists saw it as a good source of energy, then increased research to study the ground thermal regime. .It was not until the twentieth century, and the discovery of radiogenic heat (heat balance). In 1967 he was inaugurated in the Race, France, and the first floor of harnessing the tides (tidal energy).

O wave energy, which knowledge dates from the French Revolution, however, does not begin to be studied in depth until the late twentieth century.

Concerns about clean energy are creating a collective imagination, demand for countries to seek energy alternatives, and we do not stop to think about the economic and political interests of big oil companies. Automation's companies discussed the many efforts towards a hydrogen economy, and what we observe, is that this companies go years in it, and we still have a viable production car of its kind.

Somehow, as noted Sovacool and Brossmann with respect to the hydrogen economy that we have a fantasy, because really, this fantasy can be raised to other renewable, because as more actions are not undertaken research, joint and, if possible, we will occur as in 1973, which passed the mouth of alternative energy, return to the use of fossil fuels, and only when you run out of oil we'll worry about unease heavily on energy research.

Possibly, it is not hydrogen or renewable energies that will save the planet, but fusion energy, but as happens with hydrogen are still far from that reality. For the present time, which we can do is, to apply rational policies of energetic use. This one is the most positive mechanism to reduce the emission of greenhouse effect, until the longed energy of the freedom does not come

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13

Energy Technology Learning - Key to Transform into a Low - Carbon Society

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1. Introduction

Experience enhances capacity for effective action. Exploiting markets to provide experience on new technologies is the key to a low-carbon society.

As market actors in the whole chain from technology producer to technology operator and user accumulate experience, both cost and technical performance of the technology improves. This process is referred to as *technology learning* (IEA, 2000). *Learning curves* (Wright, 1936) and *experience curves* (BCG, 1968; Abell and Hammond, 1979) measure the results of the process.[1]

Understanding the process of technology learning is of fundamental importance for a cost-efficient technology-led transformation into a low-carbon society. The implications of the process for energy technology policy were discussed at a workshop convened by the International Energy Agency in 1999. The IEA Workshop recommended that experience and learning curves "are used to analyse the cost and benefits of programmes to promote environment friendly technologies" and "explicitly considered in exploring scenarios to reduce CO_2 emissions and calculating the cost of reaching emissions targets" (IEA, 2000, Appendix B). The IEA Committee on Energy Research and Technology (CERT) supported the findings of the Workshop and initiated an international collaboration (IEA, 2000, Appendix C). Technology learning is a key process in the global scenario analysis within the IEA Energy Technology Perspectives bi-annual publications (IEA, 2006; 2008; 2010a). More importantly, the IEA work together with other recent high-level policy documents embrace the insights from experience and learning curves into the crucial role of government deployment programmes to make low-carbon energy technologies cost-efficient (Stern, 2006; EESC, 2009).

The IEA 1999 Workshop and subsequent work pointed to two major areas where technology learning should inform and guide energy technology policy: exploring and calculating cost for CO_2-reduction scenarios and designing efficient deployment programmes.

Kahouli-Brahmi (2008) provides an overview of global scale models incorporating technology learning to investigate CO_2-reduction scenarios. The first investigations by

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[1] The paper follows BCG (1968) in distinguishing between learning and experience curves. The experience curve relates the performance of the learning system to total input, which is usually expressed as total costs. A learning curve relates the performance of the learning system to one of the inputs, e.g., labour, raw materials, energy, or to a subset of inputs.

Messner (1997) and Mattsson and Wene (1997) using technology-rich, bottom-up models show that technology learning drastically reduces the cost to achieve CO_2-targets compared to earlier studies. This is an expected outcome because technology learning will reduce the cost of new low-carbon technologies following their implementation in the energy system; the higher the rate of technology deployment, the higher the rate of technology cost reductions. The energy system thus creates its own cost-efficient technologies. However, the results also identified three issues for legitimacy and design of deployment programmes. The issues can be labelled as alternative technology paths, high up-front costs, and global learning vs. local deployment (IEA, 2000; Wene, 2008a).

The fact that future costs of technology depend on earlier deployment in the energy system presents the prospect of equally effective systems but relying on very different, alternative technology paths. Experiment with a global, optimising model shows low and high carbon energy systems with the *same* present cost. The costs are calculated without imposing any form of external carbon costs, e.g., in the form of tax or trading schemes (Mattsson and Wene, 1997; IEA, 2000, pp. 84-91) Alternative systems have also been studied by Rao et al. (2006). The low-carbon technologies thus have a large potential for becoming the future cost-efficient choice in the energy system. However, the annual cost profiles for the low and high carbon cases are quite different. The new technologies required for the low-carbon case requires considerable up-front investments to initiate technology learning and keep the technologies riding down the experience curve. The up-front costs function as learning investments that are paid back as the technology becomes cheaper. But in the short range they appear as a large cost barrier to climb over in order to reach and realize the low-carbon system. Without special measures to support such climbing, the energy system risks lock-in to the high-carbon technologies. The alternative technology paths and the high up-front costs for the low-carbon alternative therefore provide strong legitimacy for proactive government deployment programmes to aid development of desired energy technologies.

IEA (2003) provides an overview of deployment programmes illustrated by 22 national case studies. Cost barriers for technologies already close to cost-efficiency are a few billion US dollars and can be overcome with the help of general low-carbon incentives, e.g., carbon trading schemes. However, overcoming the cost barriers of many promising large-potential technologies, such as photovoltaic electricity and deep water off-shore wind power, may require up to several hundred billion US dollars. Such technologies need targeted deployment programmes, for instance feed-in tariffs, to initiate and maintain learning towards cost-efficiency. The large investments in learning must be shared among the market actors but their magnitude also underscores the importance of precise predictions of the learning effect. Fairly small uncertainties in experience and learning curves proliferate to large uncertainties in cost estimates.

Once an emerging new technology has reached the world market the learning is governed by global deployment, so the sharing of learning investments eventually becomes a global issue. Development of wind power illustrates the progress from national to global learning. The first measurement of the experience curve for wind turbines was made by Neij (1999) for the Danish industry for the period 1982-1997. German markets did not take off until 1992 when the government started the 100 MW Wind deployment programme which later become the 250 MW Wind (IEA 2000, pp. 52-64). Durstewitz and Hoppe-Kilpper (1999) measured the experience curve for Germany for the period 1990-1998. Comparing data from different national programmes, Junginger et al (2005) could establish a global experience curve for wind power plants.

The global learning challenges both national policies and cohesion of international community because the deployment required for the learning is based on local decisions. A technology-led transformation to a low-carbon system therefore requires concerted action on deployment programmes among governments to provide learning. National governments may hesitate to align themselves to an international scheme and prefer to wait until actions by other countries have provided cost-efficient low-carbon technologies. If too many counties take a wait-and-see stance the cost-efficient technologies will never materialize. IEA (2000, pp. 64-74) analyses the Japanese "Roof-top" programme to support learning for PV-systems and concludes that reaching the cost target requires considerable deployment outside Japan. Martinsen (2010, 2011) has studied global learning vs. local deployment from the perspective of a small, open economy. His results indicate that there may be considerable advantages for such an economy to align itself to international efforts on deployment.

Technology learning also challenges the scientific community to provide a better understanding of the technology learning phenomenon. Using experience and learning curves to argue for legitimacy and efficiency of aligned government deployment programmes requires that these curves can be confidently extrapolated into the future. The Stern (2006) report observes that "data shows technologies starting from different points and achieving very different learning rates". The observation is confirmed by compilations of experience and learning curves (Dutton and Thomas, 1984; McDonald and Schrattenholzer, 2001; Weiss et al., 2010). Nemet (2009) interprets the observed spread of learning rates for the same technology in different time-segments as an indication of the uncertainty in extrapolating the curve. The uncertainties in key parameters such as buy-down costs or year of break-even then become too large to permit quantitative policy conclusions. In their report to the 2006 G8 meeting of Head of States, the International Energy Agency finds:

"Technology learning is the key phenomenon that will determine the future cost of renewable power generation technologies. Unfortunately, the present state-of-the-art does not allow reliable extrapolations" (IEA, 2006, p. 231).

Although there is consensus on the importance of technology learning to achieve a low-carbon energy system, there are therefore considerable doubts about quantitative estimates of costs and dynamics from experience and learning curves. The uncertainty about the extrapolated curve hampers the design of efficient deployment programmes and thereby hinders the full exploitation of technology learning to transform the system. Obviously, the state-of-the-art of exploiting technology learning must be improved.

The purpose of this paper is to discuss the two challenges from technology learning: providing confidence in extrapolating experience and learning curves and achieving global learning based on local deployment.

The ambition of the paper in meeting the two challenges are quite different, however. It is argued that the uncertainty in extrapolation can be effectively reduced through a better theoretical understanding of technology learning. Recent advances in a cybernetic approach to understand the phenomenon indicate that the observed dispersion of learning rates are due to the learning system adapting an internally well-defined learning mode to external perturbations (Wene, 2007, 2008a, 2008b, 2010). The existence of these internal modes provides stability to the extrapolation. The discussion of global learning vs. local deployment is limited to an illustrative example where the new theoretical understanding is applied to the global decarbonisation curve. It is based on the approach proposed in IEA (2000, pp. 75-84) and using data and scenarios from the recent World Energy Outlook (IEA, 2010b).

The following section discusses the phenomenon of technology learning both under normal market conditions and during radical technological change. Section 3 presents the theory and applies it to explain observed distributions of learning rates. The global decarbonisation curve is discussed in section 4.

2. Technology learning: Phenomenology

2.1 Continuous improvement in equilibrium markets

Figure 1 shows the experience curve for photovoltaic (PV) power modules. Since 1976, prices have been reduced from over 60 USD(2001)/W_P to around 3 USD(2001)/W_P today. The straight line is the experience curve fitted to the time series. Both scales are logarithmic, so the experience curve can be written as

$$\text{Price}(t) = C_0 * X(t)^{-E} \tag{1}$$

Price at time t is equal to a constant, C_0, times the cumulative sales X(t) at time t raised to the power of –E. E is a constant and will be referred to as the experience parameter. The value of this constant is to be explained by the theory.

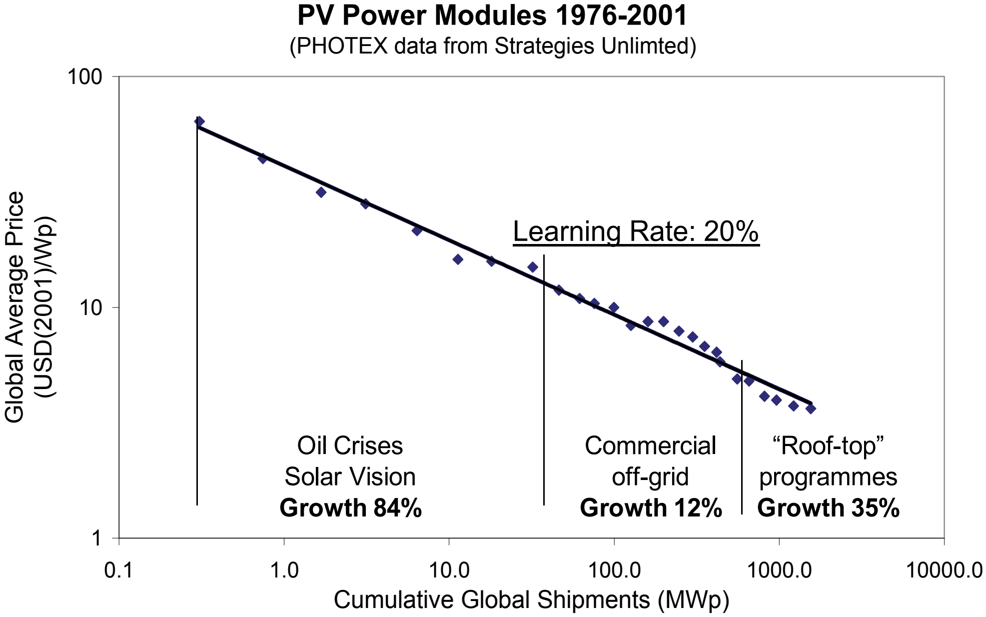

Fig. 1. Experience curve and growth in global sales for photovoltaic modules (data for experience curve from Schaeffer et al., 2004; Wene, 2008b).

The literature uses not E but learning rate, LR, or progress ratio, PR, to characterize the steepness of the curve. The learning rate is the relative reduction in price for each doubling of cumulative sales. The relation between E, LR and PR is given by

$$PR = 1 - LR = 2^{-E} \qquad (2)$$

The fit of the experience curve to the PV time series is good with a $R^2 = 0.9868$ indicating stable conditions for the learning system. The learning rate for PV modules is constant at 20% over three decades and almost four orders of magnitude in cumulative global sales. The stability of learning is quite impressive, considering the great swings in market growth caused by instable government deployment programmes. One conclusion is that learning rate is independent of growth rate. However, the example in Figure 1 raises the issue of using price or cost to measure the performance of the technology learning system.

The learning effect in Figure 1 is measured by price, which is set by the actors in the market. Competitive markets are necessary to foster learning, but the observed learning is the result of internal operations within the learning system, which in Figure 1 is the PV-module production system. Technology learning should be measured by cost rather than price. The theory will use cost as the variable to be explained. However, reliable cost data are difficult to obtain and the experience and learning curve literature usually measures the learning effect by price series. It is therefore crucial to clarify the relationship between cost and price. The analysis in BCG (1968) (see also IEA/OECD, 2000, pp.35-40) shows that the ratio between price and cost remains constant in equilibrium markets, i.e. performance measured by price and cost have the same learning rates in this case. However, market disequilibrium may initiate a price-cost cycle, which shows up as systematic deviations from the experience curve measured by price. The launching of a new product may cause such disequilibrium.

2.2 Radical innovation

Freeman and Perez (1988) distinguish between four types of technological change: incremental and radical innovations and changing technological system and technological paradigm. We look at individual technologies and are interested in the two first types for characterising processes and operations in the learning system. The continuous logarithmic form of the experience curve for PV power modules suggests that the learning system moves ahead using incremental innovations. However, stepwise changes in curves for oil exploration as in figure 2 indicate major technological changes in this area due to radical innovations.

Price-cost cycles may also lead to stepwise changes in the curves (BCG, 1968) so price curves are poor indicators for radical change. The learning curve for wildcats[2] (Wene, 2005) in Figure 2 is based on physical measurements and thus avoids price-cost ambiguity. It is, however, a learning curve[3] and does not relate performance to total inputs so it ignores effects due to changing oil resources. The following analysis assumes depletion but no stepwise changes in these resources. Between 1947 and 1968, the learning curve remains practically horizontal representing the tail end of a curve that started many decades before. An experience curve should still show improvements, the flat learning curve indicates that any such improvement is masked by depleting oil resources. The interesting features of this curve are the steep improvements in performance after 1968 and after 1989.

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[2] A wildcat is an exploratory borehole in an area that has not before produced any commercial amount of oil.

[3] See footnote 1. The output is successful wildcats and the performance of the system is related to total wildcats, that is performance = total wildcats/successful wildcats.

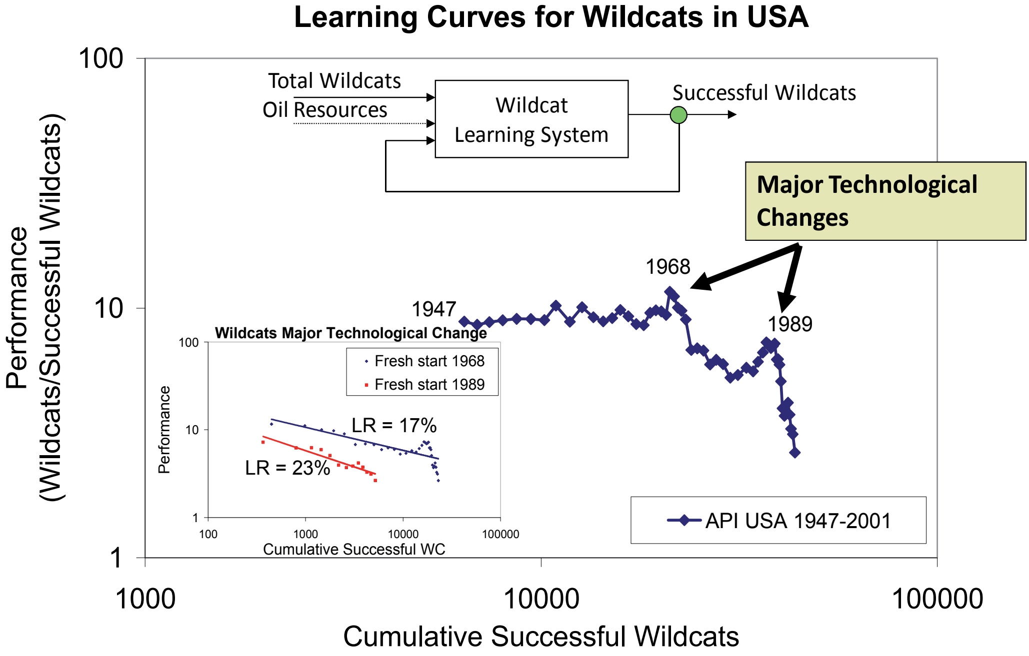

Fig. 2. Learning curve for wildcats in the USA (Wene, 2005, 2008a)

The stepwise improvement in wildcat performance is directly correlated to major technological changes in oil exploration (Wene, 2005). Computer technologies applied to seismic imaging explains major parts of these improvements. The use of 3D seismic technology for new wildcats took off around 1990 and the area covered by this imaging technology grew from five thousand to over one million square kilometres between 1991 and 2000.

The correlation to observed major changes in exploration technology permits the conclusion that the stepwise changes in the wildcat learning curve are the signature of radical innovations. The question is how radical innovations should be included in the technology learning methodology. Fitting learning curves to the steep parts of the curve result in ridiculously high learning rates. The inset diagram shows that resetting the cumulative output of the learning system to zero in 1968 and 1989, respectively, provides fairly good fits to data. It is interesting to note that the learning rates after reset are close to the 20% rate found for PV power modules. The theory for technology learning presented in the next section supports this representation of the effect of radical innovations (Wene, 2007, 2010).

Figure 3 shows the experience curve analysis of cost data for oil exploration in the period 1985-1999. Using historical cumulative findings from 1968 provide a learning rate of 76%, which obviously has not prognostic value. Resetting cumulative findings at 1989 provides LR = 28% which is still larger than for wildcats but could reflect the uncertainty in valuing oil resources. We will return to radical innovations and their representation when discussing the decarbonisation curve in section 4.

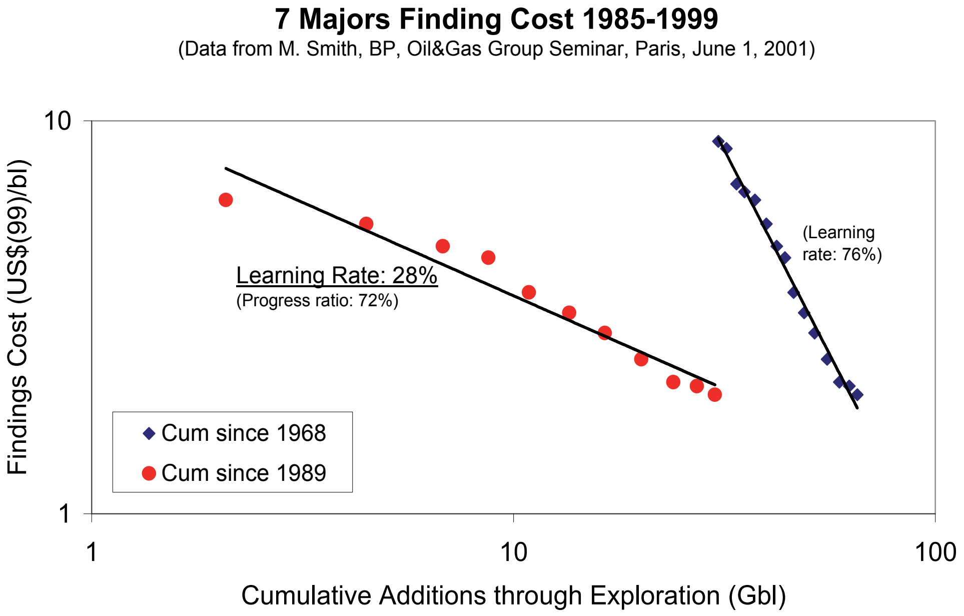

Fig. 3. Experience curve analysis of oil exploration (Wene, 2005).

3. Technology learning: Theory

3.1 The cybernetic approach

Several mechanisms have been proposed to explain technology learning and the observed relationships (Abell and Hammond, 1979; Arthur, 1988; Argote and Epple, 1990; Adler and Clark, 1991; Nemet, 2006), but generally they fail to reconstruct the shape of the curves or explain the observed learning rates. Ferioli and Zwaan (2009) using a top-down approach reproduce the shape, provided market growth is exponential and that actually realised incremental improvements diffuses out from a pool of potential improvements. All these explanations understand learning as the result of an open system reacting to demands and opportunities in the environment thus focusing on the role of environmental interactions in explaining the phenomenon. The operations of the learning system are assumed to be determined by **f**eatures, **e**vents and **p**rocesses (FEPs) in the system *environment*.

Contrary to earlier proposals, the cybernetic approach (Wene, 2007, 2008a, 2008b, 2010) considers technology learning as *inherent property* of the learning system. Experience and learning curves express the *eigenbehaviour* (Varela, 1979, 1984; von Förster, 1984, 1993) of an operationally closed system producing for a competitive market but acting autonomously based on its internal structure. The approach applies fundamental theoretical results for biological and social systems (von Förster, 1980; 2003, Varela, 1979, 1984; Luhmann, 2002).

The condition of operational closure means that the system forms and controls all its operations. The system is open to information and to material and energy flows; however, the network of internal operations closes on itself. The condition of operational closure has a very important consequence expressed in the closure theorem of cybernetics: *in every operationally closed system there arise Eigenbehaviours*. The task is to find the operational loops that represent learning and define the operators whose fixed points provide the values for the eigenbehaviour. Wene (2007; 2008a) provided a hypothesis for the operational loops and defined two operators, C_{SRL} and C^{+}, expressing system performance and the dependence of this performance on cumulative system output.

The following provides a brief review of the results from the theory. The purpose is to demonstrate the stability of technology learning and provide grounds for reliable extrapolations. Wene (2007, 2008a, 2010) provide a detailed presentation of the mathematical formalism including justification of operator loops and equations from studies of organisational learning (Kim 1993; Espejo et al, 1996).

The condition of operational closure makes it possible to postulate an internal state, Z, for the learning system. The fact that all operational loops are closed and that he system is the master of all its operations guarantees that such a postulate is meaningful. The operators act on the internal state and the results can be interpreted as, e.g., values of the experience parameter. The basic eigenvalue equation in the theory provides the results in the limit of repeated operations

$$\underline{Z}_{\infty} = \lim_{\tau \to \infty} \begin{pmatrix} C_{SRL} & W_{12} \\ W_{21} & C^{+} \end{pmatrix}^{\tau} \begin{pmatrix} \Delta P_0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} i \\ 1 \end{pmatrix} \tag{3}$$

The 2/1 matrix is the original system state, $\mathbf{Z}_0$. Following Wene (2007) it is assumed to be the base vectors of the complex Argand plane. Equation 3 is derived under the assumption that equation 1 expresses the relation between performance and cumulative output from the learning system. τ is the amount of doublings since the system became operationally closed. In this case ΔP_0 is a constant and equal to the relative improvement in performance for each doubling of cumulative output[4]. W_{12} and W_{21} are operators representing operations in the learning system in order to manage external perturbations; in cybernetic language they represent the *plasticity* of the system.

The solution of equation 3 can be envisaged in two steps. The first step calculates the main learning modes, which represent the spectrum of stable eigenbehaviours of the system. The second step considers the systems adaptation to external FEPs. The FEPs can be negative or positive that is reducing or increasing learning. Examples of FEPs are regulations, results from public Research & Development (R&D), government stimulation of private industry R&D, changing consumer behaviour, spillover and crossover from other learning systems or technology fields.

Setting $W_{12} = W_{21} = 0$ in equation 3 provides the solution for the main learning modes discussed in detail in Wene (2007, 2008a). The experience parameters corresponding to the main learning modes are

$$E(n) = 1/[(2n+1) \cdot \pi] \qquad n = 0, 1, 2, 3, \ldots \tag{4}$$

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[4] A more general formulation is that ΔP_0 is the relative improvement in performance between two logarithmically equidistant measures of cumulative output. However, we have chosen to set the numeric equal to doubling of cumulative output.

Following equation 2, the four first modes of learning are then

$$LR(0, 1, 2, 3) = 20\%, 7\%, 4\%, 3\%, \ldots \qquad (5)$$

The question of terminology should be brought up here. Wene (2010) somewhat loosely refers to all the main modes of learning as "unperturbed". Strictly speaking, however, only the basic mode of LR(0)=20% can be unambiguously referred to as "unperturbed", meaning that it represents the learning in a system exposed to no other external perturbations than those FEPs normally appearing in a competitive market in equilibrium. For the purpose here it is important however, that all the main modes are stable, meaning that if an external perturbation results in the system moving away from a main mode given by equations 4 and 5, the system will return to the eigenbehaviour representing the original main mode when the perturbation disappears. There are, however, under special circumstances exceptions to this rule of stability. These exceptions are discussed below. It is also possible that, under favourable circumstances, a learning system in a higher mode with $n>0$ could switch to the basic mode with LR(0)=20%. Borrowing terminology from physics, learning modes with $n>0$ could be characterized as meta-stable. We will not here speculate over such a bonus for technology policy, but will in the following retain the characteristic "stable" for all main learning modes with the caveats given above.

The off-diagonal operators, W_{12} and W_{21}, show how the system adapts to external perturbations. Their effects on the system are quite different. W_{12} shifts the system away from the stable eigenvalues, while W_{21} directly affects the internal memory manifested in cumulative output. One could use cumulative output to define an eigentime for the system. W_{21} can reset this internal clock and in the same way as a radical innovation can reset cumulative output. In this paper we will only discuss the effects of W_{12} on the stable eigenvalues.

Let ΔP_0 provide a measure of the strength of the perturbation and W_{12} be parameterized as (Wene, 2010)

$$W_{12} = \alpha(\tau) \cdot \Delta P_0 \cdot C^+ \qquad (6)$$

where $\alpha(\tau)$ is a negative or positive real number. For *negative* α-values the initial eigenvalues are modified by the perturbation and for a perturbation of fixed strength converge to provide an experience parameter

$$E_\infty(n, \alpha) = 1/[(2n + 1) \cdot \pi - \alpha] \qquad n = 0, 1, 2, 3, \ldots \qquad (7)$$

As expected, a negative perturbation will thus *reduce* the learning rate. When the perturbation disappears the system returns to its initial stable eigenbehaviour. The system may, however, adapt quite differently to a positive perturbation. Equation (6) continues to characterize the behaviour of the system immediately after the onset of a positive perturbation, leading as expected to an increased learning rate. However, if the positive perturbation remains the system will start to align itself to the perturbation. The result is a phase shift where the new experience parameters converges to

$$E_\infty(n, \alpha) = 1/[(2n + 1) \cdot \pi + \alpha] \qquad n = 0, 1, 2, 3, \ldots \qquad (8)$$

An external feature, event or process providing a free positive contribution to the system performance but remaining too long will eventually result in a reduction of the learning rate. At first this result seems strange and counter-intuitive, but by reflection plausible. An interpretation is that the system gets accustomed to the free contribution to its learning and start losing its own ability to learn. The time until the onset of the phase shift depends both on the strength of the positive perturbation and on the age of the learning system. A system that has gone through many doublings of the cumulative output is more resilient but a younger system will rapidly degrade its own learning ability if exposed to free positive learning contributions. The stronger the positive perturbation is the faster it will produce a phase shift. The strength dependence effectively puts upper limits on learning rates. The phase shift has consequences for the possibility to increase learning rates by public R&D.

The analysis so far has supported our original conjecture about the stability in extrapolation of learning rates with the caveat that insistent positive perturbations may induce a phase shift. The risk of a phase shift is however, larger for challengers that just enter the market than for technology that already has made several doublings of cumulative output. The next step is to search empirical support for the theory. The following section finds such support in compilations of learning rates.

3.2 Empirical support from compilations of learning rates

In order to calculate distributions of learning rates, LR, or experience parameters, E, we introduce a simple probabilistic model for the distribution of perturbations. In the model, all perturbations are additive, and negative and positive perturbations are Poisson distributed. For the simple calculations presented here we further assume that perturbations start at the beginning of each measuring period and continue throughout the period. A detailed presentation of the model is given by Wene (2010). The probabilistic model can be considerably improved by considering, e.g., distribution of strength and duration of perturbations; however, it captures the essential aspects of the distribution.

Figures 4 -6 show fits of the probabilistic model to three published distributions of learning rates. The Dutton and Thomas (1984) distribution is based on cost time series for a broad spectrum of technologies in individual enterprises. Weiss et al. (2010) provide the distribution of learning rates for energy supply and energy demand technologies based on market prices. The distributions in figures 5 and 6 show the dispersion of learning among industries rather than among enterprises. For the comparison the learning rates have been recalculated to experience parameters using equation (2).

The experience parameters and learning rates for the stable learning modes are uniquely given by equations (4) and (5). They are thus independent of any fitting procedures. However, three parameters in the probabilistic model are fitted to the *dispersion* around the stable modes. These parameters are the intensities λ_{pos}, λ_{neg} of positive and negative perturbations, respectively, and the strength S_{FEP} of each perturbation. S_{FEP} is a constant meaning that all perturbations are assumed to have the same strength. The fit only considers the two first stable learning modes and the relative strength of these modes is also a fitted parameter. The fifth parameter is the cut-off parameter indicating the limiting value for positive perturbations; all positive perturbations larger than this value is assumed to lead to a phase shift. This sharp cut-off value simplifies the theoretical results in the previous section, which showed a much smoother cut-off, but is accurate enough for the calculations here. The cut-off can be varied within a narrow band of values constrained by theory.

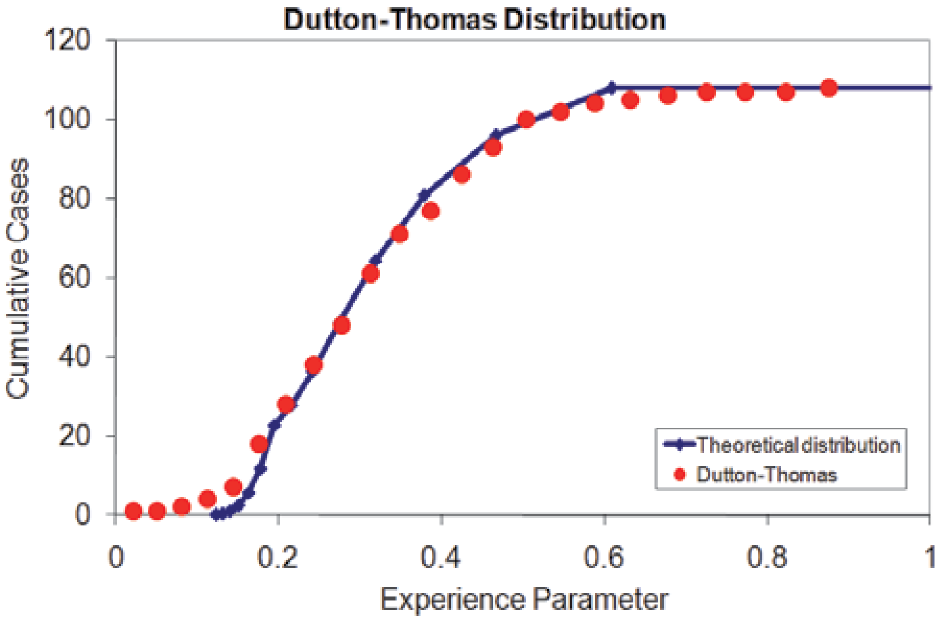

Fig. 4. Probabilistic model fitted to Dutton and Thomas (1984) distribution.

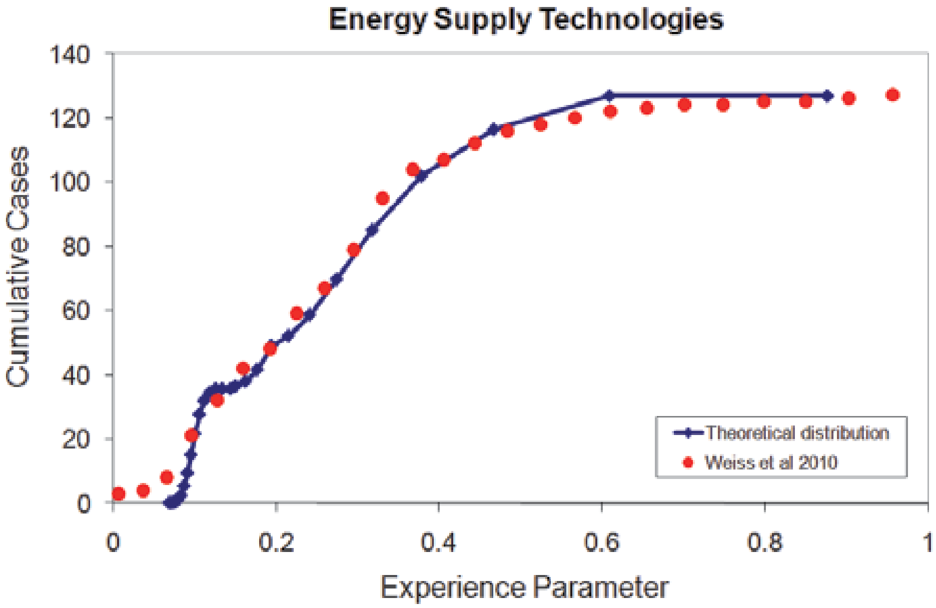

Fig. 5. Probabilistic model fitted to Weiss et al. (2010) distribution of learning rates for energy supply technologies

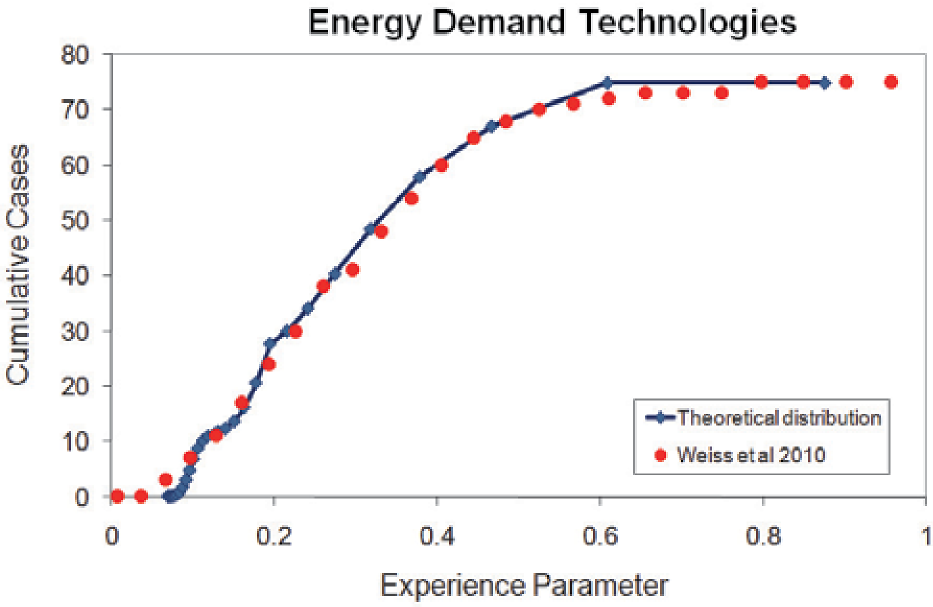

Fig. 6. Probabilistic model fitted to Weiss et al. (2010) distribution of learning rates for energy demand technologies

Table 1. shows results of fit with the probabilistic model and permit some initial observations.

Distribution	Cases	L0 strength	L1 strength	λpos	λneg	SFEP	Cut-off
Dutton & Thomas	108	1.0	0	4	3	0.5	2
Energy Supply	127	0.72	0.28	3	2	0.5	2
Energy Demand	75	0.85	0.15	4.5	3	0.5	2

Table 1. Parameters used in the probabilistic model to fit distributions. The same parameters are used for the L0 and L1 learning modes

The first observation is that the theory presented in the previous section explains the observed dispersion of learning rates or experience parameters among technologies. The probabilistic model based on the extended cybernetic theory for technology learning provides an equally good fit to all three distributions. This supports the claim that distributions are the results of learning systems adapting unique and common learning modes to external perturbations. However, the values of the fitted parameters point to differences between the distributions. These differences must be explained within the theory in order to make confident extrapolations of experience and learning curves. Wene (2008b, 2010) discusses causes for the differences and his arguments are briefly recapitulated here together with some new observations.

The three distributions are fitted assuming the same strength, S_{FEP}, and Table I shows that the relation between positive and negative perturbations are about the same for all three sets of learning systems and technologies. However, the intensities λ_{pos}, λ_{neg} are 20-30% lower for the energy supply technologies compared to Dutton and Thomas distribution, while they are almost the same as in Dutton-Thomas for the energy demand technologies. The difference for the supply technologies is expected, but the results for demand technologies will require further studies.

Moving from a set of individual enterprises to a set of industries should reduce the dispersion – provided all firms within an industry compete on the same market with the same technology. This follows from the central limit theorem in mathematical statistics (Gut, 1995, pp. 173-177). Weiss et al (2010) distribution for energy supply technologies represents industrial averages over actions of several firms, while Dutton and Thomas (1984) shows the variance for a representative set of individual firms. Applying the central limit theorem would indicate that energy supply distribution represent averages over 2-3 firms, however, more detailed probabilistic models are necessary to verify this.

The question remains why industries producing energy demand technologies do not show the same reduction in dispersion as industries producing supply technologies. A hypothesis is that there is a much bigger dispersion among firms and marketed products within an industry producing demand than one producing supply technologies. E.g., a washing machine sold to an urban apartment is quite different from one sold to a hospital or hotel. The condition of a unique technology on a unique market is therefore not fulfilled and the central limit theorem cannot be directly applied. However, this hypothesis has to be investigated further.

A major difference regards the occurrence of higher order learning modes. Dutton and Thomas (1984) distribution shows none or negligible influence from higher order learning modes. However, the analysis of the two distributions of Weiss et al. (2010) verifies the observation made for the earlier McDonald and Schrattenholzer (2000) distribution for energy technologies (Wene, 2008b). The dispersion of learning rates for energy supply and demand technologies cannot be explained without higher order learning. The application of the probabilistic model indicates that 28% of the learning systems producing energy supply technologies and 15% of those producing demand technologies are in higher learning modes. The theoretical curves in figures 5 and 6 only show the effect of the first higher learning mode (LR(1) = 7%) using the same parameters in the probabilistic model as for the zero mode. Including still higher order learning may improve the fit.

Wene (2008b, 2010) points to three possible causes for the appearance of higher order learning: system boundaries, environmental and safety regulations, and – more speculatively – government R&D. More important for this paper is to ask if switches between learning modes can take place in the future, upsetting the stability of extrapolations. The preliminary answer is that such switches cannot be ruled out but the risk of switching to higher learning modes or the opportunity of reaching a lower one will depend very much on policy design, i.e. decisions taken by policy makers. To aid such decisions requires more studies of the causes for the appearance of higher learning modes.

Another issue for the theory is the occurrence of very high learning rates in all the three distributions in figures 4-6. The rates are larger than the expected limit set by the phase switch. One explanation for the high learning rates is extreme events in input markets, e.g., labour, capital or raw material markets. Such events may decouple system dynamics from the learning loops and make it appear as trivial input-output machine (von Förster, 1984, 1993) responding to changes in the input markets.

So far, the theory is used to investigate and compare learning for individual technologies. In the following section it is used to characterize scenarios and study the collective effects of technology deployment on the global scale.

4. Decarbonisation as technology learning

Most global energy studies use energy models that build up scenarios from analysis of technology investments and energy flows in regions and major countries. They capture albeit with varying detail the effects of local technology deployment. The question is what type of learning this provides on a global scale. The focus is not on individual technologies but how learning is manifested in the total performance of the global energy system. Following a suggestion in IEA (2000, pp. 75-78) the global decarbonisation learning curve is chosen as a measure of system performance. Carbon in the form of non-renewable biomass, coal, oil and natural gas is one input to the global energy system. The useful physical energy flows drives the economic system, which also learns to use these flows more and more efficiently. Including demand technologies and energy efficiency measures into the system, global GDP emerges as a useful indicator for the output from the global energy system. The decarbonisation learning curve is the carbon intensity of global GDP as function of cumulative global GDP.

International Institute for Applied Systems Analysis (IIASA) in Austria pioneered long-range decarbonisation studies in the 1990s. Nakicenovic (1996) reports from a study of the US economy over the 140-year period from 1850 to 1990. The results show a simple power relation as in equation (1) between carbon intensity and cumulative carbon input. The learning curve concept states that performance depends on cumulative output. Converting to cumulative US GDP provides a learning rate for decarbonisation of 18% that is quite close to the 20% provided by theory.

It may seem surprising that decarbonisation was an historical trend long before climate change became an issue. However, increased energy efficiency driven by technology development and fuel switching to more easily managed fossil fuels, which just happened to have less carbon, explain most results. Macroeconomic modelling provides some quantitative insights. Economic modellers have used the concept of Autonomous Energy Efficiency Improvements, AEEI (Manne and Richels, 1992) to capture effects of technology development. AEEIs equal 0.5% and 1% are frequently assumed, which corresponds to yearly, not price-induced improvement in energy intensity of the economy of 0.5% and 1%, respectively. At 3% economic growth and everything else equal, such values for AEEI corresponds to learning rates of 12% and 21 %, respectively. Economic and learning curve analysis seem to concur on the historic trend of decarbonisation. However, this trend is by far not enough to ensure stabilisation and reduction in CO_2 emissions. The question is how to improve on the historic trend. To understand the implications of this question we turn to the scenario makers.

For the decarbonisation analysis we choose the scenarios in the well-known IEA World Energy Outlook (IEA, 2010b). There are several reasons for this choice. WEO scenarios build on considerable amounts of world statistics assembled at IEA since its foundation in the 1970s. WEO can rely on policy analysts and energy consultants within all IEA governments as well as experts from major actors in the energy markets. Experts from reforming and emerging economies, such as Russia, China, India and Brazil, contribute to the work. For the work presented here, two reasons are important. The establishment of international energy experts and commentators use the most recent WEO scenarios as benchmarks for comparison to scenarios from other actors on the energy scene; a recent example is Forbes (2011) discussion of BP and ExxonMobil energy forecasts. The WEO scenarios therefore provide an obvious starting point for the analysis of decarbonisation learning curve. Last but not least, WEO can now rely on the detailed analysis of technology development and deployment in the Energy Technology Perspective project at the IEA Secretariat (IEA, 2010a). Learning curves are important tools in the ETP technology analysis.

Figure 7 shows the global decarbonisation curve for the energy system calculated from historical data and from the three WEO Policies Scenarios. Fitting a learning curve for data up until 1994 provides a learning rate of 20%, nicely following the theoretical prediction. The learning curve is extrapolated and in the following discussion assumed to represent the autonomous decarbonisation rate, ADR. The ADR provides the baseline to which post-94 data and scenario results can be compared. For further comparison, the Breakaway Path considered in IEA (2000) is also provided. The end-point for this Path and for ADR is set to 2060 assuming the economic growth continues after 2035 at the same rate as in the WEO scenarios for the period 2020-2035.

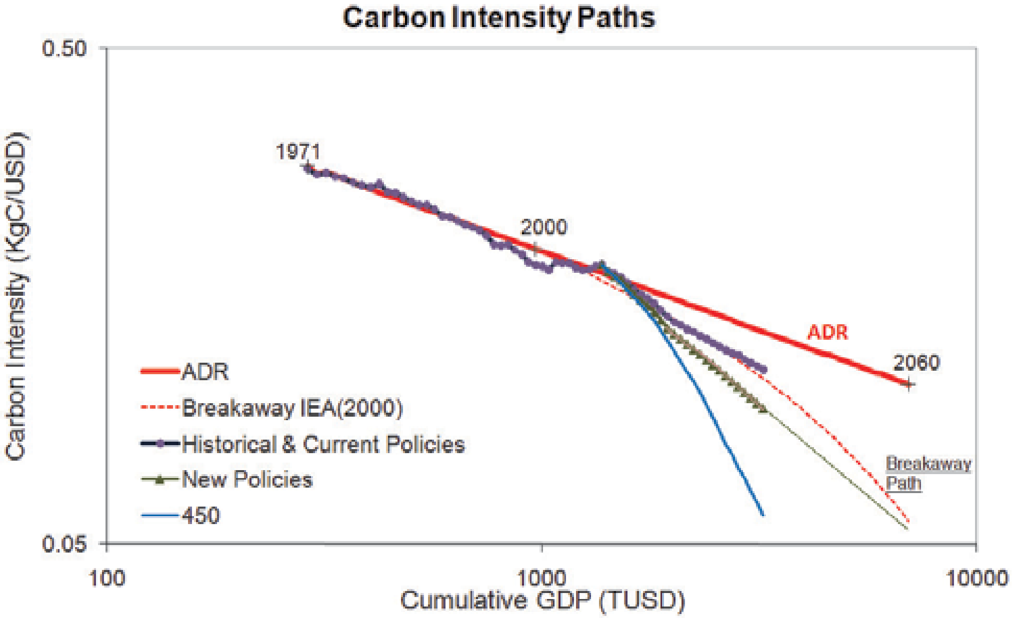

Fig. 7. Decarbonisation of the world economy according to historical data and the three WEO (2010) Policies Scenarios.

Historical data indicate some attempts to break away from the historical ADR in the second half of 1990s. (The "dip" in the curve in the first half of 1990s is a result of the changes in Former Soviet Union and Eastern Europe and not of CO_2 policies.) The breakaway was interrupted in the beginning of 2000s as economic growth took off in major emerging economies such as those of China, India and Brazil. The WEO scenarios assume that break away will resume in the 2010s.

The WEO scenarios are characterized as Current Policies, New Policies and 450 and are briefly described in WEO (2010, p. 79). Current Policies act as baseline "in which only policies already formally adopted and implemented are taken into account". New Policies assumes cautious introduction of new measures "to implement the broad policy commitments that have already been announced". The 450 Scenario limits the concentration of greenhouse gases in the atmosphere to around 450 parts per million of carbon-dioxide equivalent, which should limit the global increase of temperature to 2 degree C. The storyline in WEO (2010) focuses on the New Policies Scenario.

After peaking out and then falling in the 2010s, the decarbonisation curves for the three scenarios appear as learning curves in the period 2020 until 2035, which is the time horizon for the WEO scenarios. The learning curve for New Policies Scenario is extrapolated to the endpoint of the Breakaway Path in IEA (2000. p. 77). This Path provides an interpolation between the Current and New Policies, having the same carbon intensity as the former scenario in 2020 and as the extrapolated New Policies in 2060. The learning rates in the period 2020-2035 for Current Policies, New Policies and 450 Scenarios appear to be 28%, 40% and 67%, that is considerably larger than the ADR. Learning rates of 28% are within the distributions discussed in the previous section and even 40% can be accepted as an extreme value, but 67% is beyond any measured rate for an individual technology. The question arise how these apparently high learning rates should be understood. The following comments reflect on this question from the perspective of technology learning theory.

Today, existing and mature low-carbon and efficient technologies provides a large potential to reduce the carbon intensity of GDP. By 2020 they will still play a major role in the energy system. However, if current policies succeed most of their potential to further *reduce* carbon intensity will be exhausted. The large learning rates after 2020 require deployment of new, more efficient supply, distribution and demand technologies, whose operation provides very-low-to-zero CO_2 emissions. The decarbonisation curve shows the collective results of such deployment.

The theory sees high learning rates as a result of the system adapting to positive perturbations, which in this case must be applied to the whole global energy system. It is possible that e.g., strong support to private R&D (Guellec and van Pottelsberghe, 1993) could spur a 28% learning rate over 15 years and one doubling of cumulative GDP. However, the concerted efforts needed to achieve 40% and even 67% over a long period of time seem beyond what can be expected from the international community. The difficulties are exacerbated by the risk of phase shifts in the learning systems for the new technologies. But technology learning provides an alternative way of achieving the required learning without relying on the inherently unstable medium of positive perturbations.

The period until 2020 could be used to create radical innovations in major parts of the global energy system. Technology candidates for such innovations could be, for instance, thin film or nanotechnology solar PV, deep-sea floating wind parks, 2nd generation biomass, 4th generation nuclear plants, carbon capture and storage technology, smart grids, electric cars, zero energy housing. The radical innovation would reset cumulative output for respective technology learning system, see section 2.2. After resetting the global energy system could rely on the basic, zero learning mode with stable learning rate of 20% equal to ADR to achieve the learning needed.

For Current and New Policies Scenarios, radical innovations are not required in all of the energy system in order to provide the decarbonisation through the basic learning mode. The decarbonisation in the Current policies scenario could be achieved at learning rate 20% provided radical innovations start to be implemented in 45% of the energy system in the last years of 2010s. New Policies Scenario requires radical innovations to be ready to start deployment in 75% of the energy system. The rate of deployment should follow the same S-curve as is historically observed for the penetration of new technology. 450 Scenario seriously challenges the international community, because it requires a continuous deployment of radical innovations. To understand the magnitude of the challenge one can observe that relying on the basic learning mode of LR=20% to achieve the decarbonisation requires putting in place new radical innovations in more than 80% of the energy system every 5 years. Achieving the 450 Scenario will probably need a combination of public R&D to help create radical innovations and direct support to private industry R&D for the purpose of increased learning rates. Deployment programmes to ensure swift ride down the experience curve to cost-efficiency for new technologies is a fundamental element in all policies.

5. Conclusion

The cybernetic approach to technology learning indentifies a spectrum of stable learning modes. The learning rates for these modes are fixed by the theory without any fitted parameters. The basic learning mode has a learning rate of 20%, which explains the clustering of learning rates around this value in existing compilations of measured rates. The distribution of rates around the stable learning modes shows how the learning system adapts to positive or negative perturbations. A simple probabilistic model based on the theory fits distribution of learning rates in available compilations.

The existence of stable learning modes provides the basis for confident extrapolations of learning curves. However, extrapolations require caution. No major changes in the system environment is a condition. Learning curves for technologies moving with learning rates close to a stable learning mode can be extrapolated with larger confidence than technologies where the learning rate deviates considerably from that of a stable mode. The reason is that the first technology shows more resilience to perturbations. The typical example of such technology is solar PV. Because of the risk for phase shifts, extrapolations based on apparent high learning rates have low credibility.

The theory can be applied to analyse and characterize decarbonisation curves. The methodology is demonstrated on the latest scenarios from IEA's World Energy Outlook. The analysis questions whether a low-carbon future can be achieved through continuing incremental technology developments. Radical innovations are necessary in major parts of the global energy system in order to achieve the large decarbonisation required to for a future that can combine a low-carbon energy system with a high-growth economy.

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14

What is Green Urbanism? Holistic Principles to Transform Cities for Sustainability

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1. Introduction

This book chapter first looks at the timeline of important publications on sustainable design that emerged from different schools of thought, and how gradually the notion of *Green Urbanism* evolved. It then identifies the intertwined principles for achieving *Green Urbanism* and gives guidance for topics of further research in the field.

1.1 Different schools of thought: From *green city* to *green building*

Over the last thirty-five years or so, an international debate on eco-city theory has emerged and has developed as a relevant research field concerning the future of urbanism and the city itself. During that time, a number of architectural schools of thought have been implemented worldwide. One such school is *Technical Utopianism* (a technological idealism that relied on the quick `techno-fix', as expressed, for instance, in the work of Archigram). Other early writing on green urbanism was available from Ebenezer Howard, whose 1902 book was entitled `Garden City of Tomorrow', and whose political and social agenda has recently made a comeback. Much later, in 1969, Reyner Banham pioneered the idea that technology, human needs and environmental concerns should be considered an integral part of architecture. Probably no historian before him had so systematically explored the impact of environmental engineering and services on the design of buildings. (Howard, 1902; Banham, 1969) Some other early significant writing on green urbanism has come from Lewis Mumford and Jane Jacobs – although they didn't call it green urbanism. From `Silent Spring' (by Rachel Carson, 1962), to Victor Olgyay's `Design with Climate' (1963), to Reyner Banham's `Architecture of the Well-tempered Environment' (1969), to Ian McHarg's `Design with Nature' (1969), to the pivotal publications by authors re-connecting urbanism with the climatic condition (such as Koenigsberger, Drew and Fry, or Szokolay, in publications in the 1970s and 80s), to the remarkable `Brundtland Report' (Brundtland, 1987); the important contributions from Robert and Brenda Vale (`Green Architecture: Design for an Energy-conscious Future', 1991), and the `Solar City Charter' (Herzog et al, 1995/2007), the field of sustainable city theories and climate-responsive urbanism has constantly been expanded. An important contribution came from Guenther Moewes with his book `Weder Huetten noch Palaeste' (1995), which is a programmatic manifesto for designing and constructing longer-lasting buildings. More recent theories for `Compact Cities' and `Solar Cities' (Burton, 1997; Jenks and Burgess, 2000; Lehmann, 2005) encapsulate the visions based on the belief that urban revitalization and the future of the city can only be achieved through `re-compacting' and using clearly formulated sustainable urban design principles. These principles for achieving green urbanism have to be clearly defined and adjusted to an era of rapid urbanization, especially in the Asia-Pacific Region. In the 21st century we are working in an entirely new context, for which we need new types of cities. As noted by Ulrich Beck, we have arrived in `a new era of uncertainty', where energy, water and food supply are critical. 'We live in a world of increasingly non-calculable uncertainty that we create with the same speed of its technological developments.' (Beck, 2000)

In 1972, the *Club of Rome* formulated, in its study 'Limits of Growth', the negative effect of sprawl and over-consumption of resources. Today, we know that uncontrolled development is a damaging exercise, and that urban growth should occur in existing city areas rather than on greenfield sites. Portland (Oregon, USA) was well ahead of most other cities when, in the early 1980s, it introduced a legally binding 'growth boundary' to stop sprawl and the emptying-out of its downtown area. `Today, younger people don't desire to live in the endless suburbs anymore, but have started to re-orientate themselves back to the city core, mainly for lifestyle reasons.' (Fishman, 1987) However, as several recent studies of inner-city lifestyles reveal, an increase in consumption can be part of the inner-city renaissance, which often enlarges the ecological footprint of the urban dweller (e.g. research by the Universities of Vancouver and Sydney on the effect of higher population density and increase in lifestyle gadgets owned by urban dwellers).

At the end of the 20th century, Tokyo, Sao Paulo, Mexico-City, Mumbai, Calcutta, Shanghai and Beijing have grown to become endless urban landscapes. They are new types of mega-cities, which express an impossibility of orderly planning and strategic regulation. In his 1994 essay, Rem Koolhaas rightly asked `What ever happened to urbanism?'. In 2000, the term `Climate Change' has been getting widely introduced. We find emerging Green Urbanism theory for the 21st century, which aims to transform existing cities from fragmentation to compaction. Eco-city theory focuses on adjusting the relationship between city and nature. Leading sociologists and urban theorists, including Ulrich Beck, Saskia Sassen, Richard Sennett, Jan Gehl, Manuel Castells, Anthony Giddens, Herbert Girardet, Thomas Sieverts, to name just a few, are exploring wider areas such as globalization, urban sustainability, ecology, network systems, information and communication technologies, and other related fields. Federico Butera, Ken Yeang, Richard Burdett, Jaime Lerner and Jeffrey Kenworthy also made some important contributions to the discussion of sustainable urban planning. Solar cities in Linz-Pichling (Austria), Freiburg-Vauban and the Solar District Freiburg-Schlierberg (Germany), Hanover-Kronsberg (Germany), Stockholm Hammarby-Sjöstad (Sweden), the BedZED Development in Sutton (South of London, UK), and the green district EVA Lanxmeer in Culemborg (The Netherlands) represent some of the built milestones in sustainable urban development at the beginning of the 21st century. The Swedish city of Vaexjö has been very successful in reducing its CO2 emissions and will be, by 2015, entirely independent from fossil fuels. The industrial park in Kalundborg (Denmark) is often cited as a model for industrial ecology, while the city of Waitakere, in the Western part of the greater Auckland urban region, is New Zealand's first eco-city. More recently, excellent compilations of research on sustainable cities have been published by Satterthwaite, Wheeler and Beatley. In the meantime, `Sustainability Science' has emerged as a conceptual and theoretical basis for a new planning paradigm. Today, we can probably recognize two major breaks in the continuous development of cities. The first is connected to the introduction of the automobile, which made possible an entirely different, dispersed city model (the de-compacted `Functional City' of the 20th century). The second, the full awareness of climate change, is of equal importance and just as far-reaching, raising the possibility of entirely new city models and typologies that are likely to emerge: Green Urbanism.

Cities can and must become the most environmentally-friendly model for inhabiting our earth. It is more important than ever to re-conceptualize existing cities and their systems of infrastructure, to be compact, mixed-use and polycentric cities.

2. Formulating the principles of Green Urbanism

Green Urbanism is by definition interdisciplinary; it requires the collaboration of landscape architects, engineers, urban planners, ecologists, transport planners, physicists, psychologists, sociologists, economists and other specialists, in addition to architects and urban designers. *Green Urbanism* makes every effort to minimize the use of energy, water and materials at each stage of the city's or district's life-cycle, including the embodied energy in the extraction and transportation of materials, their fabrication, their assembly into the buildings and, ultimately, the ease and value of their recycling when an individual building's life is over. Today, urban and architectural design also has to take into consideration the use of energy in the district's or building's maintenance and changes in its use; not to mention the primary energy use for its operation, including lighting, heating and cooling. The following diagrams identify the inter-connectedness of issues impacting on urban development decisions.

2.1 Energy, water and food security

This part introduces the *15 Principles of Green Urbanism* as a conceptual model and as a framework for how we might be able to tackle the enormous challenge of transforming existing neighbourhoods, districts and communities, and how we can re-think the way we design, build and operate in future our urban settlements. These principles are partly universal, but there is no one single formula that will always work. To achieve more sustainable cities, urban designers must understand and apply the core principles of *Green Urbanism* in a systematic and adapted way. These principles can be effective in a wide variety of urban situations, but they almost always need to be adapted to the context and the project's scale, to the site's constraints and opportunities. We need to develop a specific approach for each unique site and situation, adapting the principles to the particular climatic conditions, site context, availability of technology, social conditions, project scale, client's brief, diverse stakeholder organizations, and so on. It is an approach to urban design that requires an optimization process and a solid understanding of the development's wider context and its many dimensions before the designer can produce an effective design outcome.

With all this technological progress, we should not lose sight of the fact that a key component in any society's sustainability is more than its carbon footprint. The future of our societies is not just merely a technical matter of finding more eco-friendly energy solutions, but a question of holistic social sustainability and identifying principles for healthy communities.

Fig. 1. The three pillars of Green Urbanism, and the interaction between these pillars. Diagram: courtesy the author, 2007.

2.2 Social sustainability and a healthy community need to be part of any vision of the future

The districts and cities where *the Principles of Green Urbanism* have been applied and integrated in every aspect are urban environments that:

- respond well to their climate, location, orientation and context, optimizing natural assets such as sunlight and wind flow,
- are quiet, clean and effective, with a healthy microclimate,
- have reduced or have no CO_2 emissions, as they are self-sufficient energy producers, powered by renewable energy sources,
- eliminate the concept of waste, as they are based on a closed-loop ecosystem with significant recycling, reusing, remanufacturing and composting,
- have high water quality, practicing sensitive urban water management,

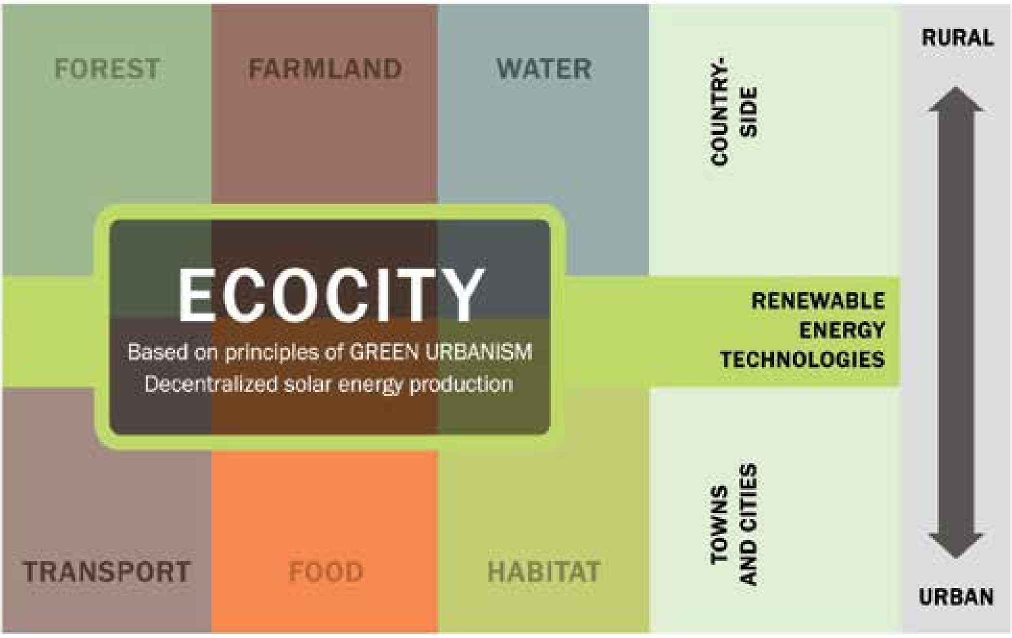


Fig. 2. The holistic concept of Eco-City has again a balanced relationship between the urban (city) and the rural (countryside). Diagram: courtesy the author, 2008.

- integrate landscape, gardens and green roofs to maximize urban biodiversity and mitigate the urban heat island effect,
- take only their fair share of the earth's resources, using principles of urban ecology,
- apply new technologies such as co-generation, solar cooling and electric-mobility,
- provide easy accessibility and mobility, are well inter-connected, and provide an efficient low-impact public transport system,
- use regional and local materials and apply prefabricated modular construction systems,
- create a vibrant sense of place and authentic cultural identity, where existing districts are densified and make use of urban mixed-use infill projects,
- are generally more compact communities around transport nodes (`green TODs'), with a special concern for affordable housing and mixed-use programs,
- use deep green passive design strategies and solar architecture concepts for all buildings, with compact massing for reduced heat gain in summer,
- are laid-out and oriented in a way that keeps the buildings cool in summer, but which catches the sun in winter,
- have a local food supply through community gardens and urban farming and which achieve high food security and reduced `food miles', and
- use multi-disciplinary approach, best practice for urban governance and sustainable procurement methods.

All these criteria make it clear that our design focus should be on the neighbourhood and district scale, with projects on urban infill or redevelopment (brownfield) sites, adjacent to existing developed areas and transport nodes (avoiding further greenfield sites or master planned developments in non-urban areas). The following *Principles of Green Urbanism* were developed to further flesh-out these ideas.

3. The 15 guiding *principles of Green Urbanism*, for local action and a more integrated approach to urban development

The following is a short list of the principles; for full discussion, see my book 'The Principles of Green Urbanism. Transforming the City for Sustainability' (2010). It must be noted, though, that in order to enable sustainable urban development and to ensure that eco-districts are successful on many levels, all urban design components need to work interactively and cannot be looked at separately. The principles are based on the triple-zero framework (triple-bottom line) of:

- zero fossil-fuel energy use
- zero waste
- zero emissions (aiming for low-to-no-carbon emissions).

\`Zero waste' means that buildings are fully demountable and fully recyclable at the end of their life-cycle, so that the site can return to being a greenfield site after use. Understandably, it requires a holistic approach to put the principles in action and to guide the available know-how to the advantage of the city. The principles describe the strategies necessary for eco-districts, although they need to be adapted to the location, context and scale of the urban development. It may be difficult at first to achieve some of the principles, but all are important; they can potentially save money, reach early payback, improve livability and increase opportunities for social interaction of residents. The principles offer practical steps on the path to sustainable cities, harmonizing growth and usage of resources. The truly \`carbon-neutral' city has not yet been built, but all projects introduced in this book are important steps towards turning this vision into a reality.

The sustainability matrix – the *15 Principles of Green Urbanism* – consists of:

Principle 1 Climate and context

The city based on its climatic conditions, with appropriate responses to location and site context. What are the unique site constraints, climatic conditions and opportunities?

Every site or place has its own unique individual conditions in regard to orientation, solar radiation, rain, humidity, prevailing wind direction, topography, shading, lighting, noise, air pollution and so on. The various aspects of this principle include: Climatic conditions, which are seen as the fundamental influence for form-generation in the design of any project; understanding the site and its context, which is essential at the beginning of every sustainable design project; optimizing orientation and compactness to help reduce the city district's heat gain or losses; achieving a city with minimized environmental footprint by working with the existing landscape, topography and resources particular to the site, and the existing micro-climate of the immediate surroundings. Maintaining complexity in the system is always desirable (be it biodiversity, eco-system or neighbourhood layout), and a high degree of complexity is always beneficial for society. Enhancing the opportunities offered by topography and natural setting leads to a city well adapted to the local climate and its eco-system. We can use the buildings' envelope to filter temperature, humidity, light, wind and noise. Due to the different characteristics of every location, each city district has to come up with its own methods and tailored strategies to reach sustainability and to capture the spirit of the place. Each site or city is different and the drivers for re-engineering existing districts will need to understand how to take full advantage of each location's potential, and how to fine-tune the design concept to take advantage of local circumstances. As an aim, all urban development must be in harmony with the specific characteristics, various site factors and advantages of each location and be appropriate to its societal setting and contexts (cultural, historical, social, geographical, economical, environmental and political). In future, all buildings will have climate-adapted envelope technologies, with facades that are fully climate-responsive.

Principle 2 Renewable energy for zero CO2 emissions

The city as a self-sufficient on-site energy producer, using decentralized district energy systems. How can energy be generated and supplied emission-free and in the most effective way?

The various aspects of this principle include: Energy supply systems and services, as well as energy efficient use and operation, promoting increased use of renewable power, and perhaps natural gas as a transition fuel in the energy mix, but always moving quickly away from heavy fossil-fuels such as coal and oil; and the transformation of the city district from an energy consumer to an energy producer, with local solutions for renewables and the increasing de-carbonizing of the energy supply. The supply of oil will last shorter than the life-expectancy of most buildings. The local availability of a renewable source of energy is the first selection criteria for deciding on energy generation. In general, a well-balanced combination of energy sources can sensibly secure future supply. A necessary aim is also to have a distributed energy supply through a decentralized system, utilizing local renewable energy sources. This will transform city districts into local power stations of renewable energy sources, which will include solar PV, solar thermal, wind (on- and off-shore), biomass, geothermal power, mini-hydro energy and other new technologies. Some of the most promising technologies are in building-integrated PV, urban wind turbines, micro CHP and solar cooling. That is to say, there should be on-site electrical generation and energy storage in combination with a smart grid, which integrates local solar and wind generation, utilizing energy-efficiency in all its forms. Solar hot water systems would be compulsory. Co-generation technology utilizes waste heat through CHP combined-heat-and-power plants. Energy-efficiency programs are not enough. Too often we find that savings from energy-efficiency programs are absorbed by a rise in energy use. Genuine action on climate change means that coal-fired power stations cease to operate and are replaced by renewable energy sources. Eco-districts will need to operate on renewable energy sources as close to 100 per cent as possible. As a minimum, at least 50 per cent of on-site renewable energy generation should be the aim of all urban planning, where the energy mix comes from decentralized energy generation and takes into account the resources that are locally available, as well as the cost and the availability of the technology. Optimizing the energy balance can be achieved by using exchange, storage and cascading (exergy) principles. It is, therefore, essential that the fossil-fuel powered energy and transportation systems currently supporting our cities are rapidly turned into systems that are supplied by renewable energy sources. High building insulation, high energy-efficiency standards and the use of smart metering technology is essential, so that if a part of an office building is not in use, the intelligent building management system will shut down lights and ventilation.

Principle 3 Zero-waste city

The zero-waste city as a circular, closed-loop eco-system. How to avoid the creation of waste in the first place – changing behaviour of consumption?

Sustainable waste management means to turn waste into a resource. All cities should adopt nature's zero-waste management system. Zero-waste urban planning includes reducing, recycling, reusing and composting waste to produce energy. All material flows need to be examined and fully understood, and special attention needs to be given to industrial waste and e-waste treatment. We need to plan for recycling centres, for zero landfill and 'eliminating the concept of waste' and better understanding nutrient flows (Braungart, 2002). Eco-districts are neighbourhoods where we reuse and recycle materials and significantly reduce the volume of solid waste and toxic chemical releases. All construction materials as well as the production of goods (and building components) need to be healthy and fully-recyclable. Waste prevention is always better than the treatment or cleaning-up after waste is formed. Some other systems that need to be put in place are: the remanufacturing of metals, glass, plastics, paper into new products needs to be a routine (without down-grading the product); waste-to-energy strategies are needed for residual waste; and an `extended producer responsibility' clause is needed for all products. In this context of waste, better management of the nitrogen cycle has emerged as an important topic: to restore the balance to the nitrogen cycle by developing improved fertilization technologies, and technologies in capturing and recycling waste. Controlling the impact of agriculture on the global cycle of nitrogen is a growing challenge for sustainable development. Essentially, we need to become (again) a `recycling society', where it is common that around 60 to 90 per cent of all waste is recycled and composted. In future, optimizing waste streams and material flows in regard to urban development will be guided by resource recovery and supply chains that use local materials, for achieving closed-cycle urban ecology and reduced material consumption.

Principle 4 Water

The city with closed urban water management and a high water quality. What is the situation in regard to the sustainable supply of potable drinking water?

The various aspects of this principle include, in general, reducing water consumption, finding more efficient uses for water resources, ensuring good water quality and the protection of aquatic habitats. The city can be used as a water catchment area by educating the population in water efficiency, promoting rainwater collection and using wastewater recycling and storm water harvesting techniques (e.g. solar-powered desalination plants). Storm water and flood management concepts need to be adopted as part of the urban design, and this includes storm water run-offs and improved drainage systems and the treatment of wastewater. As part of the eco-district's adequate and affordable health care provisions, it needs to ensure the supply of safe water and sanitation. This includes such things as algae and bio-filtration systems for grey water and improving the quality of our rivers and lakes so that they are fishable and swimmable again. An integrated urban water cycle planning and management system that includes a high-performance infrastructure for sewage recycling (grey and black water recycling), storm water retention and harvesting the substantial run-off through storage, must be a routine in all design projects. On a household level we need to collect rain water and use it sparingly for washing and install dual-water systems and low-flush toilets. On a food production level we need to investigate the development of crops that need less water and are more drought resistant.

Principle 5 Landscape, gardens and urban biodiversity

The city that integrates landscapes, urban gardens and green roofs to maximize biodiversity. Which strategies can be applied to protect and maximize biodiversity and to re-introduce landscape and garden ideas back in the city, to ensure urban cooling?

A sustainable city takes pride in its many beautiful parks and public gardens. This pride is best formed through a strong focus on local biodiversity, habitat and ecology, wildlife rehabilitation, forest conservation and the protecting of regional characteristics. Ready access to these public parks, gardens and public spaces, with opportunities for leisure and recreation, are essential components of a healthy city. As is arresting the loss of biodiversity by enhancing the natural environment and landscape, and planning the city using ecological principles based on natural cycles (not on energy-intensive technology) as a guide, and increasing urban vegetation. A city that preserves and maximizes its open spaces, natural landscapes and recreational opportunities is a more healthy and resilient city. The sustainable city also needs to introduce inner-city gardens, urban farming/agriculture and green roofs in all its urban design projects (using the city for food supply). It needs to maximize the resilience of the eco-system through urban landscapes that mitigate the `urban heat island' (UHI) effect, using plants for air-purification and urban cooling. Further, the narrowing of roads, which calms traffic and lowers the UHI effect, allows for more (all-important) tree planting. Preserving green space, gardens and farmland, maintaining a green belt around the city, and planting trees everywhere (including golf courses), as trees absorb CO_2, is an important mission. As is conserving natural resources, respecting natural energy streams and restoring stream and river banks, maximizing species diversity. At home, we need to de-pave the driveway or tear up parking lots. In all urban planning, we need to maintain and protect the existing eco-system that stores carbon (e.g. through a grove or a park), and plan for the creation of new carbon storage sites by increasing the amount of tree planting in all projects. The increase in the percentage of green space as a share of total city land is to be performed in combination with densification activities.

Principle 6 Sustainable transport and good public space: compact and poly-centric cities

The city of eco-mobility, with a good public space network and an efficient low-impact public transport system for post-fossil-fuel mobility. How can we get people out of their cars, to walk, cycle, and use public transport?

Good access to basic transport services is crucial, as it helps to reduce automobile dependency, as does reducing the need to travel. We need to see integrated non-motorized transport, such as cycling or walking, and, consequently, bicycle/pedestrian-friendly environments, with safe bicycle ways, free rental bike schemes and pleasant public spaces. It is important to identify the optimal transport mix that offers inter-connections for public transport and the integration of private and public transport systems. Some ideas here include: eco-mobility concepts and smart infrastructure (electric vehicles); integrated transport systems (bus transit, light railway, bike stations); improved public space networks and connectivity, and a focus on transport-oriented development (`green TODs'). It is a fact that more and wider roads result in more car and truck traffic, and CO_2 emissions, and also allows for sprawling development and suburbs that increases electricity-demand and provides less green space. The transport sector is responsible for causing significant greenhouse-gas emissions (over 20 per cent). To combat this effect we need to change our lifestyles by, for example, taking public transport, driving the car less, or car-pooling. Alternatively, we can ride a bike or walk, if the city district has been designed for it. Personal arrangements have the potential to reduce commuting and to boost community spirit. We want a city district which is well-connected for pedestrians, a city with streetscapes that encourage a healthy, active lifestyle and where residents travel less and less by car. `Green TODs' are the future, as these developments can create a range of medium-density housing typologies and provide a variety of transportation choices, achieving a balance of residences and employment.

Principle 7 Local and sustainable materials with less embodied energy

City construction using regional, local materials with less embodied energy and applying prefabricated modular systems. What kind of materials are locally available and appear in regional, vernacular architecture?

The various aspects of this principle include: advanced materials technologies, using opportunities for shorter supply chains, where all urban designs focus on local materials and technological know-how, such as regional timber in common use. Affordable housing can be achieved through modular prefabrication. Prefabrication has come and gone several times in modern architecture, but this time, with closer collaboration with manufacturers of construction systems and building components in the design phase, the focus will be on sustainability. We need to support innovation and be aware of sustainable production and consumption, the embodied energy of materials and the flow of energy in closing life-cycles. We need to emphasize green manufacturing and an economy of means, such as process-integrated technologies that lead to waste reduction. It is more environmentally friendly to use lightweight structures, enclosures and local materials with less embodied energy, requiring minimal transport. We need improved material and system specifications, supported by research in new materials and technological innovation; reduced material diversity in multi-component products to help facilitate the design for resource recovery, disassembly, value retention, and the possibility of reusing entire building components. Success in this area will increase the long-term durability of buildings, reduce waste and minimize packaging.

Principle 8 Density and retrofitting of existing districts

The city with retrofitted districts, urban infill, and densification/intensification strategies for existing neighbourhoods. What are the opportunities to motivate people to move back to the city, closer to workplaces in the city centre?

The various aspects of this principle include: encouraging the densification of the city centre through mixed-use urban infill, centre regeneration and green TODs; increasing sustainability through density and compactness (compact building design means developing buildings vertically rather than horizontally); promoting business opportunities around green transit-oriented developments; optimizing the relationship between urban planning and transport systems; retrofitting inefficient building stock and systematically reducing the city district's carbon footprint. Consideration will need to be given to better land-use planning to reduce the impact of urban areas on agricultural land and landscape; to increasing urban resilience by transforming city districts into more compact communities and designing flexible typologies for inner-city living and working. Special strategies for large metropolitan areas and fast-growing cities are required. Here, examples of rapid development are being provided by Asian cities. Special strategies are also needed for small and medium-sized towns due to their particular milieu, and creative concepts are needed for the particular vulnerabilities of Small Island States and coastal cities. Public space upgrading through urban renewal programs will bring people back to the city centre. This will need some strategic thinking about how to use brownfield and greyfield developments and also the adaptive reuse of existing buildings. Remodeling and re-energizing existing city centres to bring about diverse and vibrant communities requires people to move back into downtown areas. This can be achieved through mixed-use urban infill projects, building the `city above the city' by converting low density districts into higher density communities; and by revitalizing underutilized land for community benefit and affordable housing. In the compact city, every neighbourhood is sustainable and self-sufficient; and uses ESCo principles for self-financing energy efficiency and in all retrofitting programs.

Principle 9 Green buildings and districts, using passive design principles

The city that applies deep green building design strategies and offers solar access for all new buildings. How can we best apply sustainable design and passive design principles in all their forms and for all buildings?

The various aspects of this principle include: low-energy, zero-emission designs, applying best practice for passive design principles, for all buildings and groups of buildings; dramatically reducing building energy use; introducing compact solar architecture; and renovating and retrofitting the entire building stock. New design typologies need to be developed at low cost, and we need to produce functionally neutral buildings that last longer. We need to apply facade technology with responsive building skins for bio-climatic architecture, to take advantage of cooling breezes and natural cross-ventilation, maximizing cross-ventilation, day-lighting and opportunities for night-flush cooling; we need to focus on the low consumption of resources and materials, including the reuse of building elements; and design for disassembly. Other ideas include: mixed-use concepts for compact housing typologies; adaptive reuse projects that rejuvenate mature estates; solar architecture that optimizes solar gain in winter and sun shading technology for summer, catching the low winter sun and avoiding too much heat gain in summer. It is important to renew the city with energy-efficient green architecture, creating more flexible buildings of long-term value and longevity. Flexibility in plan leads to a longer life for buildings. Technical systems and services have a shorter life-cycle. This means, first of all, applying technical aids sparingly and making the most of all passive means provided by the building fabric and natural conditions. Buildings that generate more energy than they consume, and collect and purify their own water, are totally achievable. We need to acknowledge that the city as a whole is more important than any individual building.

Principle 10 Livability, healthy communities and mixed-use programs

The city with a special concern for affordable housing, mixed-use programs, and a healthy community. How does urban design recognize the particular need for affordable housing, to ensure a vibrant mix of society and multi-functional mixed-use programs?

Land use development patterns are the key to sustainability. A mixed-use (and mixed-income) city delivers more social sustainability and social inclusion, and helps to repopulate the city centre. Demographic changes, such as age, are a major issue for urban design. It is advantageous for any project to maximize the diversity of its users. Different sectors in the city can take on different roles over a 24 hours cycle; for example, the CBD is used for more than just office work. In general we want connected, compact communities, for a livable city, applying mixed-use concepts and strategies for housing affordability, and offering different typologies for different housing needs. To this end we need affordable and livable housing together with new flexible typologies for inner-city living. These mixed-use neighbourhoods (of housing types, prices and ownership forms) have to avoid gentrification and provide affordable housing with districts inclusive for the poor and the rich, young and old, and workers of all walks of life, and also provide secure tenure (ensuring 'aging in place').

Housing typologies need to deal with demographic changes. We have to understand migration and diversity as both an opportunity and a challenge. Mixed land uses are particularly important as it helps reduce traffic. Master plans should require all private developments to contain 40 to 50 per cent of public (social) housing, and have it integrated with private housing. Higher densities should centre on green TODs. Essentially, these changes will aim to introduce more sustainable lifestyle choices, with jobs, retail, housing and a city campus being close by with IT and tele-working from home significantly helping to reduce the amount of travel (motto: `Don't commute to compute'). By integrating a diverse range of economic and cultural activities, we avoid mono-functional projects, which generate a higher demand for mobility. Green businesses would be supported through the use of ethical investments to generate funding. The question is: how specific or adaptable should buildings be to their use?

Principle 11 Local food and short supply chains

The city for local food supply, with high food security and urban agriculture.
Which strategies can be applied to grow food locally in gardens, on roof tops and on small spaces in the city?
The various aspects of this principle include: local food production; regional supply; an emphasis on urban farming and agriculture, including `eat local' and `slow food' initiatives. The sustainable city makes provision for adequate land for food production in the city, a return to the community and to the allotment gardens of past days, where roof gardens become an urban market garden. It is essential that we bridge the urban-rural disconnect and move cities towards models that deal in natural eco-systems and healthy food systems. The people of the eco-city would garden and farm locally, sharing food, creating compost with kitchen scraps and garden clippings and growing `community' vegetables. Buying and consuming locally will be necessary to cut down on petrol-based transport. Such things as re-using paper bags and glass containers, paper recycling and the cost of food processing will need reconsideration. We will need to reduce our consumption of meat and other animal products, especially shipped-in beef, as the meat cycle is very intensive in terms of energy and water consumption and herds create methane and demand great quantities of electricity. Perhaps as much as 50 per cent of our food will need to be organically produced, without the use of fertilizers or pesticides made from oil, and grown in local allotments.

Principle 12 Cultural heritages, identity and sense of place

The city of public health and cultural identity: a safe and healthy city, which is secure and just. How to maintain and enhance a city's or region's identity, unique character and valued urban heritage, avoiding interchangeable design that makes all cities look the same?
All sustainable cities aim for air quality, health and pollution reduction, to foster resilient communities, to have strong public space networks and modern community facilities. This is the nature of sustainable cities. However, each city has its own distinct environment, whether it be by the sea, a river, in a dessert, a mountain; whether its climate is tropical, arid, temperate, etc, each situation is unique. The design of the city will take all these factors into consideration, including materials, history and population desires. The essence of place is the up-swelling of grassroots strategies, the protection of its built heritage and the maintenance of a distinct cultural identity, e.g. by promoting locally owned businesses, supporting creativity and cultural development. New ideas require affordable and flexible studio space in historic buildings and warehouses. Cities will grow according to the details

and unique qualities of localities, demographic qualities of the populace and the creativity of the authorities and citizens. The aim of a city is to support the health, the activities and the safety of its residents. It is, therefore, incumbent on city councils to protect the city by developing a master plan that balances heritage with conservation and development; fostering distinctive places with a strong sense of place, where densities are high enough to support basic public transit and walk-to retail services.

Principle 13 Improved urban governance, leadership and best practice

The city applying best practice for urban governance and sustainable procurement methods. Which networks and skills can be activated and utilized through engaging the local community and key stakeholders, to ensure sustainable outcomes?

Good urban governance is extremely important if we want to transform existing cities into sustainable compact communities. It has to provide efficient public transport, good public space and affordable housing, high standards of urban management, and without political support change will not happen. City councils need strong management and political support for their urban visions to be realized. They need strong support for a strategic direction in order to manage sustainability through coherent combined management and governance approaches, which include evolutionary and adaptive policies linked to a balanced process of review, and to public authorities overcoming their own unsustainable consumption practices and changing their methods of urban decision-making. A city that leads and designs holistically, that implements change harmoniously, and where decision-making and responsibility is shared with the empowered citizenry, is a city that is on the road to sustainable practices. In balancing community needs with development, public consultation exercises and grassroots participation are essential to ensuring people-sensitive urban design and to encouraging community participation. Citizens need to participate in community actions aimed at governments and big corporations, by writing letters and attending city-council hearings. Empowering and enabling people to be actively involved in shaping their community and urban environment is one of the hallmarks of a democracy. Cities are a collective responsibility. As far as bureaucratic urban governance and best practice is concerned, authorities could consider many of the following: updating building code and regulations; creating a database of best practice and worldwide policies for eco-cities; revising contracts for construction projects and integrated public management; raising public awareness; improving planning participation and policy-making; creating sustainable subdivisions, implementing anti-sprawl land-use and growth boundary policies; legislating for controls in density and supporting high-quality densification; arriving at a political decision to adopt the *Principles of Green Urbanism*, based on an integrated *Action Plan*; measures to finance a low-to-no-carbon pathway; implementing environmental emergency management; introducing a program of incentives, subsidies and tax exemptions for sustainable projects that foster green jobs; eliminating fossil-fuel subsidies; developing mechanisms for incentives to accelerate renewable energy take-up; implementing integrated land-use planning; having a sustainability assessment and certification of urban development projects.

Principle 14 Education, research and knowledge

The city with education and training for all in sustainable urban development.

How to best raise awareness and change behaviour?

The various aspects of this principle include: technical training and up-skilling, research, exchange of experiences, knowledge dissemination through research publications about ecological city theory and sustainable design. Primary and secondary teaching programs need to be developed for students in such subjects as waste recycling, water efficiency and sustainable behaviour. Changes in attitude and personal lifestyles will be necessary. The city is a hub of institutions, such as galleries and libraries and museums, where knowledge can be shared. We must provide sufficient access to educational opportunities and training for the citizenry, thus increasing their chances of finding green jobs. Universities can act as `think tanks' for the transformation of their cities. We also need to redefine the education of architects, urban designers, planners and landscape architects. Research centres for sustainable urban development policies and best practice in eco-city planning could be founded, where assessment tools to measure environmental performance are developed and local building capacity is studied.

Principle 15 Strategies for cities in developing countries

Particular sustainability strategies for cities in developing countries, harmonizing the impacts of rapid urbanization and globalization. What are the specific strategies and measurements we need to apply for basic low-cost solutions appropriate to cities in the developing world?

Developing and emerging countries have their own needs and require particular strategies, appropriate technology transfers and funding mechanisms. Cities in the developing world cannot have the same strategies and debates as cities in the developed world. Similarly, particular strategies for emerging economies and fast-growing cities are required, as is the problem of informal settlements and urban slums and slum upgrading programs. Low-cost building and mass housing typologies for rapid urbanization are required in cooperation with poverty reduction programs. It is essential that we train local people to empower communities, creating new jobs and diversifying job structures, so as not to focus on only one segment of the economy (e.g. tourism). Achieving more sustainable growth for Asian metropolitan cities is a necessity. Combating climate change, which was mainly caused through the emissions by industrialized nations and which is having its worst effect in poorer countries in Africa, Asia and Latin America, with a focus on Small Island States, is a priority.

4. Passive and active design principles for material and energy-efficient, climate-responsive buildings and cities

The presented principles are about holistic strategies and integrated approaches: The most successful solutions are now the highly effective combination of passive design principles with some well considered *active systems, for buildings that are built to last longer.*

Before electrical heating, cooling and illumination became common, architects used a combination of passive design principles to ensure that interiors were well lit and ventilated through passive means, without any use of mechanical equipment. However, since the early 1950s most architects and engineers have simply employed air-conditioning systems for cooling, as energy from fossil fuels was cheap and plentiful, and air-conditioning systems allowed for deep-plan buildings, internalized shopping mall complexes and other highly inefficient air-conditioning dependent building typologies.

The biggest energy consumers in buildings are technical installations for cooling interiors and lighting. The extensive use of glass surfaces in the facades of buildings (especially in hot, tropical or subtropical climates) and materials that easily store the heat in summer

Fig. 3. The outlined 15 principles of Green Urbanism aim to guide urban designers and decision-makers. Diagram: courtesy the author, 2008.

frequently lead to solar overheating, which has led to the widespread use of mechanical systems (air-conditioning systems) (Aynsley, 2006). Buildings in the tropics are a particular challenge due to the high humidity and temperatures. However, the tropics are home to almost two-thirds of the world's population, so practical and achievable solutions are of particular relevance. With more careful building design, energy-hungry air-conditioning systems could be avoided in almost any climate. Instead of the use of mechanical air-conditioning systems, substantial improvements in comfort can be achieved by the informed choice of materials appropriate to basic passive energy principles and the optimization of natural ventilation (cross-ventilation, night-flush cooling, mixed-mode systems), summer shading and winter solar heat gain. Solar and wind energy can provide heating, cooling and electric power.

On the other hand, buildings from a pre-air-conditioning era frequently display a convincing application of passive design principles, such as their optimized orientation, the use of evaporative cooling, strategic use of thermal mass, trompe walls, ingenious sun-shading devices for the western facade, solar chimneys, courtyards allowing for cross-ventilation of hot air at the highest point in the room, and natural cross-ventilation adjustable to the changing directions of a breeze. Sub-slab labyrinths for fresh air intake, activating the thermal mass, have recently seen a comeback in many projects. Such underground air chambers, called thermal labyrinths, are frequently used to ventilate rooms, with air cooled naturally by travelling a long distance underground through channels in the earth. Energy savings from the use of thermal labyrinths can be significant (Daniels, 1995, 2000). In addition, the use of local materials with less embodied energy (combined with local workforce and locally available technical know-how) has recently led to regional 'styles' in architecture.

Successful buildings of the future will increasingly rely on the critical examination of, and learning from, buildings of the past (Vale and Vale, 1991, 2000; Hyde, 2000). There is so much we can learn from such studies, e.g. which passive design principles have delivered the most

Source: Umweltbundesamt, 2009

Fig. 4. The average German household produces around 43.5 tonnes of greenhouse gas emissions per year. Diagram: courtesy Umweltbundesamt, Germany, 2009.

energy savings? How has adequate active and passive thermal storage mass been provided? There is a good reason why passive design principles have traditionally been preferred to (and are now once again being chosen over) active systems. 'We need solutions for buildings that can do more with less technology', argues engineer Gerhard Hausladen, adding: 'The optimization of the building layout and detailing of the facade system are essential for an integrated approach to the design of low-energy consuming buildings and cities' (Hausladen et al., 2005; 41). Just optimizing buildings through the application of passive design principles can deliver energy savings of up to 80 per cent (Hausladen et al., 2005).

A building's location and its surroundings play a key role in regulating its indoor temperature, the illumination of space and the capacity to minimize energy use. For example, trees and landscaping can provide shade or block wind, while neighbouring buildings can overshadow a building and thus increase the need for illumination during daytime. This is why the designer needs to understand the site conditions and the effective application of passive design principles fully (Hall and Pfeiffer, 2000; Gauzin-Mueller, 2002; Treberspurg, 2008).

4.1 Focusing on basic, low-tech passive design principles

For buildings to have the minimum adverse impact on the natural and built environment, energy-efficient building design needs to balance a whole range of requirements from various inter-linked issues, including (but not limited to):

- design strategies based on a deep understanding of site and context
- strategies for energy efficiency (operational and embodied)
- strategies for water efficiency
- material efficiency: focusing on material flows and embodied energy (life cycle)
- overall material and waste streams during construction, operation and demolition
- integrating passive design principles, such as optimizing the building's shape and orientation, employing natural ventilation, use of daylight, thermal mass, sun shading, solar gains, the use of courtyard typologies, etc.
- reducing overall greenhouse gas emissions from construction, operation and demolition
- integrating community well-being and sundry social dimensions
- health and quality of indoor environment (occupants' comfort).

The need to minimize non-renewable resource consumption and reduce waste poses significant challenges for the building designer as well as construction companies, and for building operators during the period of building use. It is obvious that some of the earliest design decisions have a significant impact on energy efficiency and opportunities to use passive solar power or natural ventilation, such as decisions on: building orientation, placement on site, compactness and geometry, typology, material choices, facade openings, etc.

While recognizing that using more electricity from non-fossil fuels (such as solar and wind power) will help to address climate change, the building designer is likely to focus primarily on cutting energy consumption (Keeler and Burke, 2009). Reducing energy consumption with energy-efficient building design strategies is vital because it helps to preserve finite resources, lowers costs for businesses and consumers and can often be accomplished relatively quickly (again, the *low-hanging fruit* aspect). The World Business Council for Sustainable Development (WBCSD) points out that 'realistically, the contribution of renewable energy sources is likely to be constrained for several decades, only increasing slowly, although it can be observed that values and attitudes in society towards renewable energy sources have started to change and will continue to change over time' (WBCSD, 2009; 12).

Buildings using passive design principles are usually naturally ventilated (or use mixed-mode systems, which is a combination of natural ventilation and additional mechanical cooling during summer months) and are well day-lit to minimize the need for active systems of climate control and artificial lighting (Daniels and Hindrichs, 2007). Green roofs help to cut energy consumption by providing insulation to the building and by acting as filtration for the rainwater capture system, and at the same time increasing the city's biodiversity.

Studying the built heritage plays an important role in the shift towards a low-carbon society. It offers a large resource of knowledge about design principles and how architects have operated for hundreds of years within the challenges of hot, arid or tropical climates. This knowledge has not been sufficiently discussed, taught and researched. In the light of globalization, it is increasingly necessary for the existing authentic built heritage to be a significant contributor to local identity, helping to define the unique character of a location, supporting local people to achieve social outcomes and as a memory of a place. The diversity and rich complexity of tangible and intangible heritage is a constant inspiration that deserves to be better maintained and protected.

Research in pre-air-conditioning built heritage is particularly relevant for the future of the Asia-Pacific region, where we can find rapid urbanization, sometimes combined with too much reliance on outdated models of urban growth and building designs, thus further increasing energy demands. This can include an unusually high dependency on mechanical (air-conditioning) systems, thereby creating large CO_2 emissions and high operating costs in both residential and commercial building stock. In current discussions about sustainability and climate change, we can observe a re-appreciation and evaluation of the built heritage in harmony with its climatic conditions and geographic location. The Asia-Pacific region's humid tropical climate poses a particularly difficult problem. It has temperatures often around 30 degrees Celsius during the daytime and around 25 degrees Celsius at night, and has a high relative humidity of about 90 per cent. This is typical for Singapore, Hong Kong, Bangkok, Jakarta, Manila and other large tropical cities suffering from the Urban Heat Island (UHI) effect. Such conditions leave little scope for night-flush cooling, and refreshing breezes (air flow) are often lacking for long periods (Aynsley, 2006). Serious climate engineering strategies are needed, and the de-humidification of the air as part of a cooling process is a preferable option. There are some particularly exciting developments in the innovative area of 'solar cooling'. So far, around 400 installations worldwide already use such innovative solar cooling technology (Kohlenbach, 2010).

The UHI effect has been particularly difficult for large cities located in tropical regions. Hong Kong, for instance, has a very high population density and is always praised for its efficient public transport systems (Owens, 1986; Newman and Kenworthy, 1989). But the city has an extremely high dependency on air-conditioning and the lack of natural air ventilation in the city has emerged as a serious planning issue. Most buildings are not insulated and lack any external sun shading of their facades.

Brooks and Hyde have pointed out how a site's micro-climate can be modified through careful site planning, leading to improved thermal comfort of outdoor spaces, increased capacity for natural ventilation and sun control in buildings, and therefore reduced cooling loads (Brooks, 1988; Hyde, 2000). Traditionally, in cities in Asia and the Middle East, there has always existed a large repertoire of climatically adaptive and culturally sensitive urban form, which is found in the traditional use of courtyard typologies and low-rise housing, even in high-density districts, with narrow, shaded laneways. In addition, there is a variety of passive cooling techniques that can be utilized for particular climate types, such as shaded spaces with courtyards and atria for effective cross-ventilation, open circulation with breezeways and verandahs, roof ventilation, solar chimneys and similar techniques.

The main principles of material and energy-efficient design include:

- optimal orientation, appropriate window size and sun control (effective shading)
- compact building form (building geometry with less facade surface)
- building mass modified to increase natural air flow through site (catching breezes)
- cross-ventilation and day lighting, with effective external sun shading (e.g. a louver system for sun control, using vertical shading louvers at the eastern and western

facades; these have the advantage of retaining the outside view and are more effective than horizontal louvers)

- passive solar heating for winter months
- evaporative cooling systems
- strategic selection of materials for use of thermal mass (e.g. choice of lightweight or heavy construction materials, with exposed, ‘activated’ concrete surface)
- rooftop vegetation, gardens and water surfaces for improved micro-climate and reduced heat load
- night-flush cooling through openings, activating thermal mass (using night purge)
- sub-slab labyrinths, bringing in outside air through underground, cool air channels beneath the slab
- white (not dark) facade and roof colouring
- optimal sun shading devices, with wide roof overhangs to shade windows
- landscaping for westerly facade protection
- high insulation of external walls and roofs.

These strategies are often combined to make them work together as a system; for instance, by linking high thermal capacity (thermal mass) for heat sink effects with passive solar heating, or with cross-ventilation for night-flush cooling (summer cooling). The use of lightweight exterior facade construction elements with low thermal capacity can help to avoid the accumulation, storage and re-radiation of heat.

Deep building plans, beyond a maximum of 15 metres in depth, have disadvantages, as these can significantly reduce the effectiveness of day lighting and natural ventilation, leading to greater dependency on air-conditioning systems, thereby negatively impacting on the occupants’ health, thermal comfort, productivity and overall working conditions. Therefore, four of the most applicable and widely used passive design strategies are:

- avoiding large glazing that receives direct sunlight and is without shading (design of high quality external shading)
- reducing the surface-to-volume ratio as much as possible through compact building massing
- using window sizing strategically in the design of the building (depending on orientation)
- maximizing day lighting and natural cross-ventilation through slim building plans.

4.2 The case of not Hammarby Sjöstad in Stockholm

A widely recognized green urbanism model district is 'Hammarby Sjöstad', an inner-city district of the Swedish capital city of Stockholm. It occupies an area of about 200 hectares, which, according to the masterplan, will comprise 11,000 apartments, for about 20,000 residents, and an additional 200,000 sqm area of commercial space by the year 2018. The project, which was started in the mid 1990s, expands the inner city centre towards to the waterfront, having water as a central focus for the development. It is the conversion of an old industrial and harbour area (brownfield site) into a modern, sustainable neighbourhood. Hammarby Sjöstad has a strong emphasis on design principles of ecology and environmental sustainability. The development links the city centre with the new urban district by using same street dimensions, block lengths, building heights, density and mix of uses as can be found in the city centre, delivering a high quality neighbourhood. One could say that the new district has a traditional Swedish structure, which it has combined with a modern architectural language that responds to the specific waterside context. The design promotes sustainability and follows modern architectural principles, such as maximising light and views of the water and green spaces. It follows standard dimensions of street width (18 m), block sizes (70x100 m), density, and land use. Public transport and the creation of new road and tram infrastructure make the area easily accessible.

The scale of the development varies from four to five storeys along the canal and 6 to 8 storeys along the inner area. The spine of the new district is a 37.5 m wide boulevard, which connects key transport nodes and public focal points, creating a natural focus for activity and retail. The ground floors of nearly all the buildings along this boulevard have been designed as flexible spaces, suitable for commerce, leisure or community use. Many residents work in the neighbourhood which allows them to walk to work.

The residential districts adjacent to the main spine follow a grid structure with a semi-open block form, which delivers maximum daylight and long views, as well as providing open access to the courtyards of residential blocks. Most apartments have balconies overlooking the streets and waterfront. An inter-connected network of varied parks, green spaces and walkways runs through the district as well as pedestrian paths, quays and linear parks across the waterfront, offering access to the residents towards the boat moorings in the summer. Community provisions include a modern church building, two public schools, one private school, one pre-school and nursery, a health centre, a library, a sports centre, a football pitch and basketball court and other amenities.

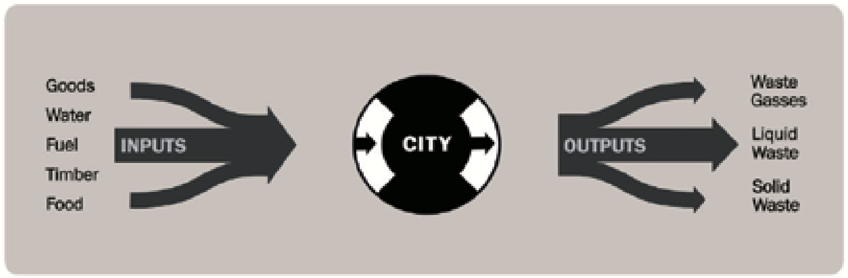
Fig. 5. a. Example of Green Urbanism in practice: The green district Hammarby Sjöstad in Stockholm, built 1995-2008 on land formerly used by the port (to be fully completed in 2018). It is widely accepted as a best practice model for sustainable urban development, having included in its urban development innovative principles of water and waste management and reduction of car dependency. Image: courtesy City of Stockholm, Sweden, 2008.

Fig. 5. b. Stockholm's green district Hammarby Sjöstad includes on-site energy generation with solar cells and green roofs, as well as principles for sensitive urban water management. Image: courtesy City of Stockholm, Sweden, 2008. See also: http://urbantheory-hammarbysjostad.blogspot.com/ for further information on this green district.

5. Conclusion and outlook: towards a circular urban metabolism

It is important to note, that a couple of innovative engineering solutions will not deliver a vibrant city. All the technology in the world cannot achieve sustainability and vitality by

NOW: LINEAR METABOLISM



FUTURE: CIRCULAR METABOLISM

Fig. 6. Moving from a non sustainable linear metabolism towards a more sustainable, circular metabolism, requires the looping and re-use of materials and products. Less required input and less waste generation are the characteristics of such a healthier city structure. Diagram: courtesy the author, 2010 (after: H. Girardet, 1999).

itself. The problem of urban design is far more complex. Designing a city requires holistic, multi-dimensional approaches, and each time the adaptation of strategies to a unique context: the integration and combination of qualitative and quantitative knowledge.

There is now a growing interest in understanding the complex interactions and feedbacks between urbanization, material consumption, energy and water efficiency and the depletion of our resources. The question how far urban form and population density impact on resource consumption is important but still not fully understood.

Much of Green Urbanism is common sense urbanism. In the future, *Green Urbanism* has to become the norm for all urban developments. The presented *Principles of Green Urbanism* are practical and holistic, offering and integrated framework, encompassing all the key aspects needed to establish sustainable development and encouraging best practice models. However, more research in these principles and their inter-connectedness is necessary, to give better guidance for urban designers and decision-makers. The replicability of models is hereby very important. The principles form a sustainability matrix, which will empower the urban designer – to use Richard Buckminster Fuller's words – 'to be able to employ these principles to do more with less.'

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Part 3

Adapting to the New Climate

15

Methods of Analysis for a Sustainable Production System

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1. Introduction

A **manufacturing process** is the set of operations required to modify the characteristics of raw materials (Wikipedia, 2011). This transformation can be of different nature, both in shape, density, strength, size, aesthetics, etc., performing in the field of industry.

In most cases, to obtain a particular product is needed lots of individual transactions so that, depending on your point of view, we could identify both the ***manufacturing process*** from supply operations of natural resources raw material to product sales, or only those in a job with a particular machine tool.

In this way we identify the magnitude of the problem, as our analysis could include the manufacturing chain or only one stage of that chain.

Are discussed below various methods to analyze, but one of the fundamental objectives that appear common in different reference articles aim is to reduce the environmental impact of product, where our goal should be along the manufacturing cycle of life, from raw material procurement, manufacturing and even the disposal of the product once it is discarded.

The importance of the approach from a global view of the product, allowing a clear identification of all the **inputs/outputs** that involve environmental impact, not only limited to our production line or a particular stage of the cycle, applying environmental measures in all its manufacturing.

Complementing the global aspect which we refer in the previous section, from the point of view of the product, we find ourselves with the global, but this time from the point of view of trade, the market is not only a local authority independent, but a gear in a globalized industry.

The global aspect has forced companies to become aware of not only the search of product quality and to work safely, but to get an environmental culture, thus was born the idea of total quality and environmental management systems environment as a necessary part of management in the company, increasingly important the Environmental Management Systems and ISO 14001, as a reference for implementation.

At this point, we can guess the concept of **sustainable development**, based on a balanced use of natural resources, and implementation of environmental concepts in manufacturing systems throughout their life cycle.

While the concept of sustainable development has created a new concept, the concept of sustainable manufacturing has undergone profound changes in professional disciplines, and specifically in engineering.

Engineering has seen the need to learn environmental knowledge and help respond to humans increasingly concerned and aware of environmental issues.

Of course we will see in this chapter the different definitions of a **sustainable production system**, but these records can provide the introductory character, to have a global perspective, before we start our development of this discipline and relatively recent boom.

2. Objectives

The aim of this chapter is a study on sustainable manufacturing systems, in several stages:

- 1° Phase: Define what you understand the various authors of the bibliography of reference for a sustainable production system.
- 2° Phase: Describe the different methods of analysis for sustainable manufacturing systems (LCA, LCIA, LCC, EDIP, etc.).
- 3° Phase: Analyze the interdependencies among the different methodologies, their advantages and disadvantages, etc.
- 4° Phase: Summary of the conclusions reached by the development of the chapter.

3. Development

As we presented in the introduction, we will understand what each of the authors of a sustainable production system, starting with first reference (Alting et al.,1998), these authors suggest that in recent years, both manufacturing industry and the culture of consumerism in which humanity has been placed in recent times is undergoing a major change due to various problems:

- Pollution and waste problem.
- Consumption of non-recyclable resources (oil, for example).
- Rapid growth in world population (which implies a growth in demand, both production and consumption).

Developed countries should be aimed at combating poverty and improving the health of the least developed countries, for it must set a target to fight because these countries have economic growth.

This mentality is slowly getting. The evidence is the aid from developed countries is limited mostly to food and supplies, that perspective is changing soon forgotten enhancing aspects such as technological development or infrastructure of the least advantaged, to ensure that economic development and can survive by themselves.

According to the authors, the definition of sustainable is becoming more common today, but is used with different meanings, and which is determined according to the appropriate group that definition.

If we take the environment of a company, sustainability criteria will be totally different if that goal comes from shareholders, customers, suppliers, employees, business locally, nationally, internally, etc. (Alting et al., 1998).

According to the study, although there are different criteria for sustainability under the entity from which they emanate, it concludes that any company have to fulfill several functions for Sustainability:

- Economically sustainable.
- Socially sustainable.
- Sustainable with the environment.

These conclusions indicated by the authors and predicted the way the company which tends today to comprehensive management, integration into the structure of the company hierarchy of different objectives, which correspond to the following pillars:

- Quality Management (ISO 9000) → Economically sustainable.
- Prevention Management (OHSAS 18000) → Socially sustainable.
- Environmental Management (ISO 14000) → Sustainable with the environment.

We observe that although at first the term sustainability figure indicates that there is environmental sustainability, this is not the unique that influences the production environment, but has a more global character, based on the pillars mentioned above.

We could give an example, in this variety of meanings, which is the definition of **sustainable process** according to the Royal Spanish Academy (Real Academia Española, 2001): "You can maintain itself, as does, i.e. economic development without outside help or depletion of existing resources".

In this definition of the Spanish Royal Academy, the **sustainable process** goes in the direction at economic sustainability, which lacks its own resource consumption. Perhaps this definition is more directed to the environment or **renewable energy clean energy**, obtaining energy resources, mainly where there is no consumption of material resources, but it gets the production of energy.

3.1 Definition of sustainable production system

First we will analyze the different reference articles, and finally we try to agree a general definition for a sustainable production system.

3.1.1 Alting et al., 1998

According to the study Elements in a new industrial culture - Environmental Assessment in Product Development (Alting et al., 1998), the direction of sustainable production has been focused on manufacturing steps and phases of product distribution.

The study perspective is centered on the product life cycle:

- Raw Material Procurement.
- Manufacture.
- Distribution and product use.

The manufacturing steps and phases of product distribution can achieve great things. Prioritization by the company from manufacturing and distribution company is located in a development phase where the meet quality requirements and costs are extremely important. Currently, the industry had a concept of economic sustainability, where the flow INPUT/OUTPUT is very important, even without optimizing the resources use. The consumption of raw material and energy consumption has grown increasingly making an impact on the environment.

In this study, the authors recommend a change focus in the product life cycle, where companies must develop products from the perspective of optimizing resources and environmental impact in all life cycle phases.

The product environmental factor is a factor that is becoming more developed today, similar to development in the manufacture of products or distribution.

The perspective of sustainable manufacturing system from the point of view of the authors must be fundamentally sustainability with the environment, both at the stage of raw material procurement, and throughout the manufacturing process and transportation, combined with sustainability social, avoiding risks to workers.
The sustainability criterion with the environment must appear from the moment of conception to the production system where the designer must take into account the conditions discussed above (client, law, economics, etc.) to its junction with following factors:

- Resources.
- Environmental Impacts (Local, Regional and Global).
- Work environment impacts (chemical, repetitive work, noise).

Only in this way we get a sustainable production system.

3.1.2 Bley & Behrning, 1998

According to the study Methods for Qualitative and quantitative analysis of lubricants and contamination on Form Surfaces (Bley & Behrning, 1998), the environment is increasing importance with the current procedures for product quality and economic viability.
Similar to the previous article (Alting et al., 1998), mentions that the success of a company has unquestionably been linked to several factors:

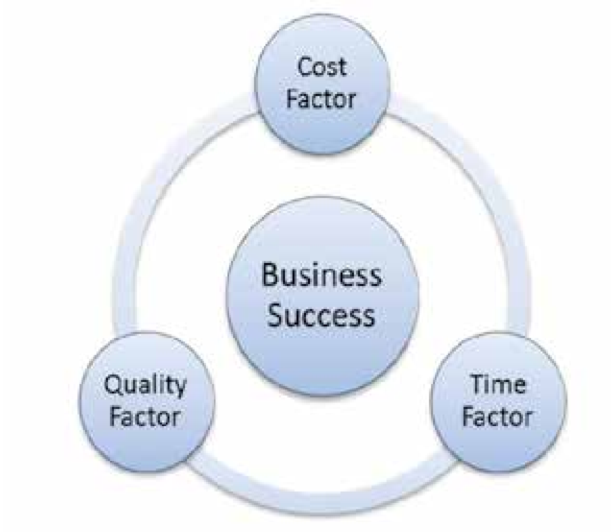

Fig. 1. Business success scheme (old)

An important factor is reflected in the study (Bley & Behrning, 1998), are the legal restrictions, this factor greatly influences industrial, since due to new environmental regulations, which require industries to change their production system to be more sensitive to the environment.
In the document, present as an important element the use of lubricants and pollution which generate on the environment, where the current laws recommended and prohibited the use of certain substances, whether they are harmful to the environment, either because they are dangerous for use by staff working in the industry.

The industry must adapt to the environment where it locates its manufacturing industry, legal requirements and the community significantly affects the prohibition of the use of certain products and even the need to reduce emissions of air pollutants on pain heavy fines have forced the industry to reinvent itself, including **the environment sustainability** for achieving business success.

The model indicated in Figure 1, to be a management model complemented by the environmental factor, such as the following:

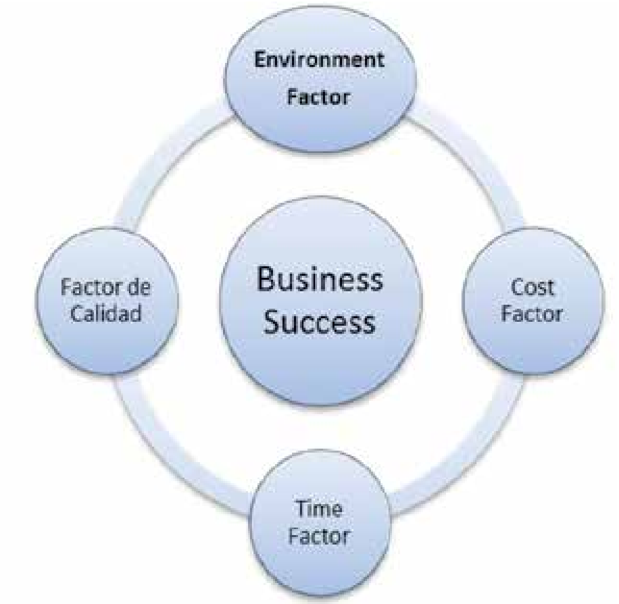

Fig. 2. Business success scheme (new)

In this case (Bley & Behrning, 1998), are indicated factors of economic and sustainability with the environment, so you get a **sustainable production system**.

3.1.3 Bley et al., 1997

According to the study Mutual effects in a sequence of cutting and cleaning (Bley et al., 1997), displayed the same premises as in the previous article, where the environmental factor is increasing its importance on the quality standards and economic viability.

In this work not only shows the legislative factors and their influence on the production system, but also it appears a new factor, the behaviour of consumers.

Also Appears a new element today is becoming more important, the environmental image provided by the company and its relationship with consumers.

Keep in mind that any production system aims to meet the need of consumers and they are finally in the market supply will become a brand.

The concepts of quality and cost are supported as already implicit in any product that is marketed, but the products need a specific character, an item that you place over your competitors; here is where the environmental factor is a necessity imposed by society, which must be understood by the employer and integrated into manufacturing process.

With regard to the needs imposed by society, not just about customer satisfaction, but in addition to implementing **social sustainability**, where the health of workers must be present in conjunction with the **sustainability of the environment**.

In this article appears another factor that has not been analyzed, but possibly had been included to indicate the improvement of the production process and minimizing environmental impact, which is the consideration of environmental aspects such as:

- Waste treatment.
- Product recycling.
- Verification and control system.
- Modification of manufacturing sequences.

The aim should be to structure and improve the production system, primarily to the reduction of waste generated, and later proceed to recycling and final verification. In part, this obligation is imposed by state laws, which require the improvement in the management and treatment of waste generated.

The strategy to reach a **sustainable manufacturing** must include analysis of all production systems individually, but sometimes it does not become possible, the problems that can generate, at least it would be important to analyze in particular the points adversely affect more critical to the process sustainability.

3.1.4 O'Brien, 1999

According to the study Sustainable production - a new paradigm for a new millennium (O'Brien, 1999), the concept of sustainable production is the most important element is to be developed for the S. XXI, similar to the twentieth century industrial automation and even the steam era of the nineteenth century.

As indicated in their study, the current industry is not sustainable in the long term due to excessive consumption of world natural resources. Current consumption rates, before present only in the developed world, have been taken as a model for developing countries, so the problem is not maintained, the problem increases exponentially.

There are several factors that will influence greatly in reaching a sustainable manufacturing, critical factors that threaten the economy and industrial development:

- The increase population.
- Food production.
- Industrialization.
- Depletion of natural resources.
- Contamination.

Gradually, through the twentieth century has worked in the pursuit of sustainability, achieving **meet present needs without compromising future needs**. This sentence clearly reflects what sustainability means.

In the twentieth century and nineteenth century there have been numerous meetings between political representatives of all nations worldwide, protected under the United Nations agency (United Nations, 2002), which have established common objectives for the pursuit of sustainability, allowing governments establish their commitment to acquire these objectives (water, education, air emissions, desertification, biodiversity, etc.)..

On a more focused, as indicated in this article (O'Brien, 1999), the industry has accepted the need to act, due largely to government law enforcement, so particular in the treatment of waste, control of air emissions, water treatment and waste transportation to landfills.

This article appears another factor that until now had not appeared, the concept of **eco-efficiency**, which means a further improvement in productivity, from the economic point of view, along with a respect for the environment. The efficiency gains with the implementation of green practices.

Also appears another important concept, the **factor 10**, this factor represents the commitment to the objectives that governments should arrive in 2040, so if the current consumption is reduced to 10% of total resources, would continuity of ongoing development and sustainability in balance with the planet, avoiding depletion of natural resources for future generations.

For a **sustainable production system** (O'Brien, 1999), the author refers primarily to a **sustainability with the environment**, where industry must not only act as a system to create wealth but to create wealth in a sustainable way, avoiding the depletion of natural resources that are becoming scarcer, accompanied by **economic sustainability**, with increased efficiency, together with **social sustainability**, to adapt to the environment and the needs of society.

3.1.5 Capuz & Gomez, 2002

According to Ecodesign - Life Cycle Engineering for Sustainable Product Development (Capuz & Gomez, 2002), establishing a parallelism between two fundamental concepts, on the one hand the **sustainable development**, and on the other hand, the industrial ecology.

Sustainable development comes rather as a response to growing concerns about environmental degradation, together with the relations between human beings, caused by the characteristics of social, economic and technical, which can be described as unsustainable in the medium term.

Sustainable development aims to build a new development model that allows one hand to meet the needs of the current population of the planet, and on the other hand, preserve the environment as it is today, or even improvement. The challenge is that future generations have the same opportunities as present generations, so they can get the same quality of life that current generations.

On the one hand, the industry should respond to society and obtain in return a profit, but to do so, the industry must have a relationship with nature, **eco-efficiency** must extract the natural resources efficiently and sustainably.

On the other hand, citizens must accept and assume the importation of nature, taking a **responsible consumption**, minimize environmental impact and fair treatment to the underprivileged as well as requiring the administration to change the economic model to a model responsible, environmentally sustainable; we need a **citizen participation and solidarity**.

These complex relationships, which link the different concepts of **economic, social sustainability** and **environment sustainability,** are reflected in the following figure:

With respect to **industrial ecology**, in the book (Capuz & Gomez, 2002) is referred to the production industry in particular, as shown in the illustration above, since it identifies the industry as the main source of environmental impact.

Industrial ecology represents the model of productive activity that will contribute to realization of **sustainable development**, which is based on three strategies:

- Eco-efficiency.
- Environmental management.
- Eco-industrial parks.

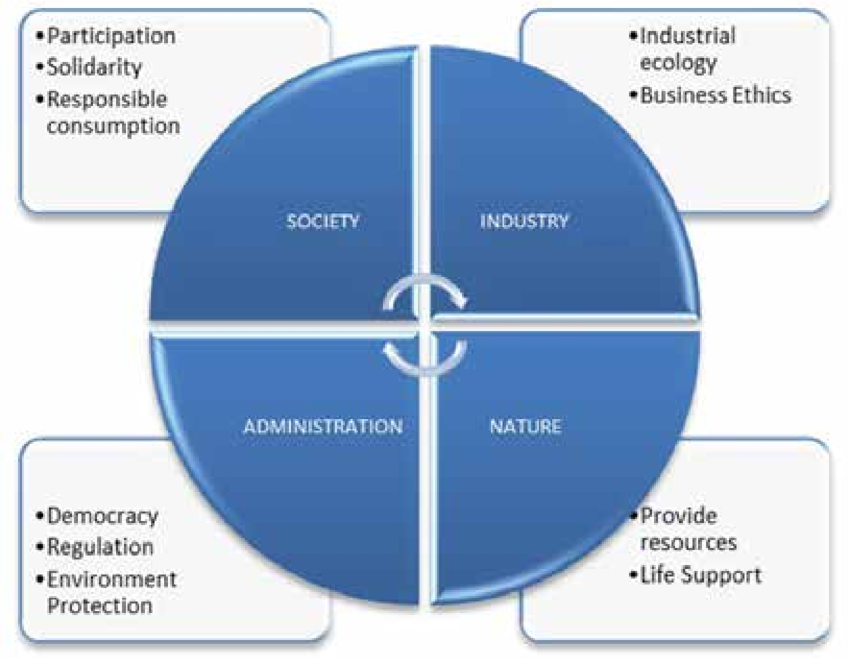

Fig. 3. Elements involved in sustainable development

The objective of **industrial ecology** is based on reaching an economic structure in which the consumption of raw materials and energy are reduced to values that the biosphere is able to replace, and waste emissions are reduced to values such that biosphere to assimilate.

We can conclude that for a **sustainable production system** (Capuz & Gomez, 2002), understood from a global view, the pursuit of **sustainability with the environment**, avoiding a consumption rate that makes impossible its regeneration by the biosphere, trying to reach **economic sustainability** with the need to integrate environmental policy, together with **social sustainability**, where both by society and governments to impose this change in global consciousness at all levels.

3.1.6 Goedkoop & Spriensma, 2001

According to the book The Eco-indicator 99 - A Damage oriented method for Life Cycle Impact Assessment (Goedkoop & Spriensma, 2001), production and sustainable consumption can only be achieved if all business actors work responsibly.

The objective is to introduce environmental consciousness at each stage, decisions made by both the industry, the SMEs and the consumer, a process that must be in continuous development and should be encouraged and promoted by governments.

Regarding the definition of environment in the book (Goedkoop & Spriensma, 2001) is guided by the type of damage, as can be seen in the following table:

The Eco-indicator 99 is a method of LCA (Life Cycle Assessment), especially for the design of products, and has proved a powerful tool for designers to interpret the results of the LCA, by simple numbers or units, called Eco-indicators.

We can conclude, similar to previous book (Capuz & Gomez, 2002), which for a **sustainable production system**, the authors (Goedkoop & Spriensma, 2001) understand overview, while product-oriented, in the pursuit of **sustainability with the environment**, led the movement for **social sustainability**, where governments and citizens are aware of the importance of environmental sustainability. **Economic sustainability** in this case is influenced by environmental conditions, where they accept that this process cannot be as economically beneficial for all companies and should be supported by governments through incentives.

Object	Damage Type	Effects
Human Health	• Number and duration of disease. • Years of life lost to premature death	• Climate Change. • Ozone Decrease. • Carcinogens and Respiratory Effects. • Ionizing Radiation.
Quality Environment	• Effect on species diversity.	• Ecotixidad. • Acidification. • Eutrophication. • Land Use.
Natural Resources	• Need extra power to extract resources future.	• Decreased gross resources.

Table 1. Effects depending on the type of damage

3.1.7 Ihobe S.A., 2000

According to the Manual of Ecodesign - Operational Implementation in 7 steps (Ihobe S.A., 2000), it is necessary to incorporate the **environmental factor** in industry and society in general, this requires a change of mind on business, as in near future will be necessary to think of producing goods, preserving environmental resources and generating less waste.

Identifies three factors that significantly influenced the integration of environmental factor, such as a business factor in the design of most industrial products:

- The evolution of European and world markets.
- The evolution of environmental legislation.
- The end customer demand.

The benefit of minimizing environmental impacts (Ihobe S.A., 2000), is not unique, there are other advantages that should be taken into account by companies to integrate environmental philosophy into their product:

- Cost reduction, both the company and the end consumer.
- Nature of Innovation, which gives it an added attraction to the product to the final consumer.
- Comply with current legislation, both the country itself, as countries to which exports the product.
- Better meet customer demands, since the consumer himself is also acquiring sensitivity to the environmental factor.
- Increased product quality by introducing environmental factors.
- Improving product image and company, projecting a green image of company and product.

With eco-design, the approach becomes important the product life cycle, as an improvement element in the production process is not limited to manufacturing, because the producer has an influence on the rest of the stages of life cycle, such as the recycling facility in the end, or the use of recycled materials, once the above product has been recycled. An example can be seen in Figure 4.

We can conclude, similar to previous authors (Capuz & Gomez, 2002; Goedkoop & Spriensma, 2001), which for a **sustainable production system**, (Ihobe S.A., 2000) understand an overview of the life cycle, but also product-oriented, in the pursuit of **sustainability with the environment**.

3.1.8 Curran, 2005

According to the book Management of Environmental Quality - An International Journal (Curran, 2005), normative regulation establishes the need for incorporating environmental factors, study of the impact of products and processes throughout the product life cycle.

Contemplating the environmental impacts of products and manufacturing processes, similar to other reference material, not limited to the manufacturing phase, but all stages of product life cycle, from procurement of resources management to end once concluded.

Fig. 4. Product Design

The author (Curran, 2005), like others, defines the concept of sustainability as keeping quality of life, without causing irreparable damage to the planet.

Is reflected the trend in international forums of lectures on the life cycle concept and its use in all areas of environmental decision-making at all levels, which include for example:

- The purchasing department.
- Management policies of the company.
- Design and development of products and processes.
- Management of supply chains.
- Efficiency of buildings.
- External communications and marketing.
- Product labeling, etc.

For a **sustainable production system** (Curran, 2005), indicates that **sustainability** means an **environment** where the company should try to seek maintain the quality of life, without compromising future needs, integrated into all levels of the company, this will also facilitate **economic sustainability**, with increased efficiency, using sustainability factors in areas that cannot even seem necessary (Purchasing, marketing, etc..), so you get the **social sustainability**, in addition to the government law enforcement.

3.1.9 General definition "sustainable production system"

A **sustainable manufacturing system** is that the manufacturing system, usually oriented product, which has been designed by introducing environmental factors (eco-design), taking into account not only the stage of manufacturing the product, but also for all stages of the **cycle of life**, from the procurement of resources, until the final treatment and recycling once their useful life.

The **objective** that seeks a sustainable product system is mainly an **environment sustainability**, balance in manufacturing systems to maintain and even improve the quality of life of present generations without causing irreparable damage to the ecosystem, can be used future generations, this is the base of **industrial ecology**.

The **origin** of this evolution to the search for a sustainable product system is clearly driven by **social sustainability**, protection by the agencies for their workers, and the maintenance of the environment, using tools such as legislation, decisions adopted by consensus of virtually all world governments.

The **integration** of sustainable manufacturing must be done at a global level, at all hierarchical levels of the company where the application of sustainability factors for efficiency of the production process, achieving **economic sustainability**.

3.2 Methodology for analysis of sustainable production system

The following section describes the different methods of analysis for sustainable production systems, based on different reference articles, and later tries to make a comparative study among them.

3.2.1 LCA methodology (Life Cycle Assessments)

According to the study Elements in a new industrial culture - Environmental Assessment in Product Development (Alting et al., 1998), the methodology of life cycle assessment is a tool used to assess the potential environmental impact of a product, process or activity throughout their entire life cycle, by quantifying the use of INPUT resources and OUTPUT environmental emissions associated with the system being evaluated.

According to Ecodesign - Life Cycle Engineering for Sustainable Product Development (Capuz & Gomez, 2002), the Life Cycle Analysis is a technique for assessing environmental aspects and potential impacts associated with a product, by:

- Compiling an inventory of relevant inputs and outputs of a system.
- The assessment of potential environmental impacts associated with these inputs and outputs.
- The interpretation of the results of the phases of inventory analysis and impact assessment in accordance with the objectives of study.

The Life Cycle Assessment, according to the methodology that has finally been extended, began as a tool for assessing environmental impacts of the product and for the private use by the SETAC (Society of Environmental and Chemistry), finally the LCA has been universalized and, in order to standardize criteria and methodologies, a number of international standards have arisen, the ISO 14040 series (and a Spanish standard, the UNE 150041). Mention that the LCA study needs peer-review and the result has to be verified by independent third party (ISO 14044).

The methodology of Life Cycle Assessment is used to respond to specific questions such as:

- What resource consumption and potential effects on the environment has the product?
- What are the most important potential effects?
- Where are within the life cycle, those most important potential effects?
- What elements in the product are mainly responsible for these potential effects?
- In which stage of the product life cycle can we potentially improve the environmental issues?

The application of LCA methodology provides great advantages such as:

- Promote a detailed design change of the product, easily and with cost savings.
- Comply with existing environmental legislation, and to respond promptly to any environmental issue.
- To obtain reliable and integrated data to issue environmental reports
- To inform the public about the environmental characteristics of products and materials, improving the image of the company.
- Statistically, the application of LCA methodology has the potential for significant environmental, product quality and cost improvement.

According to the study to the study Elements in a new industrial culture - Environmental Assessment in Product Development (Alting et al., 1998), the methodology of Life Cycle Assessment (LCA), has several common elements, according to empirical studies in different companies, such as:

- The LCA methodology allows the creation of a very detailed and coherent image of the product, a detailed understanding of the life cycle, stages individually, energy consumption, resources and environmental impacts. This view allows a better understanding of the product and a most efficient performance of the solutions proposed.
- The feedback phase within the LCA methodology, either as a simulation or as a change, allows us to know more specifically the influence of these efforts on the environmental factor.
- The LCA methodology requires a considerable initial effort to obtain all necessary information, such as the knowledge of full life cycle of the product, used materials,

manufacturing processes, operating conditions, maintenance, energy consumption, distribution and final treatment for elimination.

Regarding the analysis phases of the LCA methodology, they are defined as follows:

a. Purpose and Scope: Refers to the objective, why do it, defining the functional unit, process flow diagram or processes belonging to the system. Defining boundaries involved in the LCA.
b. Inventory: This is where you define and find the data for the LCA. It refers to the compilation of data required and it is the part that consumes more time and resources as data may come from many information sources (Industry, bibliography, Internet, databases, consultants, etc.). This chapter corresponds to the Life Cycle Inventory methodology (LCI).
c. Impact Assessment: It is the classification of issues in environmental impacts as it corresponds to the transformation of emissions of substances or molecules isolated from potential environmental impacts. This chapter corresponds to the methodology Life Cycle Impact Assessment (LCIA), discussed later on.
d. Proposals for improvement: It is the interpretation of results, where the discussion is important to analyse opportunities for improvement in the process, sensitivity analysis of results and impacts on the whole system.

3.2.2 LCIA methodology (Life Cycle Impact Assessment)

According to the book Management of Environmental Quality - An International Journal (Curran, 2005), the methodology for Impact Assessment Life Cycle Assessment (LCIA) is a methodology based on "indicators", where the effects of resource use and emissions generated are grouped and quantified in a limited number of impact categories that may be of weighted importance.

The methodology for Impact Assessment Life Cycle Assessment (LCIA) is part of the third phase of Life Cycle Analysis, which deals with environmental impact assessment; therefore we can say that it’s the development of the third stage of (LCA), before mentioned, but due to its importance it will be analysed as an additional methodology.

According to the ISO 14040 and ISO 14042, the Environmental Impact Assessment of Life Cycle Assessment (LCIA) is essentially a tool for understanding the results of the inventory phase in LCA.

The Eco-indicator 99 is an analysis method of the product's environmental aspects and the establishment of environmental priorities, among other methods such as the Matrix MET, or software such as LCA.

The Eco-indicators are the result of a project developed by a multidisciplinary team consisting of leading industries of different sectors, scientists from independent research institutes and the Dutch government. His goal was trying to get environmental impact assessment on Environment exerts the industrial activity, focusing on the impact on the ecosystem, resources and human health.

To use the Ecoindicadores properly, the following steps must be followed:

a. Definition of the purpose to calculate the Eco-indicators.
b. Definition of Life Cycle.
c. To quantify the materials and processes.
d. To fill the form.
e. To interpret the results.

3.2.3 Process chain methodology

According to the study Mutual effects in a sequence of cutting and cleaning (Bley et al., 1997), and the study Methods for Qualitative and quantitative analysis of lubricants and contamination on Form Surfaces (Bley & Behrning, 1998), the chain process model analyses the influence of factors between different phases of a process and within them.

In the model, it is shown a main flow of material, both between processes, including the modification within them, as well as the flow of energy and secondary material flow, these are precisely the most important ones to get a more efficient and more respectful system with the environment.

This model based on processes has the great advantage that it can be considered from different points of view:

- Vertical optimization: Where the optimization of a process chain is limited to measures of optimizing an unique process, for example focusing the efforts on the process for the best efficiency of the INPUT/OUTPUT use. These measures may affect the behaviour of the process in a global way, with a reduction of the negative effects of the following stages.
- Horizontal Optimization: Contrary to the vertical optimization, in this case the optimization is not limited to a single process but is directed to the entire chain. The interrelationship between processes becomes more important and the individual process control links pass to a second stage. The disadvantage is that the complexity of the optimization increases and application of measures is much more difficult.

Usually, these optimizations are performed in parallel, in this case, combining both sequences we have two possible alternatives:

- Vertical - horizontal Optimization: This strategy is suitable for problems in which a process must be modified. In this way the process can be readjusted individually (vertical optimization), later to be adapted to the rest of the process chain (horizontal optimization).
- Horizontal - vertical Optimization: This strategy is useful when your objective is to replace a process within a process chain. The replacement of an individual process is clearly a horizontal optimization, as it must be analysed as a whole, to see how it affects the rest of the system. Once you delete that process, a vertical optimization should be applied, individually, as in this case by giving greater importance to the regulation, to the detriment of relationships, a more optimal final adjustment of the system is allowed.

3.2.4 Process chain methodology

According to the book Ecodesign - Life Cycle Engineering for Sustainable Product Development (Capuz & Gomez, 2002), as a result of successive research projects carried out by the Delft University of Technology, the Dutch government published the manual PROMISE. This document was revised and completed with the collaboration of various institutes and companies and published with the United Nations Environment Programme.

The reasons for the application of Ecodesign emerge from the analysis of the strengths and weaknesses of the company and the opportunities and threats present in the market. These reasons can be divided into:

- External Motivating factors: Management, Marketing, Environment, etc.
- Internal Motivating factors: Quality, Image, Cost Reduction, etc.

The Ecodesign methodology is divided into seven phases, which are the development of product design methodology, which are reflected in the following table:

ECO-DESIGN PHASE	STAGES OF THE METHODOLOGY
1. Ecodesign Project Organization.	1.1. Achievement of Management approval. 1.2. Establishment of a project team. 1.3. Make plans and prepare a budget.
2. Product Selection.	2.1. Establishment of selection criteria. 2.2. Decision making. 2.3. Define Design Report.
3. Establishment of eco-design strategy.	3.1. Analyze the product's environmental profile. 3.2. Analyze the internal and external pros. 3.3. Generate options for improvement. 3.4. Investigate its feasibility. 3.5. Defining Ecodesign strategy.
4. Generation and selection of ideas.	4.1. Generate product ideas. 4.2. Organize a workshop on eco-design. 4.3. Select the most promising ideas.
5. Details of the concept.	5.1. To turn ecodesign strategies into operations. 5.2. Study the feasibility of the concepts. 5.3. Select the most promising one.
6. Communication and product launch.	6.1. Internally promote the new design. 6.2. Develop a promotional plan. 6.3. Prepare production.
7. Setting of follow-up activities.	7.1. Evaluate the resulting product. 7.2. Evaluate the results of the project. 7.3. Develop a program of eco-design.

Table 2. Eco-design phases

Once the methodology and Ecodesign tools are used the product development Department should draw conclusions about which of these tools are interesting for the company and how they can be integrated into the design process of new products. For that purpose in the book Practical Guide for Ecodesign - Implementation Operative in 7 steps (Ihobe S.A., 2000), the following steps are proposed:

a. To hold a meeting within the Product Development Department, in which Ecodesign methodologies are analysed in parallel and all phases of product development at the company are also analysed, trying to integrate them.
b. To establish an action plan, at company level, this will compile the necessary changes in the product development plan, ISO 9001 or ISO 14001.
c. To proceed with the development and adjustment of the necessary tools.

3.2.5 EDIP methodology (Environmental Design of Industrial Products)

According to the book Ecodesign - Life Cycle Engineering for Sustainable Product Development (Capuz & Gomez, 2002), this methodology is the result of a research program developed over 4 years by a team from the Technical University of Denmark, five Danish industrial companies, the Confederation of Danish Industries and the Environmental Protection Agency of that country.

EDIP methodology proposes the use of LCA (Life Cycle Assessment), previously described, being this the key tool to help in the decision making concerning environmental issues by the designer. Thus, while the LCA is generally considered as an environmental assessment tool, the EDIP makes an effort to adapt and integrate it into the product development process.

As the LCA tool is considered to be the main element of the EDIP methodology, the stages of its structure coincide with the phases of the life cycle:

a. Definition of the objective and scope.
b. Inventory, where you define and find the data.
c. Categorization, where emissions of the environmental impacts are classified.
d. Interpretation of results.

For the distribution of activities with environmental significance, during the development of products, four types of design activities are identified: concretion, specification, synthesis and verification, which are reflected in following table:

TASKS	**DIVISION OF ENVIRONMENTAL WORK**	
	Specialist	**Designer**
1. Concretion	*Environmental assessment of a reference product*	
analysis	• Identify potential critical impact and their main causes.	• Identify an existing product or an imagined one as a reference for the new design.
	Environmental assessment of a reference product	
	• To simulate theoretical changes in the reference product or system and thus develop an LCA. • To develop ACL specific alternatives, including products from the competence.	• Identify existing alternatives for redesign solutions, chosen on the reference product, including solutions from the competence.
diagnostics	• Identify key environmental issues in the relevant product.	
2. Especification		*Specifying environmental goals*
		• Analyze consumer environmental perceptions and priorities and make a projection of this analysis. • Define the environmental specification of the product.
3. Synthesis	*LCA of new products*	*Design for the environment*
	• Environmental assessment of concepts. • Environmental assessment of details.	• Create environmentally attractive product systems. • Adapt the product environmentally to existing systems. • If possible, adapt the system environmentally to the product.
4. Verification	*Check the environmental properties of the product*	*Verify design solutions*
	• Conducting an LCA, if necessary.	• Check that the environmental specifications and other requirements are fulfilled.

Table 3. Working Sharing Scheme

Companies, usually depending of their size, can choose between training of their own personnel specialised on environment, subcontracting external consultants or assigning this activity to the designer. In this last case, it is necessary to let a specialist to regularly access to data and methods used to verify the validity of the conclusions reached.

3.2.6 Methodology EcoReDesign

According to the book Ecodesign - Life Cycle Engineering for Sustainable Product Development (Capuz & Gomez, 2002), this approach led by the Centre for Design at RMIT (Melbourne), counts with the participation of EcoRecycle Victoria, the Corporation for Research and Energetic Development and the Environmental Protection Authority of New South Wales, all of the Australian institutions.

This methodology is, as its name suggests, a clear approach to redesign or improve of existing products, leading to an important task of market research on the product chosen. Consequently, it applies a more conservative approach than the EDIP methodology as, instead of introducing an environmental factor throughout the design process of a new product, it starts from an existing one to try to reduce their environmental impacts.

The redesign process or methodology adopted is structured in three phases, as contained in the following table:

PHASES OF ECOREDESIGN	ACTIVITIES OF THE METHODOLOGY
1. Selection and general analysis of the product.	• Prepare a dossier with the technical, aesthetic, economic and environmental characteristics of the product to serve as a starting point for the next phase. • Considerations of: market, competence, resources and capabilities of the company, pressures or potential changes, product information and its life cycle.
2. Environmental impact analysis of the product and establishment of design directions.	• LCA of the product or simplified assessment • Making a technical session of guided group work, involving the departments of production, marketing, environment, technical and management in order to generate creative responses to the impacts identified. • Apply creative thinking techniques and general strategies of eco-design. • Critical evaluation of the value of some of the ideas generated.
3. Development of a new product from a better environmental aspect.	• Classification of ideas by categories, as Figure 8 - Improvement Strategies. • Verification of the absence of contradictions or environmental collateral impacts.

Table 4. Phases EcoReDesign

The main aspect of the methodology EcoReDesign is the exploration and application of methods of life cycle assessment in order to optimize a product, when looking for technical, economic and environmental results.

The incorporation of this approach in the design process, has clearly an interdisciplinary nature, seeking a sustainable design, being this the only way to frame our product within Category 1, looking for a viable product with reference to economic, technical and with significant environmental improvements, as shown in the Figure 5.

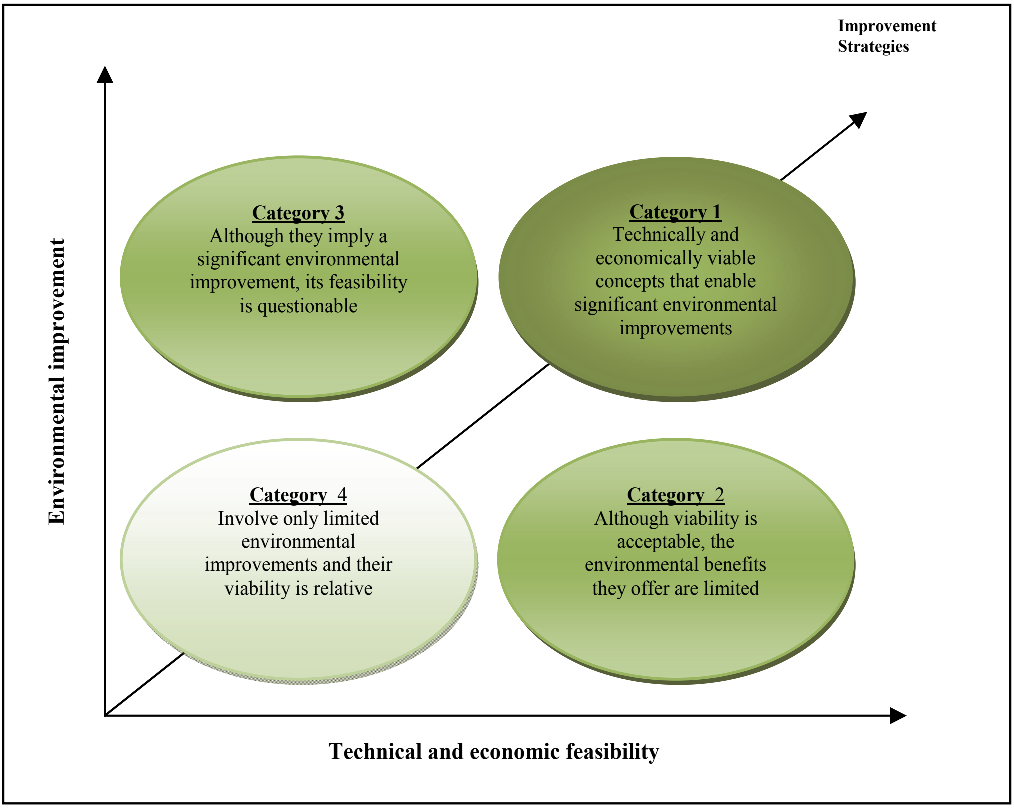

Fig. 5. Improvement Strategies (completed)

3.2.7 Methodology LCC (Life Cycle Cost)

The methodology of life cycle assessment (LCA) is a worldwide spread technique that allows us to identify and quantify the environmental impact of goods and services during their entire life cycle, however, the LCA methodology does not take into account financial aspects; that is why the LCC methodology (Life Cycle Cost) exists, in order to allow us to analyze both environmental and economic aspects.

The objective of this methodology is to minimize environmental impact and to increase efficiency, reduction of cost and waste management, these are the premises to be taken into account in the search of a sustainable manufacturing.

Regarding the analysis phases of the LCC methodology, as it is based on the methodology of life LCA cycle assessment, the phases are similar, but with additional financial perspective. These phases are as follows:

a. Objective and scope: The system objectives and functional units are defined. In this case, the LCC analysis should be performed for each functional unit within the limits of the system. It is very important to define the functional unit depending on the product or process analysis.
b. Inventory: This stage involves calculation procedures and compilation of data to quantify relevant inputs and outputs of a manufacturing system. These input / outputs may include the use of resources and emissions of the system. Regarding the LCC analysis, all items or measurable variables must be related to a cost and the cost associated with system emissions generated by each functional unit.
c. Impact Assessment: This step allows us to evaluate the significance of potential environmental impacts. In general, this stage implies the association of inventory data with environmental impacts, trying to analyze those impacts. LCC analysis at this stage manages to establish a cost hierarchy, for each functional unit, and for the entire process. It is also possible to determine the contributions of larger costs for each category.

Proposals for improvement: The assessment and evaluation of proposals for improvement is the last phase. The salary supplement and the investment required will be included in this case, compressing the information of the different categories and functional units to a decision also evaluated in monetary terms.

4. Conclusion

It is necessary to emphasize the general definition of a **sustainable production system**, which is that the manufacturing system, usually product oriented, designed by introducing environmental criteria (eco-design), taking into account not only the stage of manufacturing of the product, but also considering all life cycle stages, from the obtaining of resources, to the final treatment and recycling once their function as a product is over.

The importance of the approach from a global view of the product, allows us to clearly identify all the **inputs/outputs** that imply an environmental impact, not only those limited to our manufacturing system or a particular stage of the cycle, but also applying environmental measures as a whole.

The objective is the search of a sustainable development, the construction of a new development model to allow the maintenance of a life quality, without causing an irreparable damage to the planet, being this the basis of the industrial ecology.

The origin of this change of perspective and the reasons that move organizations to become positively aware and set guidelines of respectful behaviour towards the environment are:

- Compliance with national, regional and local legislation.
- New business opportunities.
- Local and international competence.
- Technological development.
- Pressure from consumers and groups.

With regard to the different methodologies that have been treated in this chapter we can draw the followings tables 5 and 6:

Methodology	Objective	Characteristics
Life Cycle Assessments (LCA)	• Assess the potential environmental impact of a product, process or activity. • The decisions provoke less contaminant products and with a larger commitment with the environment.	• Evaluation during the entire life cycle. • Quantification of resources and environmental emissions. • Identify process inefficiencies.
Life Cycle Impact Assessment (LCIA)	• Protection of the different categories of impact. • Ensures the maintenance of life and quality of the ecosystem, without reaching the adverse effects. • Analysis of environmental aspects of a product and establishment of environmental priorities.	• Methodology based on "indicators". • The effects of resource use and emissions generated are grouped and quantified. • Integrated in phase 3 of the LCA methodology.
Chain Processes	• Analyze the influence of factors between different stages of a process and within them.	• It graphically represents the flow of material, not only between processes, but also their modification within them, as well as the energy flow and flow of secondary materials.
Ecodesign	• Integration of environmental concept in the structure of the company (organization chart and procedures).	• It is divided into 7 phases, which constitute the design of the product • I t is used for the design of a new product.
EDIP	• Integration of environmental concept in the process for the development of the products.	• The Life Cycle Analysis (LCA) is the key tool in the process. • Need for the incorporation of an environmental expert in the design team.
EcoReDesign	• Focus on redesign or improvement of existing products. • Part of an existing design to try to reduce their environmental impacts.	• A more conservative focus than the EDIP methodology. • Main point the exploration and application of methods for life cycle assessment.
Life Cycle Cost (LCC)	• Identify and quantify the environmental and financial impact of the product.	• The Life Cycle Analysis (LCA) is the key tool in the process. • Importance of the relationship between cost and environment.

Table 5. Methodology with Objective and Characteristics

Methodology	**Advantages**	**Inconveniences**
Life Cycle Assessments (LCA)	• Obtain cost savings, although it is not its main objective. • Integration of environmental criteria in the organization chart of the company. • Wide spreading of the method (ISO Standards).	• Great effort to get all information from the entire life cycle. • It does not consider economic aspects.
Life Cycle Impact Assessment (LCIA)	• There is a good balance between the complexity of the application of different methods and interpretation of the results obtained.	• A variety of methods of analysis of indicators (Eco-indicator 99, MET, LCA software)
Chain Processes	• Better knowledge of the system. • Easy understanding of the different phases and disturbance variables. • Measurement of efficiency with checkpoints. • Different points of view to carry out the analysis.	• Previous study implies great quantity of hours for its preparation.
Ecodesign	• Widespread, Integrated Programme Environment United Nations.	• Environment joins other requirements (technological, commercial, etc.)
EDIP	• Complement to the LCA to assume the importance of the environmental factor in the company.	• Need of qualified staff in the design team: Environment expert.
EcoReDesign	• You can optimize a product, looking for a better technical, economic and environmental result. • Multidisciplinary team, looking to strengthen the product from different perspectives of work.	• Not suitable in the design of new products. • Important marketing study on the product.
Life Cycle Cost (LCC)	• Increase of the efficiency while lowering the environmental impact. • Create a profitable model with reference to the environmental impact analysed.	• Difficulty in quantifying costs in all phases of product life cycle.

Table 6. Methodology with Advantages and Inconveniences.

The eco-efficiency implies redesigning the manufacturing processes, using clean technologies that reduce the level of emissions, energy and resources used during manufacture, extract the natural resources efficiently and sustainably. Under the protection of the United Nations, all these concepts are to be applied worldwide.

The evolution of applying the concept of sustainable manufacturing, throughout the entire product life is becoming the reference point of any environmental management system, acquiring greater importance on quality standards and economic viability. From this, starts the idea of a total quality and environmental management systems as a necessary part of management in the company, come into scene the Environmental Management Systems and ISO 14001, as a reference for application, in addition to the rules of quality standards ISO 9001 and OHSAS 18000 occupational safety.

As a conclusion, we can say that due to the complexity, information needs and necessary resources (multidisciplinary team of environmental experts) to carry out a sustainable practice in the design / redesign of products, provides a great barrier between large companies and small and medium enterprises (SMEs).

All these methods are implemented by large companies such as automobile and electronics sectors, for example, but when we turn to the field of small and medium enterprises, the scope that can reach the application of different methods is limited to the application of ISO 14001 and the fulfilment of environmental specifications in the manufacturing chain, having little influence on the design, the obtaining of materials and their treatment at the end of their life.

Regarding the methodologies, there is a wide range, with common characteristics such as the necessity of their application in the Cycle Life of the Product as a whole, although as we have seen, their methodologies are clearly different.

Depending on the level of development, we can see that the Ecodesign methodology, protected under the United Nations program is perhaps the most classic and structured methodology, where the different phases and stages indicate the need to conduct a detailed and verified study by a team work. Even some phases which do not even exist in other methodologies are here outstanding, such as phases of communication, launching and monitoring, giving the importance of relationship with the customer as well as a feedback on the result of the project.

On the other hand, another item that frequently appears in different methodologies is the application of environmental considerations during the design of new products. We have found not many methodologies that change the target to the redesign of existing products (methodology EcoReDesign). The environmental aspect of this one is not only contemplated in new industries, but current manufacturing processes have the opportunity to improve, not remaining in the conformity of because of being older contaminant more the manufacturing process.

The application of design methodology for new products makes the impossibility of a "real" measurement of the environmental impact a product and the improvement achieved. The different methodologies are based on Eco-indicators, estimates of the influence of manufacturing processes on the environment due to their differences make it impossible the comparison between methodologies.

Despite the advantages and disadvantages of the different methodologies analysed in this dossier, it is proved the need of adjustment and preliminary study of the problem, because

depending on the process and / or product it is more convenient to apply a different methodology.
Finally we shall mention that the application of different methodologies imply a progressive change, the integration of environmental considerations into their own company's organizational structure, adapted depending on each company, but with the same objective, the search of the model of sustainable manufacturing system.

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16

The Infrastructure Imperative of Climate Change: Risk-Based Climate Adaptation of Infrastructure

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1. Introduction

Infrastructure provides a foundation for the quality of life civilization enjoys around the world. This includes not only the comforts of heat during the winter, reading lights at night, and convenient transportation options, but also items paramount to public health and safety such as water treated to standards suitable for human consumption, energy for critical operations, and transport to enable society's functioning on a daily basis.

Researchers, professionals, policy makers, technologists, planners and others are challenged regularly to create, maintain, and operate such infrastructure to improve quality of life, while balancing the Triple Bottom Line (environmental, societal, and financial factors). This is an amazing feat to strive for in itself, but now recognition of the greater potential impacts of climate change present additional components of uncertainty and risk that must be applied to this highly valuable and financially- and time-intensive infrastructure investment.

Water is a significant enabler of economic prosperity and well being. Water infrastructure is the medium that enables this. This infrastructure faces numerous threats and uncertainty from climate change, which directly leads to water change and subsequent needs to adapt this infrastructure in the face of a myriad of existing drivers, constraints, and expectations of water infrastructure. This chapter aims to tangibly frame the structure for adapting water infrastructure to climate change in the reader's mind.

This complex situation becomes additionally compounded by much of the infrastructure reaching the end of its useful life, which also provides an opportunity to renew it with much more planet-friendly approaches and designs. In many areas across the globe, megatrends add an additional layer of complex challenges and opportunities, as do applicable design standards. The impacts of these infrastructure complexities are already rippling through facets beyond utilities and governing districts that operate and maintain infrastructure to industry, banking, insurance, and policy.

The level of success that can be achieved in integrating and balancing these additional levels of complexity associated with or driven by climate change will ultimately influence the level of quality of life that can be reached or preserved for future generations and the impact on environmental assets that should not be squandered in a way that would negatively impact future generations. Several key concepts can help to optimize success, such as:

- Considering Potential Impacts of Climate Change on Infrastructure
    - Examples of Infrastructure Vulnerability and Consequences
    - Importance and Challenges of Mitigation in Infrastructure
    - Importance and Challenges of Adaptation in Infrastructure
- Infrastructure Asset Management Planning
    - Importance
    - Approach
    - Climate Adaptation - Incorporating Risk and Climate Change to Prioritize Renewal

This chapter aims to build and communicate the complex picture of the risks that climate change presents to infrastructure, largely focused on the context of water infrastructure as a specific case for analysis. It also examines how to pursue more sustainable and resilient ways in which to address these challenges. Included in this chapter is a solution framework for addressing the imperative need for adapting water infrastructure to climate change. This is accomplished through an investigation of how successful asset management is executed and the role it can play in adaptation. Also presented is how climate change adaptation planning can be rolled in to asset management to consider risks and appropriate strategies for moving forward.

A framework is needed to identify, assess, strategize, plan, and act on the risks that this infrastructure faces due to climate change. This chapter shows how climate adaptation planning and prioritization may be incorporated as a component of risk in what has been identified as a sound, successful, and actionable risk-based asset management program. The chapter aims to connect related best practices in infrastructure climate adaptation assessment, planning, and implementation in a robust, yet flexible manner for the long term.

2. Climate change and infrastructure

Key terms used in this chapter include "climate change". For the purposes of this chapter, "climate change" is defined as "any significant change in measures of climate (such as temperature, precipitation, or wind) lasting for an extended period (decades or longer)" (EPA, 2011a). "Adaptation" in the context of climate change for the purposes of this chapter is the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (Intergovernmental Panel on Climate Change [IPCC], 2007).

2.1 Climate change implications on infrastructure

Climate change can impact infrastructure in a variety of ways, and can present significant uncertainty and risk to natural resources and related infrastructure. The Intergovernmental Panel on Climate Change (IPCC) (Bates et al., 2008) notes that climate, freshwater, biophysical, and socio-economic systems are interconnected and interdependent. It also notes that water, its availability, and quantity will be the main climate change issues for societies and the environment.

Connor et al. (2009) agrees with this general philosophy. Specifically, Connor et al. (2009) calls out these major ties between climate change and the translation of the significance of its impacts on the key medium of water:

- "There is evidence that the global climate is changing. The main impacts of climate change on humans and the environment occur through water.
- Climate Change is a fundamental driver of changes in water resources and an additional stressor through its effects on other external drivers.

- Policies and practices for mitigating climate change or adapting to it can have impacts on water resources, and the way we mange water can affect climate."

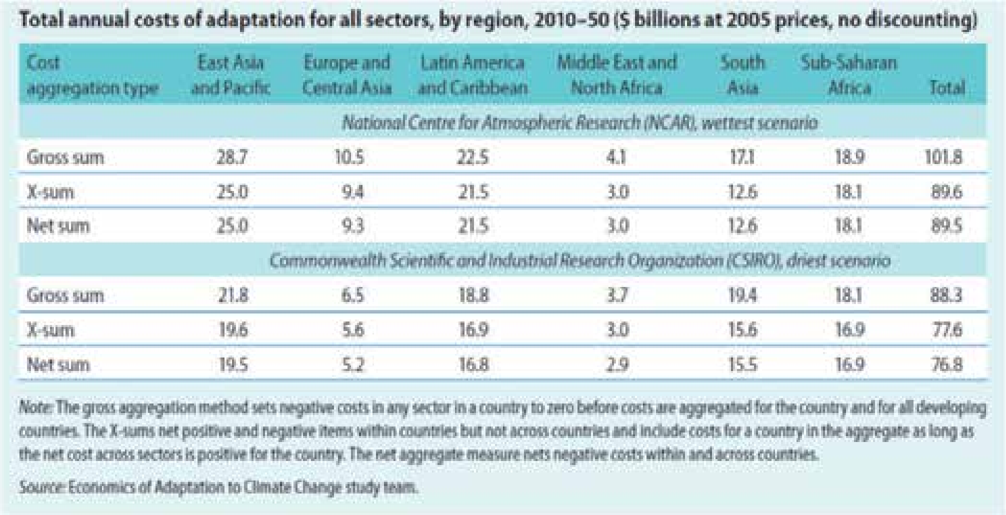
To emphasize the scale of the issue of climate change impacting water resources, often in a way that increases risk to society's and natural resources' well being note that Grey and Sadoff (2006) link water resources to being the foundation of economic well being. Below is a breakdown of all world-wide freshwater supply use purposes, as provided by the World Water Development Report (2006):

- 70% used for agriculture irrigation
- 22% used in manufacturing and energy applications
- 8% used for domestic applications such as consumption, sanitation, and recreation

In these applications, demand is expected to rise from 54% of available supply in 2001, to 70% in 2025 (90% if at developed country levels) (UN, 2006). The uses outlined above compete for this supply. This resource is additionally constrained by accessibility, quality, and the affects of climate change as outlined in this chapter and numerous other sources. This is especially problematic when 700M people already facing water scarcity and 900M lack access to safe drinking water. Climate change has the potential of magnifying this problematic situation and subsequently further undermining health and livelihoods (Water and Climate Coalition, 2011).

The magnitude of the water infrastructure needs in the face of climate change related to in costs (USD) is presented in Figures 2.1-1 and 2.1-2 (North America/US is outlined in subsequent tables of this chapter):

- Water adaptation to climate change, generally = US$ 9-11B by 2030 (United Nations [UN], 2007), up to US$ 20B in developing countries (Water and Climate Coalition, 2010B).
- Water adaptation to specific scenarios of climate change = US$ 13.7B in drier scenarios, US$ 19.2B in wetter ones for water supply and flood management (World Bank, 2008)
- Having the proportion of people without access to safe drinking water and sanitation (generally, without specific climate change adaptation considered) = US$ 10B/year through 2015 (Toubkiss, 2006).



Total annual costs of adaptation for all sectors, by region, 2010–50 ($ billions at 2005 prices, no discounting)

Cost aggregation type	East Asia and Pacific	Europe and Central Asia	Latin America and Caribbean	Middle East and North Africa	South Asia	Sub-Saharan Africa	Total
National Centre for Atmospheric Research (NCAR), wettest scenario							
Gross sum	28.7	10.5	22.5	4.1	17.1	18.9	101.8
X-sum	25.0	9.4	21.5	3.0	12.6	18.1	89.6
Net sum	25.0	9.3	21.5	3.0	12.6	18.1	89.5
Commonwealth Scientific and Industrial Research Organization (CSIRO), driest scenario							
Gross sum	21.8	6.5	18.8	3.7	19.4	18.1	88.3
X-sum	19.6	5.6	16.9	3.0	15.6	16.9	77.6
Net sum	19.5	5.2	16.8	2.9	15.5	16.9	76.8

Note: The gross aggregation method sets negative costs in any sector in a country to zero before costs are aggregated for the country and for all developing countries. The X-sums net positive and negative items within countries but not across countries and include costs for a country in the aggregate as long as the net cost across sectors is positive for the country. The net aggregate measure nets negative costs within and across countries.

Source: Economics of Adaptation to Climate Change study team.

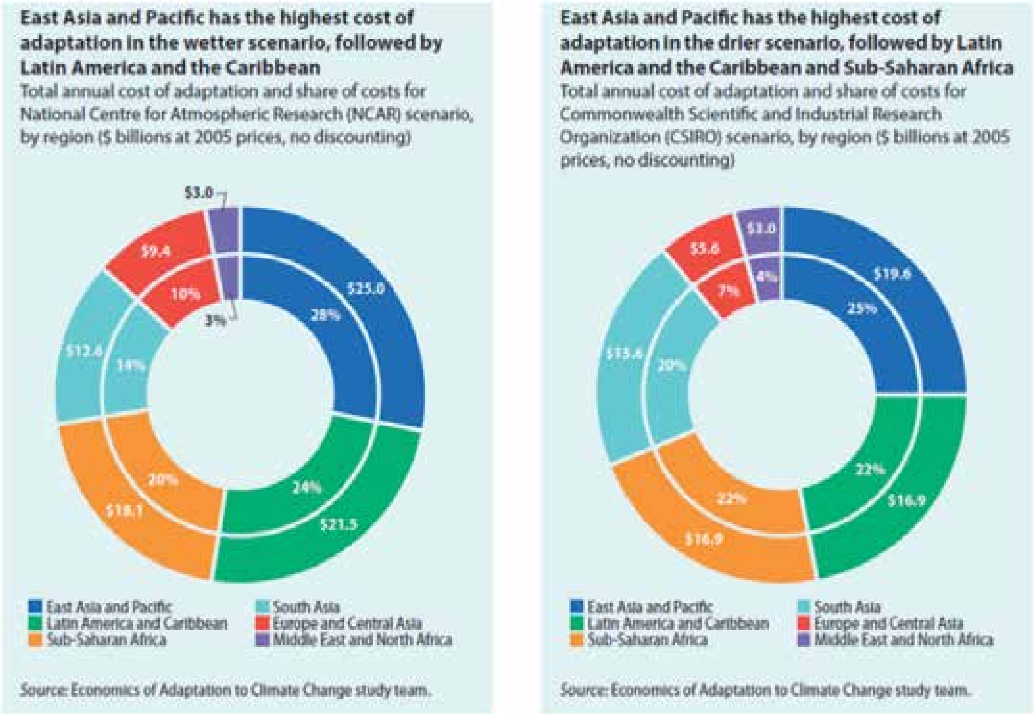
Fig. 2. 2-1. Annual adaptation costs (Source: World Bank, 2008).

With the resource put at risk (i.e., uncertain changes in water availability, quality, and timing), its infrastructure is also put at risk. Climate change impacts are expected to become increasingly severe, with the risk of more abrupt and large-scale changes at higher temperature (Stern, 2007). With high uncertainty and severe shifts, adaptation must enable infrastructure to be more dynamic and resilient, while playing within the bounds of much infrastructure being time and financially expensive, relatively static in many instances, and a direct enabler and potential risk (if neglected or inadequate) to the public's and environment's health and well-being. As noted from various sources, (Bates et al. 2008 and Water and Climate Coalition [Coalition], 2010b), climate change is ultimately water change. For these reasons, this chapter is largely focused on infrastructure that serves water needs and concerns as they relate to climate change for this infrastructure that serves societies public health and livelihood needs.

Bates et al. (2008) calls out the following evidence that freshwater sources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and natural ecosystems:

- "Observed warming over several decades has been linked to changes in the large-scale hydrological cycle.
- Climate model simulations for the 21st century are consistent in projecting precipitation increases in high latitudes (*very likely*) and parts of the tropics, and decreases in some subtropical and lower mid-latitude regions (*likely*).
- By the middle of the 21st century, annual average river runoff and water availability are projected to increase as a result of climate change at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics.
- Increased precipitation intensity and variability are projected to increase the risks of flooding and drought in many areas.
- Water supplies stored in glaciers and snow cover are projected to decline in the course of the century.
- Higher water temperatures and changes in extremes, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution.
- Globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits (*high confidence*).
- Changes in water quantity and quality due to climate change are expected to affect food availability, stability, access and utilisation.
- Climate change affects the function and operation of existing water infrastructure – including hydropower, structural flood defences, drainage and irrigation systems – as well as water management practices.
- Current water management practices may not be robust enough to cope with the impacts of climate change.
- Climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions.
- Adaptation options designed to ensure water supply during average and drought conditions require integrated demand-side as well as supply-side strategies.
- Mitigation measures can reduce the magnitude of impacts of global warming on water resources, in turn reducing adaptation needs.
- Water resources management clearly impacts on many other policy areas.

- Several gaps in knowledge exist in terms of observations and research needs related to climate change and water."



East Asia and Pacific has the highest cost of adaptation in the wetter scenario, followed by Latin America and the Caribbean

Total annual cost of adaptation and share of costs for National Centre for Atmospheric Research (NCAR) scenario, by region ($ billions at 2005 prices, no discounting)

Source: Economics of Adaptation to Climate Change study team.

East Asia and Pacific has the highest cost of adaptation in the drier scenario, followed by Latin America and the Caribbean and Sub-Saharan Africa

Total annual cost of adaptation and share of costs for Commonwealth Scientific and Industrial Research Organization (CSIRO) scenario, by region ($ billions at 2005 prices, no discounting)

Source: Economics of Adaptation to Climate Change study team.

Fig. 2. 1-2. Total annual cost of adaptation and share of costs (Source: World Bank, 2008).

To further develop the profile of impacts and why to be concerned about climate change impacts on water, it is worth noting that with an intensifying water cycle, seasonal and annual water supply variations will determine the consequences of climate change in the form of droughts or floods. Billions of people will be exposed to either having more rainfall or less, which can lead to greater water availability (although not always quality or the ability to capture it) or scarcity, respectively (Stern, 2007). This can serve as the foundation for the conclusion that the impacts of climate change will be felt most strongly through the changes in water, its variability in availability, quantity, and subsequently quality to serve health and livelihood needs (Water and Climate Coalition, 2011).

An examination of potential climate change-induced water impacts on water infrastructure is worthwhile to better understand the criticality and magnitude of the issue of risk that water infrastructure (and subsequently quality supply faces). First, the simple issue of supply exists; that is, is enough water of a sufficient quality available to address the needs of the community and the environment that it serves. Availability relates to several important components; is the water supply consistent, sufficient in quality, protected from natural and humanistic disasters, economically viable to claim and transport, allocated appropriately among users, and part of a dynamic supply system that can adapt to changing needs, seasons, political drivers, etc.? If so, then is the necessary infrastructure in place to obtain the additional supply, and is that infrastructure managed in such away to maintain the investment in that infrastructure and the levels of service expected from the supply?

Next, is the quantity of the supply of water adequate and managed in a way to serve the needs of people without detracting from other natural resources? If more water is needed regularly or during particular seasons, is infrastructure in place to enable access to additional supplies? What about storing the supplies during high precipitation or runoff seasons – is infrastructure in place for this? Can additional benefits be achieved such as through claiming clean and substantive hydropower through streamflow or reservoir dams? Can runoff be captured and channeled by infrastructure to capture the necessary supply for community and environment uses and management in a way that protects, maintains, or enhances water quality to the levels necessary for society's use? These are all important issues and highlight how critical infrastructure is to providing water, as well as why it is important to protect, maintain, and adapt this infrastructure investment to changing conditions so that it can continue to serve society's water needs and provide for its well-being.

A few, more specific examples are worth considering to make the concepts of infrastructure criticality and vulnerability more tangible. As mentioned earlier, more severe water droughts and floods are expected. These directly impact the quantity and quality of water available for various forms of consumption. Depending on the particular local scenarios of climate change, runoff impacts, and various water infrastructure, the potential to overwhelm this critical infrastructure exists, subsequently jeopardizing critical water supplies, especially on an annual basis.

For instance, reservoirs and other types of infrastructure units are often used to store annual supplies of water captured during the high runoff season. If climate warms significantly in the area, increasing the ability of the atmosphere to contain moisture and subsequently leading to fewer but more severe precipitation events, rivers, canals, pipelines, reservoirs and other water infrastructure may not have sufficient capacity to capture the supply necessary for annual consumption; the water could simply top-out the infrastructure and flow downstream and the reservoir subsequently may not be able to meet demands over the course of the dry season when the reservoir has no replenishment refilling it.

A similar scenario could develop with increased temperatures and short winters in areas of glacial and snowpack water sources, frequently located in mountainous regions. With shorter winters and higher temperatures, the snowpack might not develop as greatly which would reduce the supply initially.

The same factors could lead the snowpack to melt more and melt sooner in the year, which could overwhelm water infrastructure in volume, leading to the demise of the supply's annual quantity due to the inability to store or convey the planned annual amounts allowing a portion of the supply to pass downstream, possibly resulting in flooding and subsequent risk to life. To provide an idea of the scale of this issue, more than one-sixth (1B people) of the world's population living in the impacted river basins could be affected (Stern, 2007 and UN, 2008). Additionally, the demise of the quality may be encountered as overall there could be less annual supply, and the earlier runoff may have encountered greater turbulence and pollutants from the watersheds, resulting in a higher concentration of quality degradents.

These issues associated with snowpack are specifically identified as a forecasted issue for the Indian sub-continent, over 250B people in China, and 10 of millions in the Andes. The issue can be exacerbated with long run dry season water disappearing permanently once the icepack has been completely terminated (Stern, 2007). If the snowpack would instead continue to melt more gradually as for which the canals and reservoirs were designed, a more consistent supply would be available through much more of the year. This would help to enable the infrastructure to more feasibly meet expected supply levels.

In some instances, these runoff supply issues may also be present in coastal areas. However, coastal areas are exposed to additional risks as well. For instance, more severe precipitation events could exceed soil and shallow aquifer abilities to retain runoff, if their available capacities are exceeded over the course of these events. The freshwater rainfall would just run out to sea and less would be stored and available in the dry season.

Another challenging risk is salt water intrusion into freshwater delta and wetland systems and aquifers. Rising sea levels bring rising pressures and elevations of sea water, which could potentially penetrate freshwater reserves lying geographically close to coastal waters, or those which lie at low elevations near coastal waters. This risk is further magnified if climate change in an increase of civilization's historic records of temperature has already caused delta and wetlands freshwater levels to drop through increased evaporation. The UN has identified that a high probability exists for rising sea levels to contaminate and subsequently reduce adequate freshwater supplies in Bangladesh, Egypt, and Thailand (UN, 2006). Bloetscher et al. (2010) includes a case focused on mitigating climate change impacts on coastal water supplies and infrastructure.

Additionally, with ice cap melting and subsequent sea level rise, stormwater infrastructure at low-lying, shallow elevations may not have the capacity to contain the rainfall events themselves, nor convey the rate of stormwater flow to outfalls, nor be physically capable of discharging if sea levels rise significantly enough to obstruct stormwater outfalls. As most stormwater pipe networks are not continuously pressurized, rising sea levels could complicate their ability to discharge, or worse, yet, result in backflow contamination or public health hazards and nuisances as stormwater backs up in combined sewer systems (those that convey both wastewater and stormwater flows) into neighborhoods, streets, households, and businesses. These scenarios or others could lead to the vulnerability of millions of people in low-lying coastal areas being at greater risk of flooding by storm surges over the course of the present century (Connor et al., 2009).

Another issue can arise when water supplies are over-allocated. For instance, it is common knowledge that the watershed and subsequent water supply to the Colorado River in the United States is overallocated. The allocation of the river's water supply was based on unusually wet years, as exemplified by tree ring data (Barnett and Pierce, 2009). Additionally, climate change is expected to compound the problem with warmer, shorter winters, and reducing snowpack and accelerating runoff, as shown in research on the river's Upper Basin by Hamlet et al. (2005) and Stewart et al. (2004). In general across the western part of the US, decline in snowpack has been commonly identified over the period of 1925-2000, especially near the middle of the century (Mote et al., 2005). This further decreases the projection of availability of the already over-allocated water supplies.

In all of the infrastructure vulnerability examples cited above, the common consequence of increased flooding with subsequent risk to public health and well-being, decreased supply and quantity, and subsequent rising costs for mitigation, adaptation, management, insurance, etc. are all inherent. AWWA (2005), EPA (2008c), and IPCC (2007) provide additional examples of climate change impacts on water and its infrastructure and subsequent implications.

2.2 Importance and challenges of adaptation and mitigation in infrastructure

Water is critical for adaptation and mitigation of climate change, as climate change is to a great extent water change (Water and Climate Coalition, 2010a). As mentioned earlier, water has been identified as the primary medium through which society and the environment will be impacted by climate change (Bates et al., 2008). The drivers, constraints, stakeholders, and various scenarios imposed on water resources are numerous. The *World Water Report 3* (UN, 2009) outlines these as decision-making criteria affecting water in Figure 2.2-1.

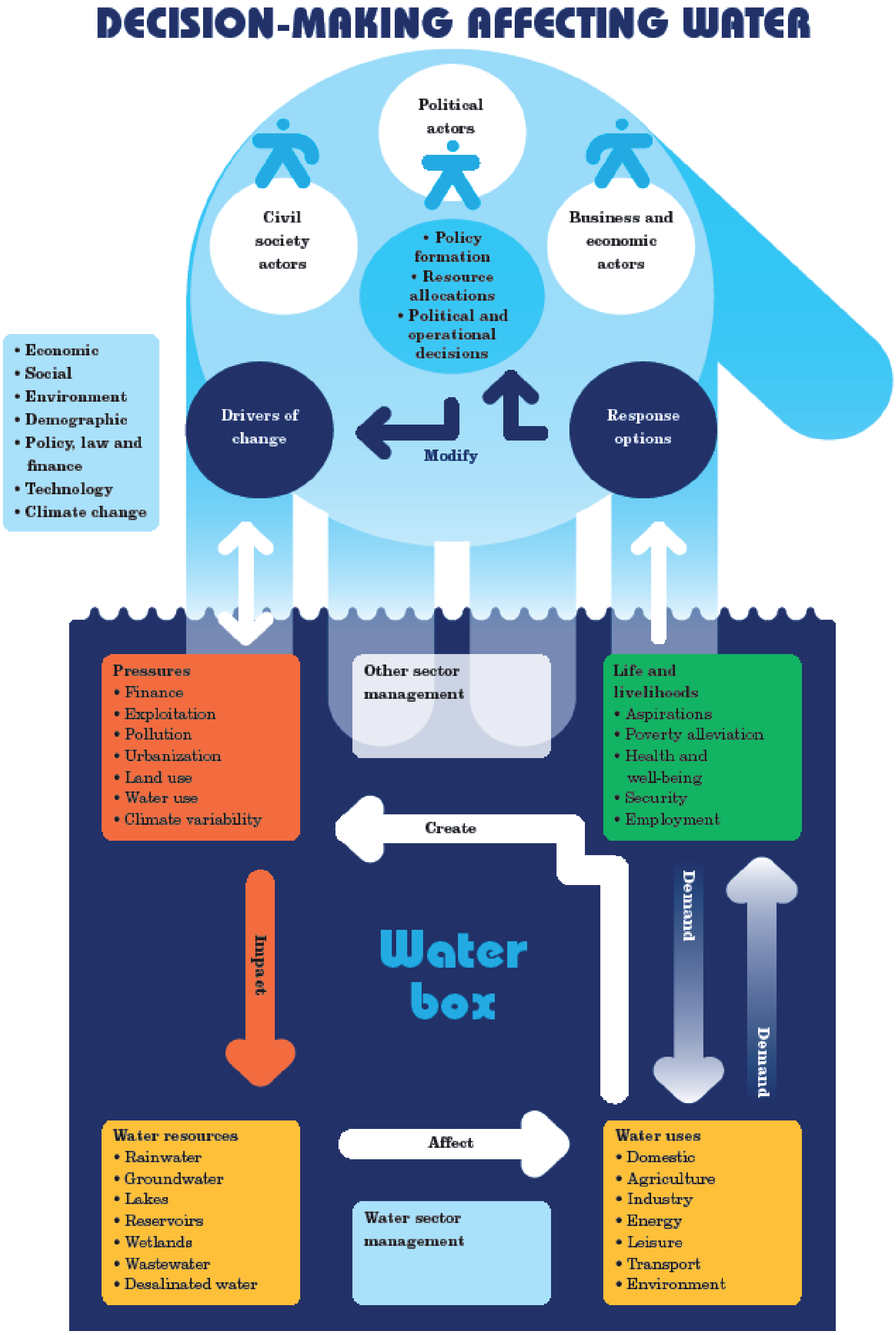


Fig. 2. 2-1. A Schematic of Water Resource Drivers, Constraints, and Issues (Source: UN, 2009)

Additionally, it provides a synopsis of challenges and stakeholders on the cover of the report, which help to provide additional context, as shown in Figure 2. 2-2.

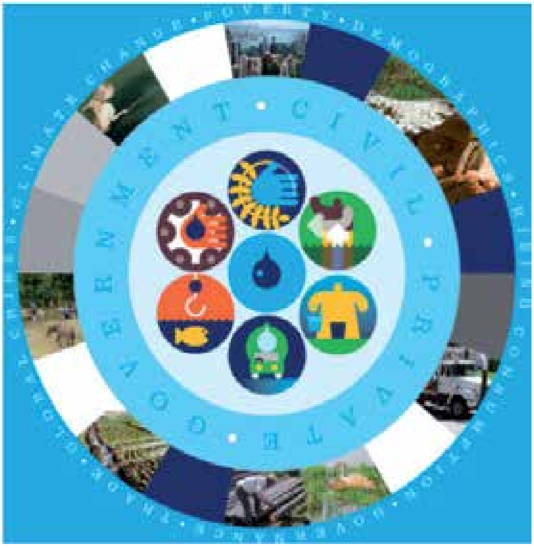


Fig. 2. 2-2. A snapshot of water challenges and stakeholders (Source: UN, 2009).

At the United Nations Framework Convention on Climate Change's (UNFCCC) 16th Session of the Conference of the Parties (COP 16) in Cancun (UN, 2010), the Water and Climate Coalition (2010b) called out important fundamental concepts about water change due to climate change to be considered in further climate change examination (Water and Climate Coalition, 2010b). These are grouped in three categories: Climate Change Adaptation, Climate Change Mitigation and Water, Climate Change Finance and Water as interpreted below. These key philosophies are important to reflect upon in developing a deeper understanding of climate change adaptation and mitigation needed via water and its infrastructure.

Climate Change Adaptation and Water

- Climate change is water change.
- Resilience should be achieved through Integrated Water Resources Management (IWRM).
- National Adaptation Programmes of Action (NAPA) and IWRM should be integrated.
- Regional cooperation is necessary to respond to climate change impacts on transboundary waters.
- Adaptation that is eco-system based is necessary for the foundation of adaptation.
- Water supply and sanitation resilience must be strengthened in the face of climate change.
- Adaptive water management is important for life and livelihoods.
- Risk reduction strategies must be integrated with water resources management to address severe water events.

Climate Change Mitigation and Water

- The reciprocal relationship between climate change mitigation and water (and its eventual nexus with energy) must be recognized.

- The carbon (and energy) footprint of the water sector must be addressed, as it is a high contributor.
- Climate change mitigation should be integrated with water resources management to achieve "no regrets" scenarios.
- Avoid assumptions about future water availability, and fundamentally revisit plans.
- Energy efficiency must be enhanced in the water sector, and "smart" infrastructure can help to achieve this.
- Recognize the mitigation impacts of adaptation actions and vice versa in the water sector (i.e., scarcity drivers of desalination with large energy/carbon footprint).

Climate Change Finance and Water

- Economic resources need to be developed and grown for water adaptation infrastructure, especially in developing countries.
- Additional funding is needed to meet the United Nation's Development Program's Millennium Development Goal 7 of halving the proportion of people without access to safe drinking water and sanitation by 2015, as even just the costs of climate change (US$ 10B/year through 2015) (Toubkiss, 2006) greatly exceed the sole costs of basic supply and sanitation at US$ 9-11B by 2030 (UN, 2007) , or US$ 13.7B in drier scenarios, $19.2 in wetter ones for water supply and flood management (World Bank, 2008).

EPA (2008c) examines the water infrastructure adaptation to climate change in a similar light. In 2008, it developed the National Water Program Strategy on a response to climate change. This strategic response outlines the priorities of the EPA in terms of helping and enabling the U.S. to address climate change adaptation, mitigation, and finance (via research and other means) of water. This program is a supporting facilitator for water infrastructure adaptation that aligns well with the Coalition's key philosophies.

The Water and Climate Coalition ([Coalition], 2010b) elaborates on its key philosophies. In its Water and Climate Change Roadmap for introducing a program on water and climate change under the UNFCCC, the Water and Climate Coalition (2010 a) distills these thoughts into generally recommended approaches. In its discussion, the Coalition explains that participatory water governance and function IWRM are essential for building social, economic, and ecological resilience to climate change (Water and Climate Coalition 2010a & 2010b). IWRM is important for recognizing, planning for, and actively balancing needs, allocations, and consumption, taking into account changing land use.

IWRM should be aligned with NAPAs and regional efforts to sustain freshwater supplies and ecosystems. As with many existing basic water management practices and plans, allocations should be optimized (i.e., efficient use), users should be prioritized based on need, and regular monitoring, evaluation, and adjustment should be made.

As mentioned in the Coalition's (2010a) key concepts, regional cooperation and collaboration is necessary to manage and adapt in addressing climate change impacts on transboundary supplies in the face of various laws and conventions. Such supplies are most effectively managed at a basin level (Aspen Institute, 2009), which may include dynamic, hydraulically interconnected basins strategies to help to alleviate the impacts of water change caused by changing climate. Such infrastructure has been used to harden water resources against climate change, as well as to incorporate sustainability and other numerous key criteria into decision making (Conner et al., 2009).

The Coalition (2010b) also distills the key points of mitigation and water. Bates et al. (2008) importantly points out that water adaptation and mitigation to climate change have a reciprocal relationship, in that the same efforts that are used to adapt water in the face of climate change, may be counter to mitigation of climate change, and vice versa. Options and benefits must be carefully considered and balanced in this context. Examples of this reciprocal relationship include:

- Desalination to adapt to water scarcity and cost, which subsequently creates the mitigation challenges of greater energy and carbon footprints, especially if undertaken by a large number of countries.
- Hydropower which aims to mitigate carbon footprints, while often relying on non-readily adaptable water resources in some ways, and environmental requirements and strategies.
- Biofuels which aim to mitigate carbon footprints, but do not always necessarily incorporate energy efficiency strategies, and which are frequently water intensive.
- In general, water purification and treatment facilities which are used to guard public and environmental health are enormously energy intensive and have high carbon footprints. In fact, water services (treatment, pumping, etc.) contribute about 4% of the global GHG emissions (Coalition, 2010a), which is on the same order of magnitude as air traffic. Additionally, they are often the largest energy consumers of municipalities and local governments (Coalition, 2010a), consuming 30-60% of a city's energy bill through 2006 (Energy Information Administration, 2007 and United States Environmental Protection Agency [EPA], 2008a), in the US equaling 3% of its national energy use among 60,000 water systems and 15,000 wastewater systems (Carlson et al, 2007). However, Carlson et al. (2007) and EPA (2008a) present some solutions to addressing high energy usage at treatment plants via benchmarking and energy reduction approaches and strategies. A breakdown of electricity use at treatment plants is provided in Fig. 2.2-3.

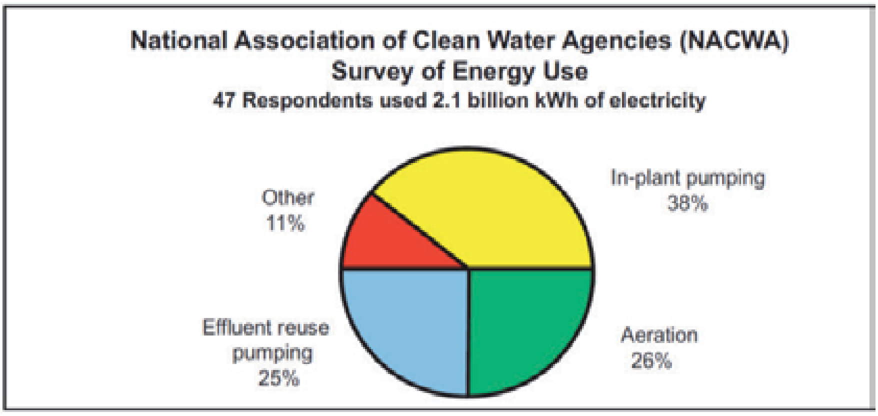


Fig. 2. 2-3. Breakdown of electricity use at treatment plants (Source: Jones, 2006).

Note that all of these reciprocal relationship examples may often require a high capital investment, and may require additional significant investment to become more dynamic and subsequently resilient against climate change, or at least provide energy to these water investments.

Now that relationship of water change to climate change, infrastructure importance, and infrastructure vulnerability and footprints has been established, a suggested framework is outlined in following sections to examine how to specifically go about assessing, planning, and implementing infrastructure adaptation.

3. Infrastructure asset management planning as a strategic solution

3.1 Importance, benefits, and opportunities

With the case established for the significance of adapting water infrastructure to climate change, utilities, water managers, regulators, designers, operators, and other stakeholders need a practical method for addressing it. A structured approach for managing such infrastructure is known as asset management. Asset management may be the best framework on which to support and enable climate adaptation risk management for infrastructure in a realistic and capable fashion. Cromwell et al. (2010) also supports this notion.

Understanding some important definitions are important for context and greater comprehension. New Zealand Asset Management Support ([NAMS] 2011) defines infrastructure assets as, "…stationary systems (or networks) that serve defined communities where the system as a whole is intended to be maintained indefinitely to a specified level of service by the continuing replacement and refurbishment of its components." Assets also are defined as having a life of greater than one year (Urquhart et al., 2007).

In the context of discussion in this chapter, examples would include canals and pipelines, lakes and reservoirs, dams (may include hydropower), water purification facilities, water distribution networks, wastewater collection systems, wastewater treatment facilities, stormwater and other flood controls such as levees and combined sewer overflows, fisheries, and other such water infrastructure. NAMS (2011) also notes that the assets of infrastructure networks are interdependent, both within a particular asset network, as well as from one network to another (water supply and water purification), and across different types of infrastructure networks (i.e., water distribution and transportation).

Another important term is "asset management". Asset management may be defined as, "the combination of management, financial, economic, engineering, and other practices applied to assets with the objective of providing the required level of service to customers and the environment at acceptable levels of risk and in the most efficient manner" (Urquhart et al., 2007). NAMS (2011) notes that "customers" should include the consideration of both present and future customers. In the context of this chapter, the set of assets under consideration is the water one noted in the discussion of defining infrastructure assets

The key elements of infrastructure asset management are (NAMS, 2011):

- Utilizing a lifecycle approach
- Developing cost-effective management strategies for the long-term
- Providing a defined level of service and monitoring performance
- Understanding and meeting the impact of growth through demand management and infrastructure investment
- Managing risks associated with asset failures
- Sustainable use of physical resources
- Continuous improvement in asset management practices

Asset management is applied to (IPWEA, 2011):

- Determine how to meet the increasing demand for new and upgraded infrastructure
- Determine how to [choose] to prolong the life or renew existing infrastructure
- How to pay for these

Asset management is a core component of effective utility management. It helps to mitigate potential risks and is often targeted towards addressing a major concern, such as regulatory compliance or critical asset failure (Baird, 2011). Such potential risk and failure could be associated with water change due to climate changes.

Other reasons for undertaking asset management efforts include aging infrastructure, more defensible budgets and utility rates in the face of limited funding, and workforce transitions (Parton et al., 2011), evidence of prudent leadership, transparency of sound financial management, protecting credit scores, gaining better interest rates for issuing debt, and helping to gain access to low-interest-rate loans and grants (Baird, 2011). These additional reasons tie directly into addressing climate change because they ultimately are important enablers for water infrastructure climate change adaptation. The benefits align well with the Aspen Institute's (2009) recommendations for making water systems more sustainable.

The underlying benefits of asset management help to enable several important components for the adaptation of water infrastructure for climate change. Parton et al. (2011) notes that underlying benefits of quality asset management include more transparent and defensible budgeting, more efficient and effective knowledge transfer, improved performance management and reporting, better communication with staff and stakeholders, as well as improved customer responsiveness and service.

Additionally, quality business enhancements associated with asset management in an organization can lead to better understanding and communication of near term and long term system risks and capital needs and better efficiency in business and data management (MWH, 2009). Through achieving these benefits associated with asset management, and incorporating climate change within the asset management process, utilities will be able to better adapt their water infrastructure to climate change, making it more sustainable over the long term to serving the water supply and quality needs of its customers.

Recalling the water infrastructure investment needs mentioned earlier and considering the tremendous undertaking of adapting water infrastructure to climate change, society must look for opportunities in these challenges. One such opportunity is with respect to infrastructure in the U.S. Although sophisticated, robust, well-designed and well-constructed, infrastructure in the U.S. is generally in poor condition, and much of it is generally near the end of its design life.

Of particular concern to the discussion of this chapter, water infrastructure in U.S. has received a grade of "D" or below in the American Society of Civil Engineers' Report Card on America's Infrastructure (ASCE, 2009), which translates to a condition rated as "poor", as noted in Table 3.1-1. Of the $2.2T in estimated infrastructure needs in the U.S. (breakdown shown in Table 3.1-2), at least US$ 367B is needed for water infrastructure over five years (ASCE, 2009). The U.S. is not alone; other modern, developed countries are experiencing a similar challenge, such as Australia (Institute of Public Works Engineering Australia [IPWEA], 2011).

Why are these ratings and costs important to take into consideration when examining approaches for adapting water infrastructure to climate change? These are important to consider because they present an opportunity; if this magnitude of infrastructure investment is needed, then this investment should be designed and managed in such a way that takes into account climate change and the ways in which water infrastructure can best be adapted within what is determined to be an acceptable level of risk.

Risk assessments, strategies and plans, and implementation and processes will need development and to be executed to successfully and sustainably enable this. The next sections delve into some of the approaches for delivering these in an effort to adapt water infrastructure to climate change. The first examines proven components of successful asset management. The second section, considers how to integrate climate adaptation planning for infrastructure into proven asset management approaches.

Infrastructure Category	**Grade**
Aviation	D
Bridges	C
Dams	D
Drinking Water	D-
Energy	D+
Hazardous Waste	D
Inland Waterways	D-
Levees	D-
Public Parks & Recreation	C-
Rail	C-
Roads	D-
Schools	D
Solid Waste	C+
Transit	D
Wastewater	D-
America's Infrastructure G.P.A.	**D**
Estimated 5-Year Investment Need	**US$ 2.2T**
Note: Each category was evaluated on the basis of capacity, condition, funding, future need, operation and maintenance, public safety, and resilience	
A = Exceptional, B = Good, C = Mediocre, D = Poor, F = Failing	

Table 3. 1-1. 2009 Report Card for America's Infrastructure (Adapted from: ASCE, 2009)

CATEGORY	5-YEAR NEED (BILLIONS)	ESTIMATED ACTUAL SPENDING*	AMERICAN RECOVERY AND REINVESTMENT ACT (P.L. 111-005)	FIVE-YEAR INVESTMENT SHORTFALL
Aviation	87	45	1.3	(40.7)
Dams	12.5	5	0.05	(7.45)
Drinking Water and Wastewater	255	140	6.4	(108.6)
Energy	75	34.5	11	(29.5)
Hazardous Waste and Solid Waste	77	32.5	1.1	(43.4)
Inland Waterways	50	25	4.475	(20.5)
Levees	50	1.13	0	(1.13)
Public Parks and Recreation	85	36	0.835	(48.17)
Rail	63	42	9.3	(11.7)
Roads and Bridges	930	351.5	27.5	(549.5)
Discretionary grants for surface transportation			1.5	
Schools	160	125	0**	(35)
Transit	265	66.5	8.4	(190.1)
	2.122 trillion***	903 billion	71.76 billion	(1.176 trillion)
Total Need****	**$2.2 trillion**			

* 5 year spending estimate based on the most recent available spending at all levels of government and not indexed for inflation
** The American Recovery and Reinvestment Act included $53.6 billion for a State Fiscal Stabilization Fund for education, as of press time, it was not known how much would be spent on school infrastructure.
*** Not adjusted for inflation
**** Assumes 3% annual inflation

Table 3. 1-2. Estimated 5-year investment needs in the US in billions of dollars (USD) (Source: ASCE, 2009).

3.2 Approaches of asset management

Becoming familiar with a realistic, proven approach to managing such infrastructure is important to enable better understanding of how a framework for climate adaptation planning for water infrastructure may be structured, and the underlying foundation on which it must rely for many important components such as strategic direction, communication and buy-in, identified areas of improvement, useable data, and process implementation for execution and ongoing evaluation and revision. This section examines some key components for quality asset management.

Asset management planning can be envisioned in three major steps: service planning, asset management planning, and financial planning (Baird, 2011). Strategy must be developed based around business drivers, such as those mentioned earlier, and desired service levels of the assets, as well as an awareness of present strengths and weaknesses of the organization and its asset base. Service levels are "defined measures of performance or benefit as received by the community and environment. [They] usually relate to quality, quantity, reliability, responsiveness, environmental acceptability, and cost" (Urquhart et al., 2007). The State of Victoria Department of Treasury and Finance ([Victoria], 1995) diagrams the myriad of considerations in effective asset management. An agency's asset management program should encompass all of the activities illustrated in Fig. 3.2-1.

To account for and coordinate the implementation of these many complex components in a comprehensive and cohesive manner across a utility, more robust asset management endeavors are implemented via a programmatic approach for an organization. A programmatic approach can also help to enable asset management to be managed as an ongoing effort, revisited and revised as necessary, and communicated across a utility on a regular basis. Managing assets in a programmatic manner can help to best realize the benefits of asset management. (Parton et al., 2011)

Fig. 3. 2-1. Components of an effective asset management plan (Source: Victoria 1995).

Major objectives of quality asset management problems are for their analysis to look into the future, rather than the past to determine budget needs, and to be proactive. Being proactive is important to optimize a utility's expenditure by determining the most appropriate time for refurbishment or replacement to maintain the levels of service at an acceptable level of risk and budget (Urquhart et al., 2007). These risk and budget components will need to evolve to take into consideration issues associated with changes in water due to climate change. Once the business drivers and service levels are defined for the asset set, then an assessment can be performed to identify the capabilities of the business processes of the organization and the capabilities of its assets. EPA (2008b) provides a general approach that is based on seeking the answers to "5 Core Questions of Asset Management Framework":

- What is the current state of my system's assets?
- What is my required sustainable level of service?
- Which assets are critical to sustained performance?
- What are my minimum life cycle costs?
- What is my best long-term funding strategy?

The flow chart in Figure 3. 2-2 shows the relationships and dependencies between each one of these core asset management questions (EPA ,2008b).

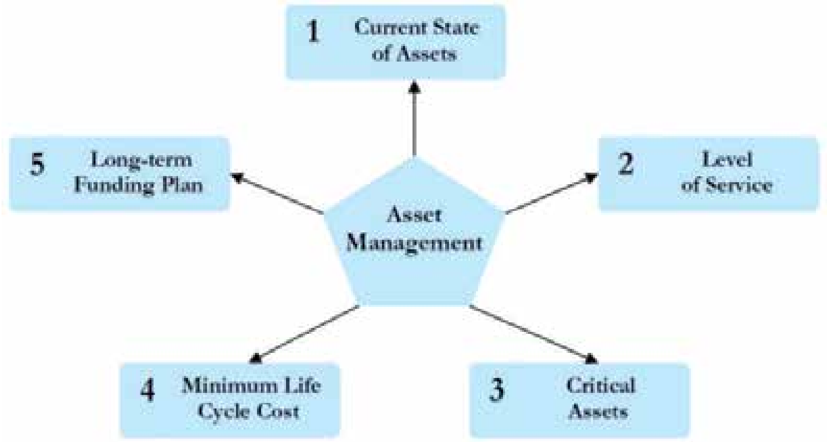


Fig. 3. 2-2. Relationships and dependencies among the core framework questions (Source: EPA, 2008b).

Asset management can evolve to more sophisticated analysis (Urquhart et al., 2007):

- Condition-based
- Performance-based
- Service-based (service-driven)
- Risk-based

Risk assessment is defined as "the process of identifying sources of hazards, estimating risk, and evaluating the results" (American Bureau of Shipping [ABS], 2003). Note that "risk-based" asset management is regarded as the highest level of sophistication. This is important, as "risk" is defined as accounting for both condition- and criticality-based failure of assets (Association of Local Government Engineering New Zealand, Inc. [INGENIUM], 2006). The condition analysis takes into account the likelihood that an asset would fail, based on the health, applied type of use, time in use, and typically-accepted life expectancy of that asset. These components can help to construct the declining functionality of an asset, as represented by the following curve in Figure 3.2-3 representing an asset's probability of failure ("P-F") over its lifespan:

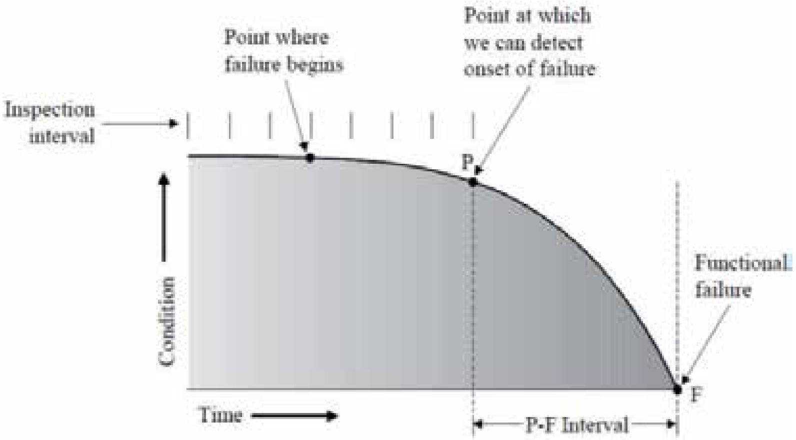


Fig. 3. 2-3. Asset condition deterioration curve (Source: ABS, 2004).

The criticality analysis considers how crucial the asset is to meeting the business drivers and levels of service, as well as enabling its system and its components to also meet these. For instance, if the asset fails, what is the consequence to service, public safety and health, and how would it impact the rest of the system, integrated water resources infrastructure, or the environment if it were to fail? Combining these condition and criticality components helps to define risk for assets and numeric scales may be utilized to quantify this risk (ABS, 2003, INGENIUM, 2006, Urquhart, 2007). Risk can be expressed quantitatively as a measure of loss per unit time or presented qualitatively (ABS, 2003), as shown in Figure 3.2-4.

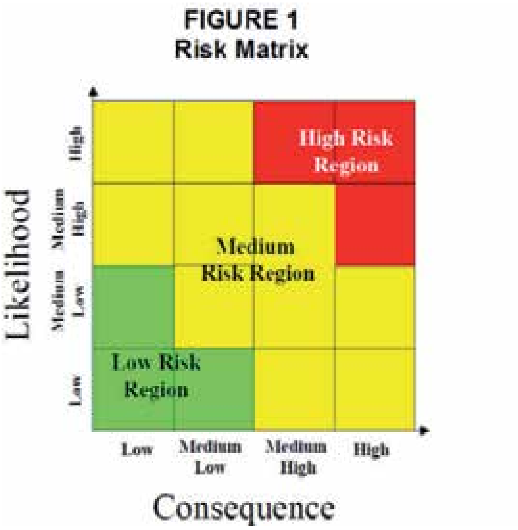


Fig. 3. 2-4. Components of risk which can be evaluated as a function of time (Source: ABS, 2003).

Risk is the product of condition deterioration and criticality (ABS, 2003, INGENIUM, 2006, Urquhart, 2007). This is expressed in Equation 3.2-1 as likelihood and criticality.

$$\text{Risk} = \text{Likelihood x Criticality} \qquad 3.\ 2\text{-}1$$

This product may be further evaluated based on detectability. "Detectability" indicates how easy or difficult the identification of a symptom of failure is, preferably before it occurs or before a process enabled by the asset is affected. Sydney Water Corporation (SWC) has applied detectability in its asset management practices (Urquhart et al., 2007). Incorporating climate change via water change impacts on infrastructure should be a component included in this risk analysis. This is addressed later in this chapter.

Asset data and asset systems have an important role in asset management, and when climate adaptation is overlain upon it. Data must be accurate and complete. Data systems must be useable, consistent, and up-to-date, and usually include computer maintenance management systems (CMMS) and geographical information management systems (GIS) in conjunction with an asset database at a minimum. Sound business processes must also be refined, integrated, and communicated across utilities striving for successful asset management programs. Life cycle management planning is important to maintain the value of the infrastructure asset investment and to sustainably operate it in a manner that meets service level expectations within the constraints of business drivers.

Additional approaches, details, and cases of asset management best practices are included within, ASCE (2008), Bloetscher et al. (2011), INGENIUM (2006), Urquhart et al. (2007), and other sources.

3.3 Climate adaptation planning to incorporate risk and climate change to prioritize renewal

As noted earlier, the Water and Climate Coalition (2010b) stated that one of the key philosophies related to climate change adaptation and water is that "risk reduction strategies must be integrated with water resources management to address severe water events". Now that an understanding of how successful asset management of water infrastructure is conducted has been achieved, this section examines how to fold-in climate adaptation planning on such an asset management platform to enable water infrastructure to be adapted to climate change. As Cromwell et al. (2010a) notes, asset management may be the best approach to climate adaptation risk management.

As mentioned earlier, climate vulnerability ratings of water infrastructure should be assigned during the risk analysis step of asset management. A framework is needed to facilitate the roll-in of climate change risk into this risk analysis.

Cromwell et al. (2010a) presents an approach for evaluating the vulnerability of water infrastructure. Additional studies also provide further specifics that complement this approach well. The approach is based on the typical risk management paradigm:

- Risk identification – what constitutes a risk
- Risk assessment – defining what risks exist, and to what degree information and data competencies are important
- Risk management – deciding what to do about the risks at hand to achieve "low regrets" situations and implement a strategy forward for adaptation

The challenge of identifying climate change risks on infrastructure is broken into pieces, or "deconstructed", for individual analysis and possible action. Deconstruction is initiated with the use of cause-effect climate change impact tree diagrams to provide a framework for understanding the full scope of the challenges at hand and to organize relative information. The tree diagrams represent four major "chains" of causation expected from the global warming scenario, including:

- Sea level rise
- Warmer and shorter winters
- Warmer and drier summers
- More intense rainfall events

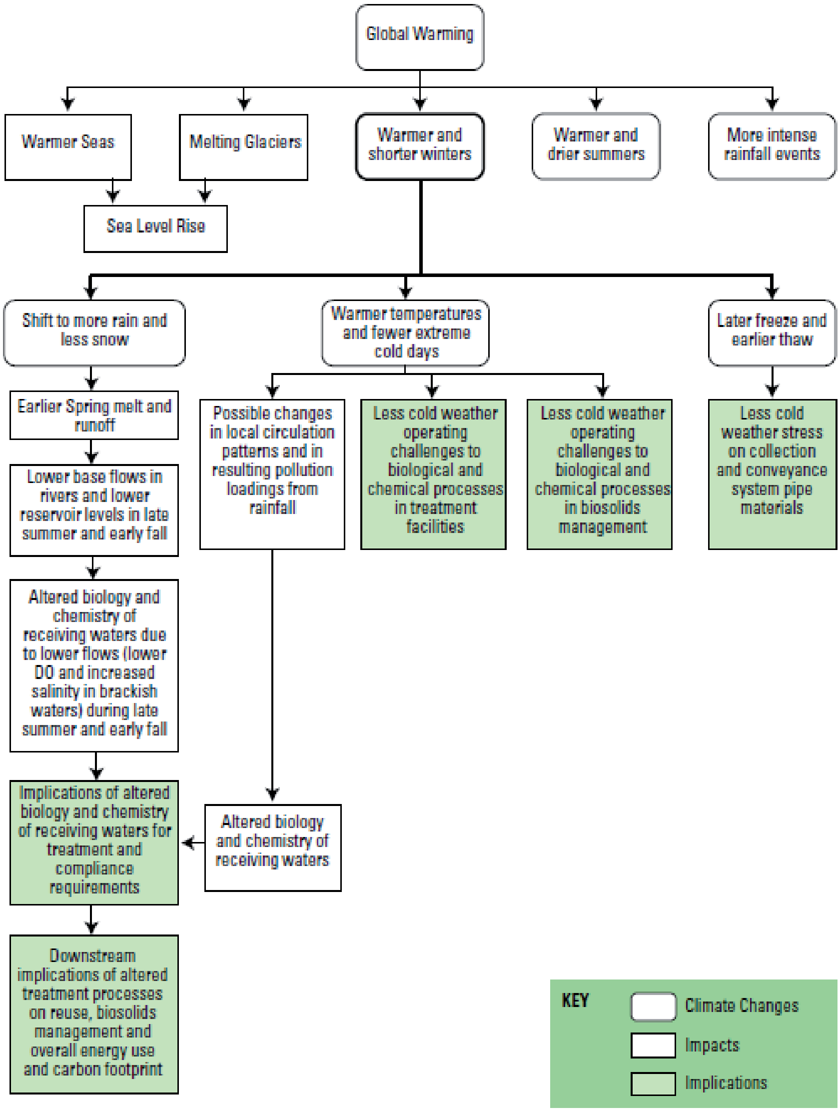


Fig. 3. 3-1. An example of cause-effect tree diagrams for use in climate change risk evaluation: "Impacts and implications of warmer and shorter winters for wastewater agencies" (Source: Cromwell et al., 2010a).

An example of the cause-effect tree diagrams is shown in Figure 3.3-1. A similar platform could be considered for additional scenarios of climate change. Tracing through the cause-effect logic of the trees shows how climate changes produced by the global warming scenario may result in impacts on hydrologic and environmental processes that may have implications for water infrastructure (Cromwell et al, 2010b).

Next, an assessment of the magnitude and timing of the various potential climate change impacts and subsequent implications should be performed to use in a risk assessment of the water infrastructure (includes both human-made infrastructure and natural assets such as lakes and streams, etc.). The IWRM (Integrated Water Resource Management) can help in this analysis.

As noted earlier, the Water and Climate Coalition (2010b) called out IWRM as a key philosophy of climate changed adaptation and water. Others agree as well (Bogardi et al., 1994, Kindler, 2000, Miller et al., 2005). IWRM can be the most effective method for assessing adaptation options for water infrastructure and their implications in the context of an evolving regulatory environment that inherently presents competing demands (Miller et al., 2005).

IWRM is defined as a systematic approach to planning and management that considers a range of supply-side and demand-side processes and actions, incorporates stakeholder participation in decision processes, and continually monitors and reviews water resource situations. It must simultaneously address the biophysical system and the socio-economic management system that both influence water management. The associated analysis relies on hydrologic models for physical processes and must account for the operation of hydraulic structures (i.e., dams and diversions) and institutional factors that govern the allocation of water between competing demands. (Miller et al., 2005).

In the face of the high amount of uncertainty presented by climate change on water infrastructure planning, important in the analysis of climate change implications on infrastructure is what is known as the "top-down" and "bottom-up" approaches (Miller et al., 2005), as summarized in Figure 3.3-2.

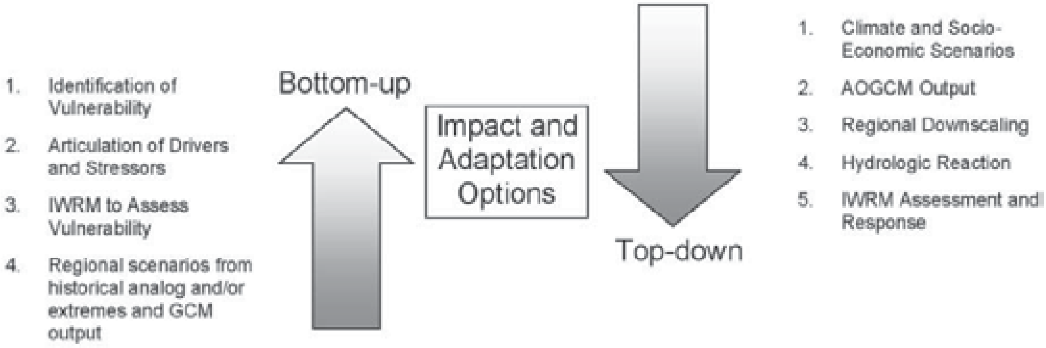


Fig. 3. 3-2. Bottom-up and top-down approaches to climate change assessment (Source: Miller et al., 2005).

The bottom-up approach relies on water system managers' knowledge of their operations to assess the wide array of practical consequences of climate change, especially over the course of years or a couple of decades, that cannot be predicted by climate models. The typical climate models have analyses based on larger geographical and time horizons. The staff knowledge of water management organizations is used to consider the performance characteristics and tolerances of its water systems in extreme operating conditions. (Cromwell et al., 2010a).

This leads back into the specific methodology proposed by Cromwell et al. (2010a) for determining climate change risk to which water infrastructure is exposed, which also aligns well with the decision-making approach recommendations for water utilities in the U.S. as presented in Means et al. (2010). Once defined through the course of the rest of this approach, the risk component could then later be integrated into the risk analysis and subsequent planning components of a successful asset management program. The first fundamental question of assessing the risk of climate change on a water asset is now presented (Cromwell et al. (2010a): *"What threshold level of change in the combination of climatic hydrologic and environmental parameters would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations?"* This question should be answered by the water management staff based on their expertise of each of their particular assets in the analysis at risk in the face of climate change.

Once the potential risks to assets have been defined in terms of a critical threshold, Cromwell et al. (2010a) presents the second guiding question: *"What is the likelihood of seeing a threshold level of change in the combination of climatic, hydrologic, and environmental parameters that would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations within capital planning or other meaningful time horizons?"* The answer to this second question will need to consider climate change science to determine what climate changes and subsequent impacts and implications could exceed the thresholds defined in the first question, including the likelihood (remember the defining equation of risk) of occurrence and timing. Much of the best science, if it is even known for the particular issue, often encompasses such a high uncertainty, that the best scientific answers may be presented in the form of ranges. (Cromwell et al., 2010a)

With this high degree of uncertainty present, Cromwell et al. (2010a) emphasizes not to freeze planning decisions to await more refined scientific information, which will take much time to develop. This point is where the top-down approach depicted in Figure 3.3-2 comes into consideration. The top-down approach involves refining predictions of climate change, downscaling of climate models to apply them to local geographies and streamflow situations, and eventual IWRM planning (Miller et al., 2005). Some of this downscaling of models to local streamflows has progressed, including developing a transferable model of the process to expand applications (Bloetscher et al., 2010, Colorado Water Conservation Board [CWCB], 2011, King County, 2007, and Means et al., 2010).

To address the high uncertainty associated with the timing and possible magnitude thresholds of climate impacts, Cromwell et al. (2010a) proposes a third questions to guide the analysis: *"What is the overall adaptation strategy that leads to more sustainable infrastructure over the course of this century – the sustainable path?"* This question can be broken down into two considerations for analysis: "How can the consequences of an anticipated threshold level of impact be avoided or mitigated through adaptive responses?", and, "How are short term adaptation options different from longer term choices, and what is the strategic path that leads from one to the other?" Cromwell et al. (2010a) presents this third set of questions to help formulate adaptation decisions by distinguishing between the short term and long term responses to a climate change threat to give the progression of the decisions some traction. With the high degree of uncertainty inherent in such decisions, and pursuing low-or no-regret actions to adapt infrastructure to climate change, the key is to keep the selected strategies flexible. To keep them flexible, such decisions are often targeted with incremental, short-term solution. Very important, these incremental steps should keep options for the longer term open without restricting the ability to adapt the infrastructure in a way to respond to new revelations and changing conditions among climate, water, targeted service levels, and the regulatory environment. (Cromwell et al., 2010a).

In Figure 3. 3-3, Cromwell et al. (2010a) depicts the framework of its components of the above overall suggested approach of this section in Figure 3.3-3. Its structure reveals how each of the climate change impacts identified in the cause-effect trees can be distilled into possible adaptation strategies via the methodology described above to keep water infrastructure on the "sustainable path"(Aspen Institute, 2009) in the face of climate change.

The impacts can be grouped into "threat bundles" to be evaluated as a package to asses which specific influences are likely to be the most critical to a water manager's assets to consider adaptation options in a composite approach, rather than piecemeal (Cromwell et al. 2010b). These likelihoods, consequences, risks, and possible solutions can then be overlain with the same components in the asset management planning mentioned earlier to roll-up into overall strategies, budgets, communications, and organizational business for the water utility.

At the high level, Cromwell et al.'s structure may be massaged at this point into further detail and analysis to consider life safety, cost/benefits, and initial categories of action, including "must do", "investigate further", etc. as shown in Figure 3. 3-4. Other criteria that can be incorporated at this point include commitment, regulations, readiness, catalysis, sustainability, complimenting opportunities, and other important considerations (DeGeorge et al., 2008).

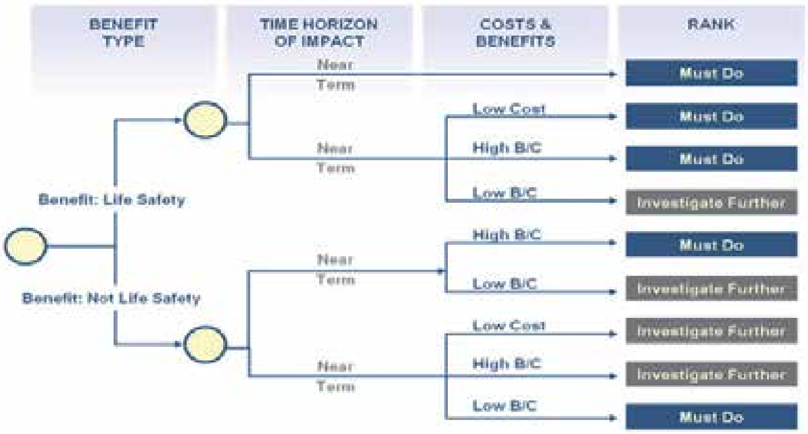


Fig. 3. 3-4. Additional structural details for identifying and prioritizing adaptation (DeGeorge et al., 2008).

As criteria and solutions continue to build in complexity, formal, proven decision making approaches and tools may be necessary to aid in analysis, prioritization, feasibility, transparency, communication, reconciliation, opportunity identification and efficient and effective comparisons and breakdown analyses. An outline of how to apply such decision making is presented in Conner et al. (2009).

Additionally, the criteria and solutions enable important sustainability considerations such as:

- Gray vs. green infrastructure
- Low Impact Development (LID)
- Sustainability visions and plans
- Life Cycle Analysis (LCA)

Opportunity identification could include such strategies as (Conner et al., 2009):

- Energy recovery
- Enhanced water quality
- Supply optimization (i.e. water rights) and reuse
- Shared infrastructure/finance
- Conservation
- Environmental impact mitigation

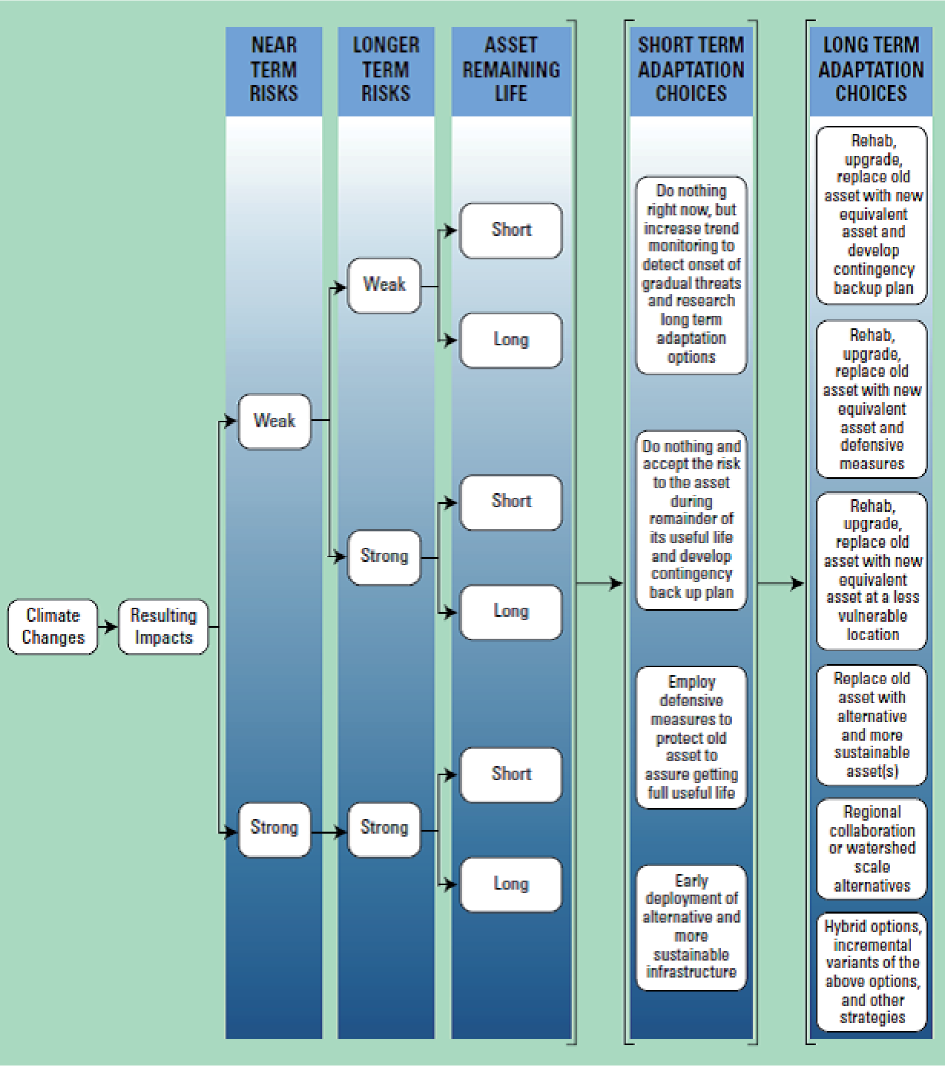


Fig. 3. 3-3. Finding the sustainable path in adaptation planning (Cromwell et al., 2010).

While continuing to tie together suggested methodologies for adapting infrastructure in a cohesive manner in this chapter, Bloetscher et al. (2010) presents another subsequent step. Bloetscher et al. (2010) assesses vulnerable infrastructure for climate change impacts and presents specific strategies that could address the effects of climate change on that infrastructure. Once the adaptation options have been determined, Bloetscher et al. (2010) develops very specific strategies for addressing climate change impacts on the community on which their case focuses.

The community examined in the case is Pompano Beach, Florida, a coastal city which could encounter various effects of climate change on their water assets. The implications examined include those arising from the impacts of sea rise and more intense rainfall events, such as sea level rise, salt water intrusion, hydrodynamic barrier challenges, and programs involving new wells, reclaimed water, and aquifer recharge. The conclusions of the case align well with Cromwell et al. (2010), Water and Climate Coalition (2010b), and others that regional solutions will be needed and long-term water management should consist of vulnerability analysis, short- and long-term applicability of current practices. Additionally, a toolbox of technical and management solutions and a planning framework for increasing resilience and sustainability using adaptive management to deal with uncertainties was found to be necessary. Table 3.3-1 shows the specific implementation program of adaptation alternatives and supporting analysis that is considered when evaluating solutions and choosing the path forward for the community's water infrastructure and vulnerabilities.

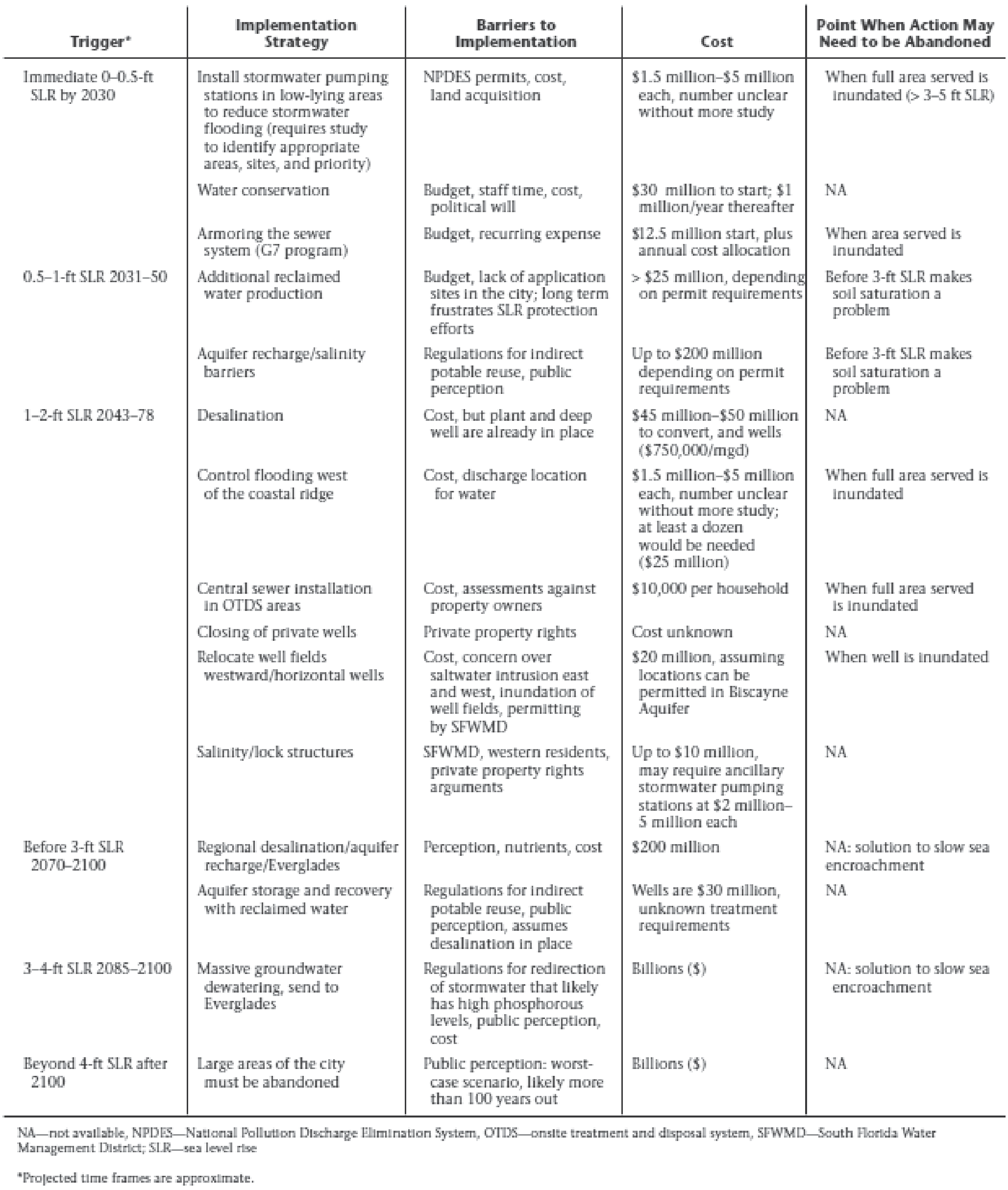
Bloetscher et al.'s (2010) implementation program of adaptation alternatives provides an example of how to structure the consideration, analysis, and action related to specific climate change implications on local water infrastructure. The researchers examined very specific strategies, barriers, costs, and strategy changes. These could be generally included in the "hybrid" classification of scenarios as mentioned as an adaptation alternative in Cromwell et al., 2010) for evaluating implications and action necessary for sea level rise.

Bloetscher et al. (2010) also provided a toolbox of general recommendations, largely in a coastal context, for protecting various water resources from climate change effects, as shown in Table 3.3-2.

Impact criteria and ratings can be defined, and weighting assigned to show the correlation the severity of climate change impacts and the importance of needed adaptation activities for infrastructure. This may be accomplished in a manner similar to the method presented by EPA (Johnston, 2010) for identifying the vulnerability of EPA Region 8 areas to climate change impacts. These impact rankings will help to create a ranking that can be used to prioritize adaptation activities.

For instance, a ranking of "1" would be the most severe or most threatening climate change impact to infrastructure. This would be the highest priority vulnerability to address, and its adaptation solution the highest priority adaptation activity to pursue. In many cases, this ranking would be determined as the climate change risk ranking of the product of likelihood and consequence. This can be rolled into the asset management risk scoring as an additional weight on the overall risk score.

Considering non-climatic drivers applicable to each of the applicable climate impacts and adaptation activities of concern is also important. Non-climatic drivers are, "external dynamics that have the potential to exacerbate climate change impacts". In this sense,



Trigger*	Implementation Strategy	Barriers to Implementation	Cost	Point When Action May Need to be Abandoned
Immediate 0–0.5-ft SLR by 2030	Install stormwater pumping stations in low-lying areas to reduce stormwater flooding (requires study to identify appropriate areas, sites, and priority)	NPDES permits, cost, land acquisition	$1.5 million–$5 million each, number unclear without more study	When full area served is inundated (> 3–5 ft SLR)
	Water conservation	Budget, staff time, cost, political will	$30 million to start; $1 million/year thereafter	NA
	Armoring the sewer system (G7 program)	Budget, recurring expense	$12.5 million start, plus annual cost allocation	When area served is inundated
0.5–1-ft SLR 2031–50	Additional reclaimed water production	Budget, lack of application sites in the city; long term frustrates SLR protection efforts	> $25 million, depending on permit requirements	Before 3-ft SLR makes soil saturation a problem
	Aquifer recharge/salinity barriers	Regulations for indirect potable reuse, public perception	Up to $200 million depending on permit requirements	Before 3-ft SLR makes soil saturation a problem
1–2-ft SLR 2043–78	Desalination	Cost, but plant and deep well are already in place	$45 million–$50 million to convert, and wells ($750,000/mgd)	NA
	Control flooding west of the coastal ridge	Cost, discharge location for water	$1.5 million–$5 million each, number unclear without more study; at least a dozen would be needed ($25 million)	When full area served is inundated
	Central sewer installation in OTDS areas	Cost, assessments against property owners	$10,000 per household	When full area served is inundated
	Closing of private wells	Private property rights	Cost unknown	NA
	Relocate well fields westward/horizontal wells	Cost, concern over saltwater intrusion east and west, inundation of well fields, permitting by SFWMD	$20 million, assuming locations can be permitted in Biscayne Aquifer	When well is inundated
	Salinity/lock structures	SFWMD, western residents, private property rights arguments	Up to $10 million, may require ancillary stormwater pumping stations at $2 million–5 million each	NA
Before 3-ft SLR 2070–2100	Regional desalination/aquifer recharge/Everglades	Perception, nutrients, cost	$200 million	NA: solution to slow sea encroachment
	Aquifer storage and recovery with reclaimed water	Regulations for indirect potable reuse, public perception, assumes desalination in place	Wells are $30 million, unknown treatment requirements	NA
3–4-ft SLR 2085–2100	Massive groundwater dewatering, send to Everglades	Regulations for redirection of stormwater that likely has high phosphorous levels, public perception, cost	Billions ($)	NA: solution to slow sea encroachment
Beyond 4-ft SLR after 2100	Large areas of the city must be abandoned	Public perception: worst-case scenario, likely more than 100 years out	Billions ($)	NA

NA—not available, NPDES—National Pollution Discharge Elimination System, OTDS—onsite treatment and disposal system, SFWMD—South Florida Water Management District; SLR—sea level rise

*Projected time frames are approximate.

Table 3. 3-1. Implementation program of adaptation alternatives (Source: Bloetscher et al., 2010)

Water Resource Issue	Tool
Water Conservation	Reduce requirements for additional treatment capacity and for development of alternative water supplies
Protect Existing Water Sources Against Saltwater Intrusion	Create hydrodynamic barriers: aquifer injection/infiltration trenches to counteract saltwater intrusion using treated wastewater
	Drill horizontal wells
	Build salinity structures and locks to control advance of saltwater intrusion
	Relocate well fields when saltwater intrusion or other threats render operations impractical
Develop Alternative Water Resources	Desalinate brackish waters
	Acquire regional alternative water supplies
	Capture and store stormwater in reservoirs and impoundments
Wastewater Reclamation & Reuse	Irrigate to conserve water and recharge the aquifer
	Apply to industrial uses and cooling water
	Implement indirect aquifer recharge for potable water
Stormwater management	Re-engineer canal systems, control structures, and pumping strategies

Table 3. 3-2. Tools for protecting water resources from climate change (Adapted from: Bloetscher et al., 2010).

climate change activities should be developed and implemented using a holistic approach, rather than considered in isolation. Non-climatic drivers include:

- Land use change
- Population change
- Failing infrastructure
- Increased demand
- Demographic shifts (rural to urban migrations)
- CO2 effects on vegetation (Johnston, 2010)

As mentioned earlier, infrastructure asset systems can be inter-related and should be coordinated. The climate change risks and adaptation approaches should be considered in conjunction with climate water change risk as well, perhaps considering the risk and adaptation findings of approaches for other infrastructure systems.

One such approach is for transportation. The U.S. Federal Highway Administration has identified a useful approach for evaluating the vulnerability of the national highways to climate change, largely subsequent water change and risks (ICF, 2009). Such analysis and possible integration of climate change assessments on other such infrastructure will ultimately be useful in a more complete, efficient, and likely effective adaptation of infrastructure to climate change. Well-designed asset management approaches can help to coordinate and execute the coordinated climate adaptation of multiple infrastructure systems.

4. Adapting infrastructure intelligently, sustainably

As may be concluded from the discussion within this chapter, a variety of considerations, drivers, constraints, stakeholders, and other issues will be considered in actionable adaptation decisions, strategies, and actions. Ideally, and hopefully with purposeful intent, the infrastructure adaptations should be made in as resilient, dynamic, intelligent, and sustainable manners as possible:

- **Resilient** in the sense that the water infrastructure is modified, protected, or managed in a way that helps to serve its business drivers and levels of service commitments, while protecting and serving the health and welfare of society and the environment. Emergency management plans and contingency plans should be in place.
- **Dynamic** as being enabled to adapt to changing climate, and subsequently, water conditions to the extent possible, and, otherwise, strategically managed in a regular, ongoing manner to incorporate new knowledge, new risks, and new actions.
- **Intelligent** as in short-term steps are taken in the best interest of critical present vulnerabilities and in the best interest of the long term by not limiting the paths ahead that can be taken. Also, the management of the infrastructure includes new technologies and approaches to operating, maintaining, managing, and sustaining the infrastructure. Tools include strategic metrics and key performance indicators, real time monitoring technology, reporting performance dashboards, and other “smart” technology. The organization(s) managing the infrastructure must also have a solid foundation to enable this intelligence including a well-defined strategic direction, communication, and alignment; strong organizational capabilities and processes; and quality, applicable, accessible and well-managed data. This also includes regional collaboration and knowledge sharing.
- **Sustainable** in the sense of balancing the triple bottom line across the interests of society, the environment, and financial enablers and feasibilities. This includes sustainable infrastructure design, life cycle assessment, life cycle management planning to maintain asset value while operating it to meet service levels, mitigating negative impacts of the infrastructure on society, natural resources and surroundings , and closing the loop of resource use to reduce waste streams and unneeded resource consumption (Conner et al., 2009).

As mentioned earlier, much of the infrastructure in developed countries has reached the end of its designed life. The time has come to significantly refurbish, or often, replace this infrastructure (ASCE, 2009). This presents an enormous opportunity to green significant amounts of infrastructure that will serve society for decades to come, often 50 years or more. Examples of some general green infrastructure opportunities and strategies are included from Conner et al. (2009) in the previous section of this chapter. Additional approaches may be found at the Institute for Sustainable Infrastructure ([ISI], 2011) and WERF (2011).

Standards provide a framework for greening infrastructure in a sustainable manner. For instance, ASCE, the American Council of Engineering Companies (ACEC), and the American Public Works Association launched a new standards organization and rating system for sustainable infrastructure (ASCE, 2011). ISI’s (2011) rating system for sustainable infrastructure aims to be:

- Performance-based (outcomes) rather than prescriptive
- Scalable for size and complexity of projects
- Adaptable for specific needs and circumstances
- Conducive to self-assessment, as well as independent verification
- Voluntary

The demand for water resources will also have to be managed. Two main channels exist to accomplish this (Miller et al., 2005):

- Improve water efficiency – for instance, through price incentives, water transfers, technology improvements, regulations, and reduction of system water loss.
- Effective reallocation of saved water – this could often require regional collaboration and infrastructure and management mechanisms in place for the future.

5. Conclusions and recommendations

As discussed in this chapter, water is a significant enabler of economic prosperity and well-being. Water infrastructure is the medium that enables this. This infrastructure faces numerous threats and uncertainty from climate change, which directly leads to water change and subsequent needs to adapt this infrastructure in the face of a myriad of existing drivers, constraints, and expectations of water infrastructure.

A framework is needed to identify, assess, strategize, plan, and act on the risks that this infrastructure faces due to climate change. This chapter has shown how climate adaptation planning and prioritization may be incorporated as a component of risk in what has been identified as a sound, successful, and actionable risk-based asset management program. The chapter has aimed to connect the dots among related best practices in infrastructure climate adaptation assessment, planning, and implementation in a robust, yet flexible manner for the long term.

Additional efforts and knowledge need to be pursued to better define specific climate change impacts on local water and its infrastructure to reduce the level of uncertainty. This information should be shared and leveraged in a collaborative manner through Integrated Water Resources Management, and on a watershed, rather than political, basis when considering water supplies.

Also, ripple effects will be felt throughout associated sectors that are important to infrastructure. These include the banking, insurance, business policy (i.e., U.S. Securities and Exchange climate change disclosure risk requirements, corporate social responsibility, etc.), and industrial sectors.

Very importantly, to successfully enable and implement this adaptation, organizations that manage water and its infrastructure must develop the readiness to address climate change vulnerability and provide strategy for ongoing monitoring with needed adjustments. The organization must develop both the capacity and the capability to adapt its infrastructure, for which sound leadership, knowledge management and transfer, tools, internal and external communication, and possible change management will be needed.

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17

Mainstreaming Climate Change for Extreme Weather Events & Management of Disasters: An Engineering Challenge

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1. Introduction

World climate and sea level are changing. The decade of 2000-2009 was the warmest in modern record (NASA, 2010). In the period 1905-2006, global mean surface temperature has increased by three-quarter of a degree Celsius. Ocean temperature has also risen. Overall, global land precipitation has increased but there is no spatial or temporal uniformity. More intense and longer droughts observed in the tropics and sub-tropics. Large scale decreases in melting of glaciers and ice caps were recorded that had contributed to global sea level rise. Average temperatures in the Arctic increased at the rate as twice as the rest of the world in the past century but there were regional variations. Future projections are a warmer world with more extreme temperature episodes, intense precipitation activities, likelihood of increased intense tropical cyclone activity and expansion of area affected by droughts (IPCC, 2007).

Climate change will pose a formidable challenge to the engineering society in particular. Since the dawn of civilizations, engineers built infrastructure to protect human society and property from the onslaught of natural hazards. Despite failures in many occasions which contributed to disasters (however, failure of structures alone cannot cause disasters; there must the other socio-economic and human factors), engineering infrastructures indeed saved lives and property and contributed to human-well being. Changing climate can increase occurrence of more extreme weather events as well as their intensities may increase (IPCC, 2007). Infrastructures built with only the consideration of historical risk may be inadequate to provide the required protection. Many engineering projects are being undertaken now will experience climate change in their life cycle. Therefore, it is an imperative to mainstream additional climate risk in planning, design and implementation of engineering infrastructures to provide safety. It is not an easy task. There are many challenges ahead.

2. Overview of natural hazards and disasters

2.1 Is frequency increasing?

Is frequency of extreme weather events increasing? By analyzing data from 1980 to 2010, Munich Re (2010) concluded that there was a gradual increase in hydro-meteorological extreme events worldwide. Many of the recent extreme events have left behind trails of devastations. Particularly two hydro-meteorological events that occurred in 2010 deserve discussion. Pakistan and Russia experienced flood and wildfire of disproportionate nature in 2010. About 1800 people lost their lives and six millions were made by the floods in *Pakistan*. The devastating floods started in the north-west of the country in the basins Swat and Kabul Rivers and gradually traveled to the south through the Indus River. Most of the gauging stations displayed record breaking water levels since the continuous measurement began in 1947. The country incurred an economic loss of US$ 9.5 billion (Munich Re, 2010; ADB, 2011). *Russia* witnessed doubling of the number of wildfires and the area affected from 1985 to 2004. Two major factors-extreme dryness and heat contributed to the outbreak of fires in the 2010 summer. In July, the observed rainfall in Moscow was just 12 mm or 13% of the normal. The July and August temperatures were the highest in the recorded history of 130 years. The flames were additionally fanned by strong winds (Munich Re, 2010). The fires killed 130 people directly. However, indirectly an estimated 56,000 people died due to an increase in the number and intensity of heart attacks, strokes, asthma attacks and bouts of coughing, as well as skin and eye disorders. Economic and insured losses were $3.6 billion and $20 million, respectively from the wildfire events (Munich Re, 2010).

Although globally extreme hydro-meteorological events are on the rise, but there are regional variations in of their categories. In the north Atlantic region, no increasing trend was found in hurricane frequency (BAMS, 2000). Singh *et al.* (2000) studied changes in the frequency of tropical cyclones developing over the Arabian Sea and the Bay of Bengal utilizing 122 years (1877-1998) of data. They revealed significant increasing trends in the cyclone frequency over the Bay of Bengal during November and May which are main cyclone months. Analysis of long-term flood data in the Ganges, Brahmaputra and Meghna basins in India, Bangladesh and Nepal did not show any general increasing or decreasing trend (Mirza *et al.*, 2001).

The North-Atlantic hurricanes and typhoons have become stronger and longer-lasting since 1970s (Emanuel, 2005). Since 1949, the annual average storm peak wind speed summed over the North Atlantic and eastern and western North Pacific increased by 50%. The duration of storms also increased roughly by 60%. Both duration and peak intensity of trends contribute to the overall increase in net power dissipation. In a recent paper, Pielke Jr. *et al.* (2005) found no precise causation for this trend. Analyses conducted by Landsea *et al.* (1999) and Chan and Liu (2004) could not identify any secular trend in tropical cyclone intensity in both Atlantic and North Pacific, respectively. Lal (2001) detected increased intensity of cyclones in the Bay of Bengal region.

2.2 Are damages on the rise?

Globally economic damage from extreme natural events is on the rise (**Figure 1**). Munich Re (2010) estimated overall economic loss of about $150 billion in the year 2010 of which extreme weather hazards accounted for more than two-thirds of it. Previously, Munich Re (2004) estimated that economic losses increased by seven folds in the period 1994-2004 compared to that of 1960-1969. The main reason behind huge economic losses is economic development in the areas under risks of natural extreme events. The human population has increased (more than doubled) since 1960s, and that these increase are especially intense in the developing countries. However, in the same period, insured losses were increased by 15 folds. This is due to the expansion of insurance business, coverage and higher rate of claims.

Date	June-July	December	July-August	September	Summer
Country/ Region	China	Australia	Pakistan	Mexico	Russia
Event	Floods – landslides	Floods	Floods	Hurricane Karl Floods	Heatwave, drought, wildfires
Fatalities	>800	-	1760	16	Direct: 130; indirect:56, 000
Economic Losses (US$m)	15,000	>10,000	9,500	3,900	3,600
Insured Losses (US$m)	270	>5,000	100	150	20

Source: Munich Re, 2010

Table 1. Five Largest hydro-meteorological catastrophes Occurred in 2010

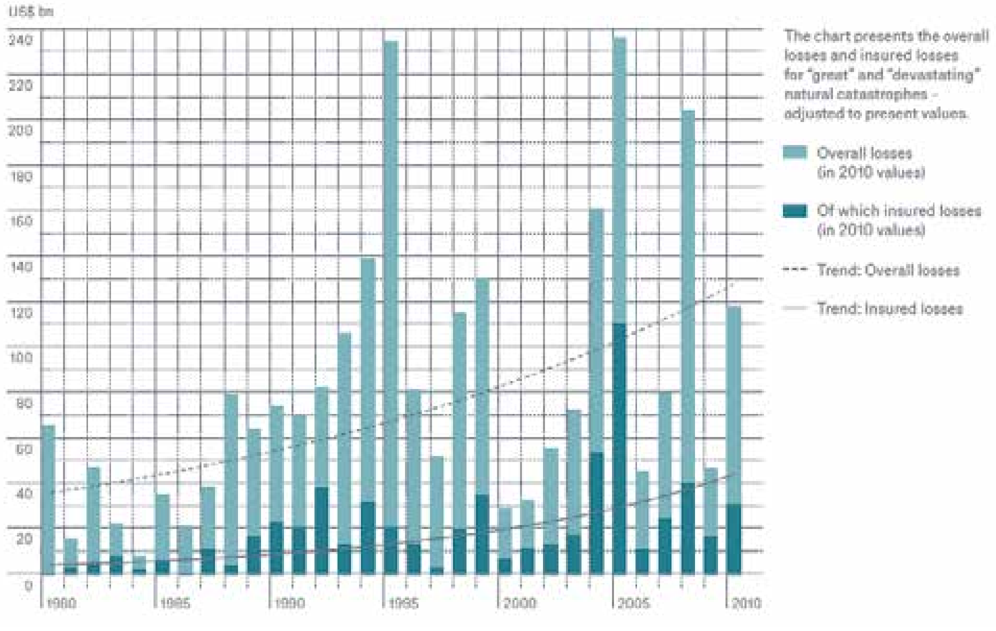


Fig. 1. Economic losses and insured losses – Absolute values and long-term trends. Source: Munich Re, 2010.

Any extreme event has a long term effect on insurance industry as well on the clients. For example, after Hurricane Andrew, a number of insurance companies in the USA went bankrupt because the number and amount of claim were so high (Changnon *et al.*, 1996).

The rate of premium goes up for both the insurer (re-insurance) and the policy holder. The reinsurance prices nearly doubled (CBO, 2002).

3. Climate change & future hazards

Based on the analysis of observed temperature records, the IPCC's Fourth Assessment Report concluded "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. (IPCC, 2007., p.5.)" In different time-periods of the 100 years (1905-2006), the rates of warming are showing an upward trend. For example, from 1955-2005, the rate of temperature increase per decade was 0.128^{o}C. But from 1980-2005, the rate has increased to 0.178^{o}C per decade. The mid- and high latitudes of the Northern Hemisphere demonstrate the largest rates of warming. The evaluation also indicates significant warming of sea surface temperature in the extra-tropical North Atlantic since the mid-1980s. Although sea surface warming is assumed to be associated with the warming phase of natural cycle (Folland *et al.*, 1986; Delworth and Mann, 2000), global warming is likely to be a contributing factor (IPCC, 2007). Changes in the amount, intensity and type of precipitation occurred which exhibited large natural variability as well as influenced by El Nino and the North Atlantic Oscillation. Observational records from 1900-2005 demonstrated significantly wetter in eastern North and South America, northern Europe and northern and central Asia. On the other hand, drier conditions observed in the Sahel, southern Africa, the Mediterranean and parts of southern Asia. In the northern regions, the amount of rain exceeded the snowfall. Heavy precipitation events increased significantly even in places where the total amount of precipitation displayed a reduction. Some regions also experienced occurrences of both floods and droughts (IPCC, 2007).

Knowing that global surface temperatures and precipitation patterns are changing, one question posed by the IPCC Third Assessment Report asks if and how climate variability or climate extremes have changed. The answer to this question is difficult to achieve since each climate variable is described by a different statistical distribution, which in turn exhibits case by case interactions between the changes in mean and variability. **Figure 2** illustrates this concept in terms of temperature. As the mean temperature increases, so does the occurrence of high temperatures (**Figure 2a**). As the variability increases, so does the probability of occurrence for both hot and cold extremes as well as the absolute value of the extremes (**Figure 2b**). Increases in both the mean and the variability can exacerbate the increase or decrease in probability of either hot or cold extreme temperatures (**Figure 2c**). The problem is further complicated by the presence of non-linear relationships between changes in one variable on another variable. For example, changes in mean temperatures correspond with changes in extreme weather events (Wigley, 1985; Wigley, 1988; Meehl *et al.*, 2000).

As part of the IPCC's Fourth Assessment Report (2007), the changes in variability and extremes for temperature and precipitation were evaluated simultaneously. The results from limited regional studies suggest that variations in temperature on both intra-seasonal and daily time-scales are decreasing. Thus, increases in global temperatures are influenced mainly by a significantly reduced frequency of extreme temperatures that are below normal supplemented by a smaller increase in the frequency of extreme temperatures that are above normal. More specifically, studies by Frich *et al.* (2001) show a reduced number of days with frost across much of the globe with a corresponding increase in heat-wave frequency in the Northern Hemisphere and Australia. The results are illustrated in **Figure 3**. The Frich *et al.* (2001) study also suggests an overall increase daily rainfall intensity with certain regions

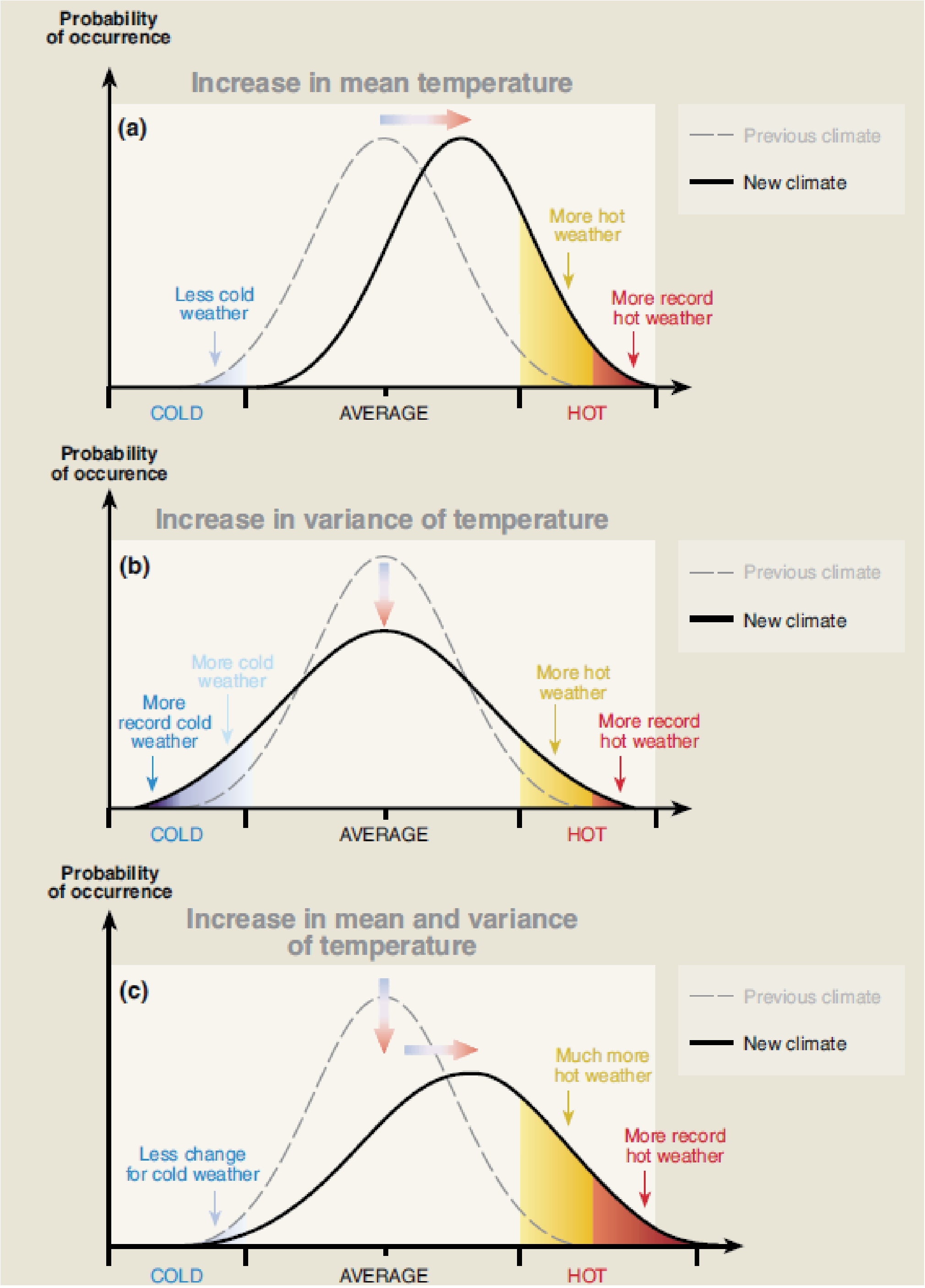


Fig. 2. Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature (Source: IPCC, 2001a).

experiencing increases in both the proportion of mean annual total precipitation falling into the upper five percentiles and in the annual maximum consecutive 5-day precipitation total. This is illustrated in **Figure 4**. The results published by Frich *et al.* (2001) were verified and updated by Alexander *et al.* (2006). The new study focused on changes in extreme events and included data for most of Central and South America, Africa, and southern Asia, which was previously absent. The project also led to the development of a more comprehensive and appropriate suite of climate change indices and a user-friendly software package for analyzing the indices and creating seasonal time series from the results.

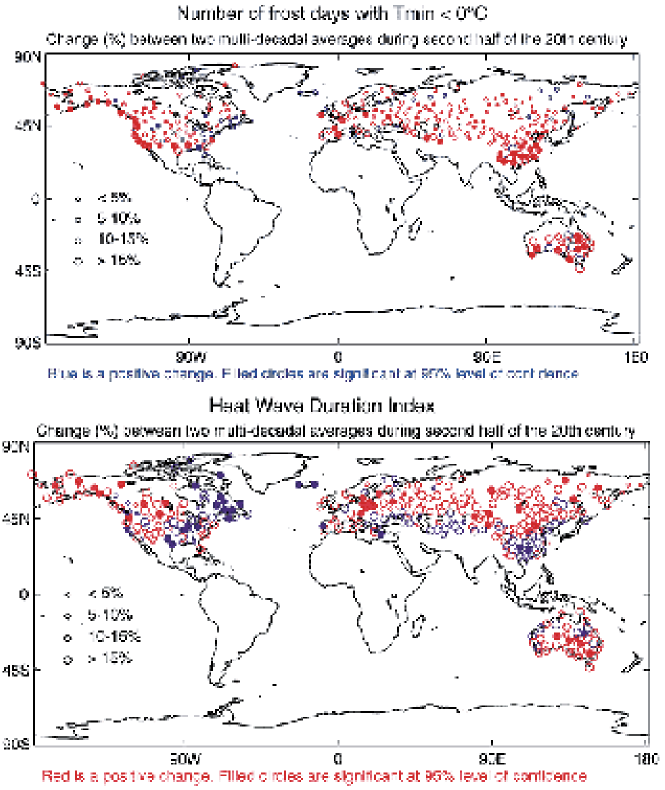
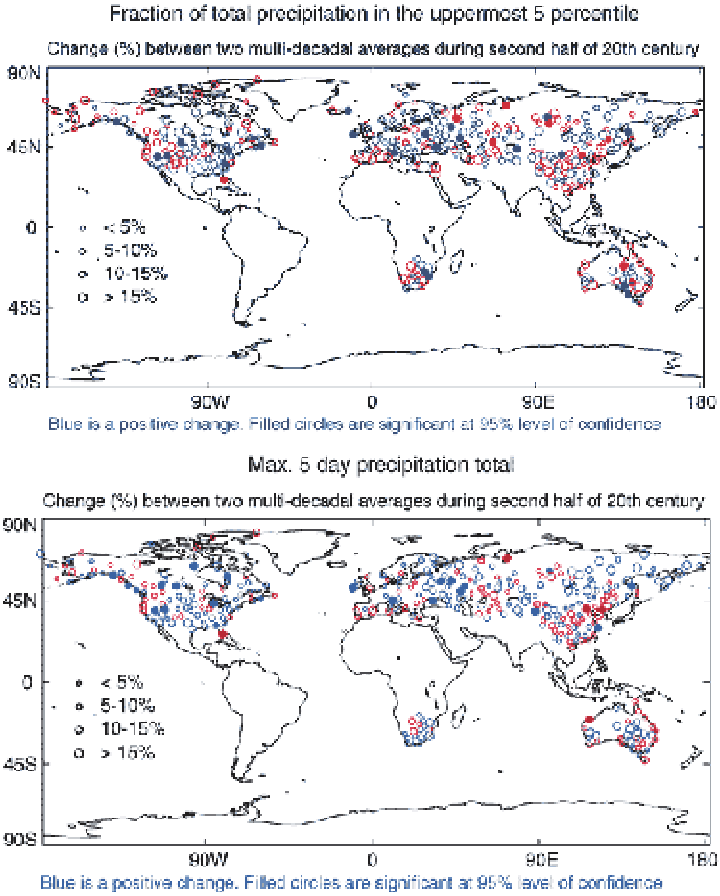


Fig. 3. Changes in the number of frost days and in heat-wave duration between the first and last half of the period 1946 to 1999 (Source: Frich *et al.*, 2001, cited in IPCC, 2001a).

The AR4 of the IPCC (2007) also included analyses of data related to changes in extreme weather and climate phenomena. For example, regarding the tropical cyclonic activity, the report concluded about intensification in the North Atlantic region since 1970 and that was correlated with increases with tropical sea surface temperatures. Although the intensification of cyclonic activities has been identified in some other regions, the IPCC (2007) expressed concerns about the quality of the data. In light of the difficulties involved with determining trends in climate variability and extreme events, numerous studies based on appropriate statistical analyses are being carried out. For example, Webster et al. (2005) have published studies that suggest an increase in hurricanes in the Atlantic basin, as well as a higher percentage of more intense ones. These results are illustrated in **Figure 5**.

However, a review by Michaels (2005) disputes these conclusions and suggests that increases in tropical storms can actually be attributed to natural cycles. Extending the starting point for analyzing observed hurricane data from 1970 to 1945 reveals a bigger picture that shows an oscillatory pattern of active and inactive periods rather than an increasing temporal trend (**Figure 6**). In a recent research results, Saunders and Lea (2008) concluded that tropical cyclonic activity in the Atlantic was related to sea surface temperature. They found a statistical relationship that 0.5°C increase in sea surface temperature increases cyclonic activity by 40% in August-September. Although it is acknowledged that increases in tropical storm intensity can be related to increases in sea surface temperature, consideration should also be given to other factors that determine the ability of the tropical cyclones to attain Category 4 and 5 intensities (Pielke, 1990, 1997).



Fraction of total precipitation in the uppermost 5 percentile

Change (%) between two multi-decadal averages during second half of 20th century

Blue is a positive change. Filled circles are significant at 95% level of confidence

Max. 5 day precipitation total

Change (%) between two multi-decadal averages during second half of 20th century

Blue is a positive change. Filled circles are significant at 95% level of confidence

Fig. 4. Changes in the proportion of annual precipitation occurring on days on which the 95th percentile of daily precipitation, defined over the period 1961 to 1990, was exceeded and the maximum annual 5-day precipitation total between the first and last half of the period 1946 to 1999 (Source: Frich *et al.*, 2001, cited in IPCC, 2001b).

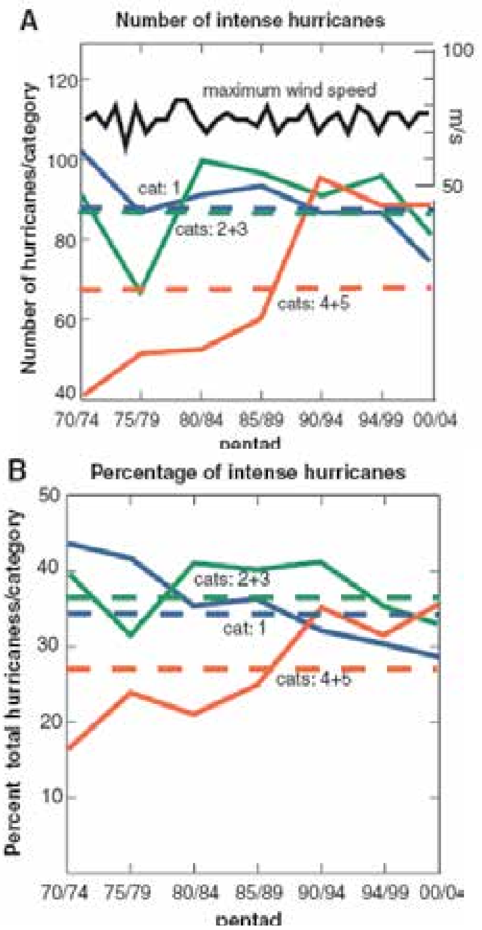


Fig. 5. Total number of storms (a) and percentage of the total annual storm count (b) for each category of intensity over 5-year periods from 1970 – 2004 (Source: Webster *et al.* 2005).

Despite the discrepancy in data analyses, most scientists concur that the recent increase in frequency and intensity of hurricanes in the Atlantic basin is consistent with increasing sea surface temperature trends and simulations that correlate escalations in GHG emissions with frequency intense tropical storms. However, there is also agreement that a longer data record is required to determine whether the frequency and intensity of hurricanes are following a natural oscillation or a temporal trend and if climate change is having a direct influence over these tendencies (Micheals, 2005; Pielke *et al.*, 2005; Webster *et al.*, 2005). A similar argument is made for studies of extreme temperature trends, such as Griffiths *et al.* (2005), as well as for the frequency and intensity of floods (Kundzewicz *et al.* 2005).

In addition to understanding the past and current trends in climate change, it is important for decision making and design processes to simulate and project future climate and associated extremes. The AR4 of the IPCC (2007) made an assessment of and quantified projections of possible future climate extremes from a variety of global coupled atmosphere-ocean models with different forcings. The results are summarized in **Table 2**. The projected future impacts of climate change that will have a direct impact on engineering practices include sea level rise, increasing precipitation, augmentation of both tropical and extra-tropical storm frequency and intensity, general drying of the mid-continental areas, reclining permafrost layer and melting of glaciers (IPCC, 2007).

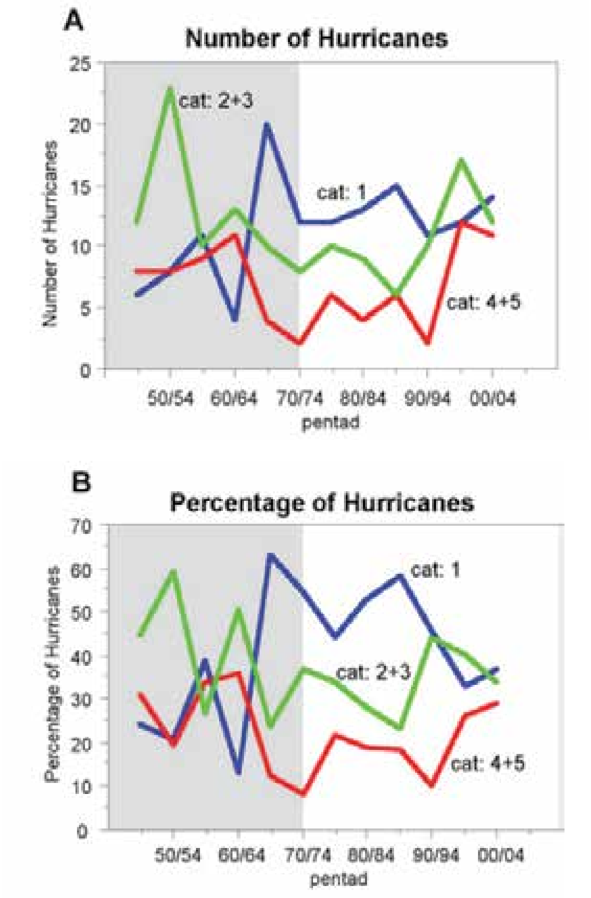


Fig. 6. Total number of storms (a) and percentage of the total annual storm count (b) for each category of intensity over 5-year periods from 1945 – 2004 (Micheals, 2005)

Although these forecasts are global in scale, different climatic and geographic regions around the world will be impacted in different ways and to varying degrees. In order to determine the level of risk associated with climate variability at a country level, researches are developing risk assessment techniques. For example, Brooks and Adger (2003), compiled fatality data from historical and recent climate related natural disasters to develop proxies indicating climatic risk. Using the CRED (2009) data, World Bank (2010) demonstrated that the number of people affected by climate related disasters are on the rise in lower-middle income countries due to rapid urbanization (**Figure 7**). Death toll from natural hazards and disasters has fallen but the number of the affected people has doubled every decade. Note that only climate cannot be blamed for such as increase, Factors like population growth, greater exposure of infrastructure to disasters and improvement in disaster reporting are also attributed to the increase in number of affected people (World Bank, 2010). Climate change induced increased weather events together with these factors, number of affected people would increase.

Phenomenon and direction of trend	**Likelihood that trend occurred in the late 20th Century (typically after 1960)**	**Likelihood of a human contribution**	**Likelihood of future trends based on projections for 21st Century using SRES scenarios**
Warmer and fewer cold days and nights over most land areas	*Very likely*	*Likely*	*Virtually certain*
Warmer and more frequent hot days and nights over most land areas	*Very likely*	*Likely (nights)*	*Virtually certain*
Warm spells/heat waves. Frequency increases over most land areas	*Very likely*	*More likely than not*	*Virtually certain*
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	*Very likely*	*More likely than not*	*Virtually certain*
Area affected by droughts increases	*Likely in many regions since 1970s*	*More likely than not*	*Likely*
Intense tropical cyclone activity increases	*Likely in some regions since 1970s*	*More likely than not*	*Likely*
Increased incidence of extreme high sea level (excludes tsunamis	*Likely*	*More likely than not*	*Likely*

Note: Virtually certain > 99% probability of occurrence, Extremely likely >95%, Very likely > 90%, Likely > 66%, More likely than not > 50%, Unlikely< 33%, Very unlikely < 10%, extremely unlikely < 5%.

Table 2. Estimates of confidence in observed and projected changes in extreme weather and climate events (Adapted from IPCC, 2007)

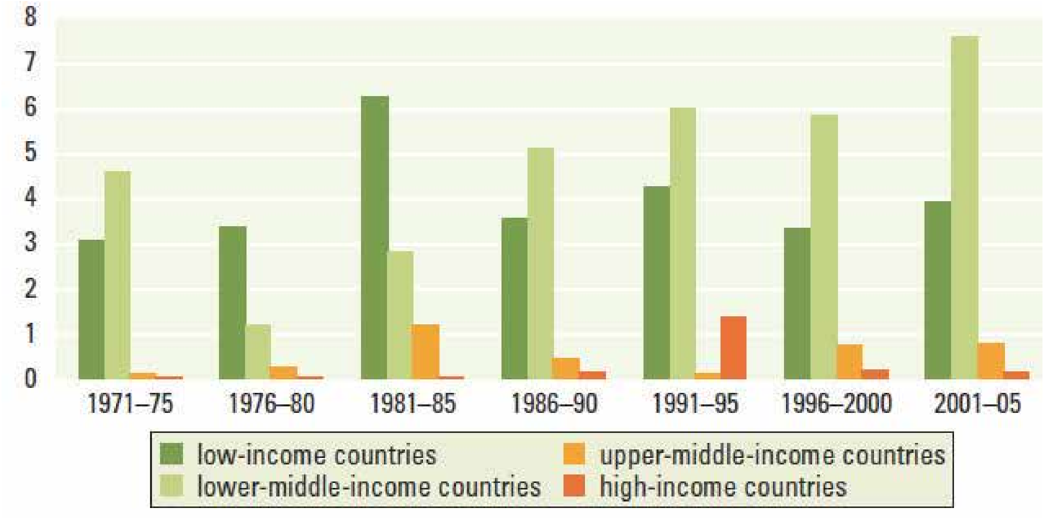


Fig. 7. People affected (as % share of population) by climate related disasters are increasing. Source: World Bank, 2010.

4. Hazards, engineering infrastructures and disasters

Since the dawn of civilization, human constructed engineering structures to sustain civilization, save human lives and property. Remnants of ancient civilizations of Harappa and Mohenjodaro (Pakistan), Mesopotamia (Iraq) and Maya Civilizations (Mexico) carry footprints of ingenious engineering structures. The Mohenjodaro civilization extended from the Indus valley in Pakistan to the Yamuna along the bed of the river Ghaggar in Rajhastan, Gujarat and up to the mouths of the rivers Narmada and Tapi in India. The Mohenzodaro and the Maya civilizations of Mexico believed to have ruined by the floods, and droughts, respectively (Dasgupta and Chattopadhyay, 2004; Dahlin, 1983). Following are some modern day engineering infrastructures constructed to reduce vulnerability of natural hazards. These infrastructures have already provided enormous protection to communities and property. Note that future climate change has not been factored into the designs of these structures. On the other hand, failure of the New Orleans Flood Levees during the landfall of Hurricane Katrina in August 2005 caused a widespread disaster. Failure of a structure can happen due to a variety of reasons which include: under-design, lack of data for decision making, resource constraint that leads to design compromise, political decisions, bad workmanship, quality of materials used, etc. These infrastructures along with many other thousands need to be strengthened worldwide to manage additional risks to be posed by future climate change.

4.1 Red river floodway, Winnipeg

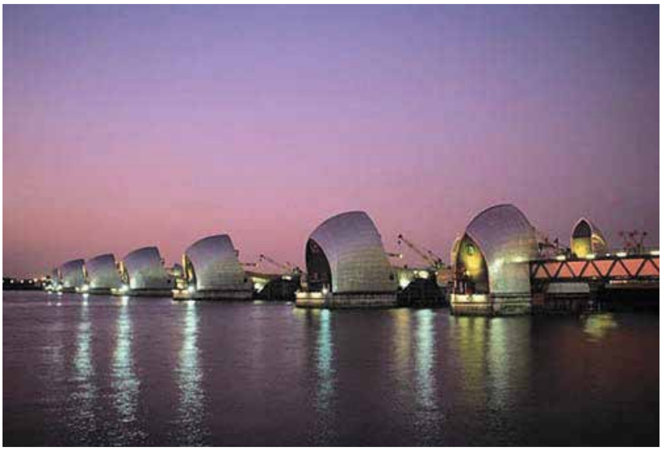
The Red River Floodway (**Figure 8**), in conjunction with the Portage Diversion and Shellmouth Reservoir, has proven to be very effective in protecting City of Winnipeg from flooding (RRFORC, 2000). The then Provincial Government was severely criticized for borrowing money to build the Floodway in the 1960s. The return on this investment has been substantial in terms of minimizing the environmental and economic damage to

Winnipeg. Since the commissioning of the structure, the floodway has operated approximately 28 times, preventing approximately $30 billion in flood damages. It was estimated that only in 2009, by diverting a peak water flow of approximately 1,218 m^3/sec of water into the channel, CAD$10 billion flood damage was averted (RRFEP, 2009). However, in 1997, the capacity of the flood way exceeded its design capacity. The floodway was not designed to provide benefits to residents of the valley south of Winnipeg (RRFORC, 2000). The International Joint Commission (IJC) (2000) made recommendations to upgrade the Floodway to accommodate a wide range of flow regimes, including those expected under future climate change. The Manitoba Floodway Authority has undertaken an expansion project of the floodway at an estimated cost of CAD$ 665 million. The cost is being equally shared by the Federal Government and the Provincial Government of Manitoba. Once completed, the project would be able to protect people from a flood larger than the 1926 flood magnitude. The floodway expansion will substantially increase the drainage capacity of the current channel from 1,700 m^3/sec to 4,000 m^3/sec or an estimated magnitude of a 700-year flood event (RRFWA, 2011; RRFEP, 2009).

Fig. 8. The Winnipeg Floodway (Photo: Courtesy of Manitoba Floodway Authority, 2011)

4.2 The Thames barrier

The last time that central London flooded was in 1928 that killed 14 people. In 1953, a disastrous flooding occurred on the East Coast and the Thames Estuary when lives of over 300 people were lost. If this flood had reached central London's highly populated low lying areas the result could have been devastating. After the flood, a decision was taken to construct the Thames Barrier (**Figure 9**) and other ancillary flood defence improvements. Since its commissioning in October 1982, the Thames Barrier has been used to protect London from the risk of flooding (EA, 2006). However, tide levels are steadily increasing owing to a combination of factors. These include higher mean sea levels, greater storminess, increasing tide amplitude, the tilting of the British Isles (with the south eastern corner tipping downwards) and the settlement of London on its bed of clay. There is a plan underway to strengthen the barrier so that it can continue to provide protection against higher flooding risk due to the effects of climate change (see Section 5).



Source: Guardian.co.uk.

Fig. 9. The Thames barrier, UK

4.3 Storm surge barrier, the Netherlands

The Dutch Government implemented the Delta Plan in the aftermath of a disastors flooding in 1953 that killed 1836 people in the lowlands of the Province of Zeeland (Gerritsen, 2005). This ambitious and costly plan shortened the Netherlands coastline by 700 kilometers. It closed off the sea by using a string of dikes and dams. However, the government decided to retain movement of tidal waters in the Eastern Scheldt through the storm surge barrier (**Figure 10**). Despite some environmental consequences caused by the project, the barrier has successfully provided protection from tidal flooding.

Source: http://images.world66.com/st/or/m_/storm_surge_barrie_galleryfull

Fig. 10. Storm Surge Barrier, the Netherlands

4.4 New Orleans flood levees

A large part of City of New Orleans is below sea level. The City has been under the treat of flooding from the periodic high waters of the Mississippi River and waters of Lake Pontchartrain pushed by occasional severe hurricanes. Construction of the levees along the

River undertaken soon after the city was founded, and more extensive river levees were built as the city grew over the centuries. In the past, the levees protected the city from flooding in many occasions. However, when Hurricane Katrina landed, levees overtopped and breached in dozens of places and water inundated more than 75% of the City and killed more than 1,000 people. An American Society of Civil Engineers Commission found different failure mechanisms which include: scour erosion caused by overtopping, seepage, soil failure, and piping (ASCE, 2005).

5. Mainstreaming climate change: an engineering challenge

Since climate change is apparently already effecting development, future climate change impacts may need to be considered in engineering project planning, design, implementation and operation. The act of integrating both mitigation and adaptation measures into engineering projects to reduce and avoid damage from climate related risks is called mainstreaming. Mitigation refers to measures that reduce the propagation of climate change. The Kyoto Protocol is one such measure. On the other hand, Adaptation measures intend to reduce the impacts of and vulnerability to climate change that has either already occurred or is expected to take place in the future. The difference between mitigation and adaptation is illustrated in **Figure 11.** The different levels of adaptation are outlined in **Figure 12**.

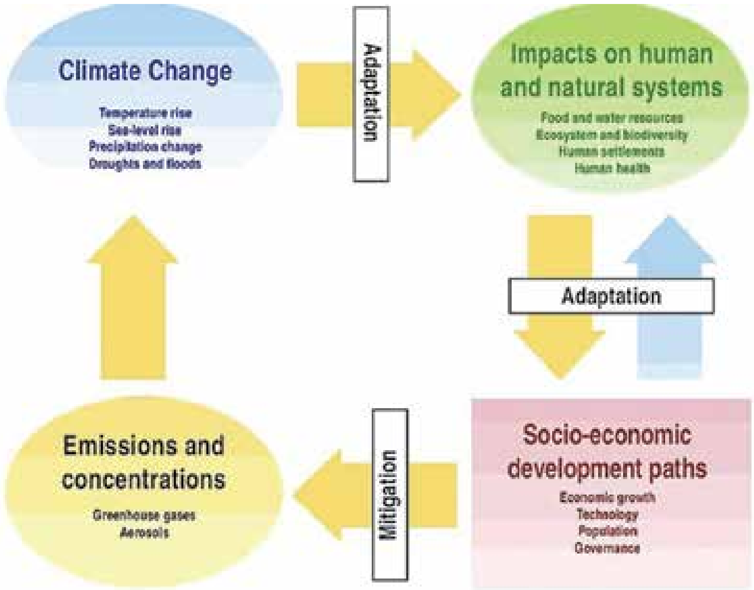


Fig. 11. Schematic depicting the concepts of mitigation and adaptation (Source: IPCC, 2001b)

Mainstreaming is accomplished by incorporating climate risks and weather extremes into short term decision making as well as long term visions. In addition, current engineering practices should be modified since they often take into account historical climate, which may not be suitable for predicted future climate and extremes. On the other hand, mainstreaming climate change into engineering projects is only possible when adequate levels of capacity and development exists. Therefore, mainstreaming climate change involves a dynamic cycle of mitigation, adaptation and development that aims to enhance the efficiency and sustainability of climate change initiatives (ADB, 2005; Agrawala, 2005; Swart *et al.*, 2003).

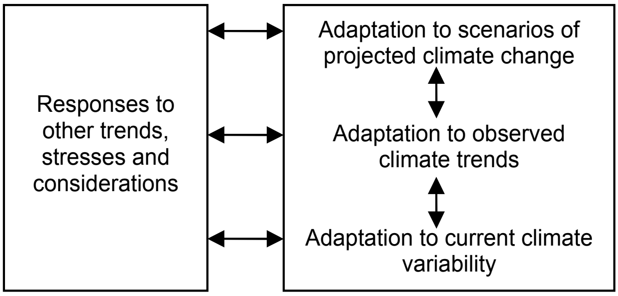


Fig. 12. Levels of Adaptation (Source: Agrawala, 2005)

However, mainstreaming climate change into development objectives is made difficult due to barriers such as short term funding and competing/conflicting agendas within governments and donor agencies. In order to reduce or eliminate these hurdles, private and public institutions must promote programs that increase awareness in climate change issues, improve access to credible, accurate and relevant information and expand resources to implement response measures. This mainstreaming-friendly environment will help enable the implementation of specific climate proofing activities within the broader sustainable development context (ADB, 2005; Agrawala, 2005).

Since issues such as poverty, water scarcity, food availability and security are prevailing issues for the general population and climate change mitigation and adaptation require a certain level of capacity to be implemented, short-term economic benefits are usually prioritized over long term climate change goals. However, short term development goals may provoke maladaptation (Agrawala, 2005). For example, hydropower projects, which are anticipated to increase electricity production and thus improve development, may increase the risk of flooding if future river flows exceed the design parameters of the dam. Therefore, climate oriented risk screening, project selection and decision making tools that can be integrated into environmental impact assessments, disaster response strategies, land use planning and urban design should be developed. The benefits from these tools can be augmented through the creation of national, regional and global linkages that facilitate sharing and cooperation.

The Asian Development Bank, under its Climate Change Adaptation Program for the Pacific, has developed a set of guidelines that are to be followed as part of the developmental process. They include (ADB, 2005):

- Managing climate risks as a part of sustainable development projects
- Ensuring intergenerational equity
- Adopting an integrated long-term approach to adaptation
- Taking full advantage of partnerships
- Exploiting the full potential of sustainable technologies
- Strengthening and utilizing national capacity
- Improving the credibility and application of information

- Improving regulations
- Climate proofing legislation
- Reinforcing climate change institutions
- Adapting economics in favor of climate proofing
- Increasing access to financial support
- Carry out risk assessments
- Complement other development goals with climate change adaptation
- Provide for continual improvements

5.1 Examples of mainstreaming

The mainstreaming of climate change mitigation measures into engineering projects is a common practice that has been going on before the introduction of the Kyoto protocol in 1997. Mitigation measures include energy efficient equipment and systems, renewable energy, air pollution control techniques, afforestation, etc. (Agrawala, 2005). Although the development and implementation of climate change adaptation measures is a recent phenomenon, initiatives have been taken to develop infrastructure and legislation that reduces or eliminates the risk of climate related events such as floods and droughts. This includes dykes, evacuation strategies, public awareness campaigns, insurance schemes, sustainable land use plans, rain water harvesting techniques, crop diversification, etc. It is well recognized that both mitigation and adaptation measures must not only include physical projects but "soft" techniques as well (Kabat and Vellinga, 2005).

A study by the Organization for Economic Co-operation and Development (Agrawala, 2005) explored the extent of climate change mainstreaming activities around the world. For example, Nepal is at risk from flooding due to accelerating glacial melt and increasing glacial lake levels. The resulting increase in river flows has been recognized as a potential benefit with regards to hydropower generation but also as a possible detriment to settlements and infrastructure. As such, Nepal has come up with a number of adaptation strategies that promote the benefits while inhibiting the risks. They include building more micro-scale hydro power facilities in low risk areas, developing early warning systems, and incorporating stream flow variability into project designs. Another example surrounds the Nile River in Egypt. Egypt depends on the Nile for both irrigation and navigation. In recent decades the river level has fluctuated significantly, putting stress on the duality of the river's role. In order to adapt to future declines in the river water level, Egypt is modifying the navigable channel in order to preserve water depth for navigation without sacrificing irrigation capacity. This physical adaptation is complemented with water use regulations and improved irrigation and crop water efficiency. A governmental department was also created to monitor, manage and forecast the Nile water levels.

Another study was made by the Asian Development Bank (ADB, 2005) to document various case studies of climate change adaptation in the Pacific Islands. The intent of the case studies was to provide successful examples for other communities, regions and nations to follow. For instance, Micronesia is at risk from cyclones, typhoons, sea level rise, extreme precipitation, land slides and El Nino influenced droughts. In order adapt to these potentially detrimental events, numerous small, climate proof infrastructure projects are being implemented. They included new road networks that are a minimum elevation above sea level and incorporate drainage technologies, revitalization of breakwater facilities based on projected increases in design requirements for wave heights, revamping building codes to require minimum floor elevations and relocation buildings that are in high hazard zones. These physical measures were accompanied by a total climate proofing of the Micronesia National Strategic Development Plan.

Other case studies that focus on mainstreaming climate change adaptation into national strategies include:

- The formulation of flood preparedness programs into Bangladesh's National Disaster Management Plan (Mallick *et al.*, 2005).
- The development of institutional mechanisms for the distribution of local, drought adaptable seed varieties in Kenya (Orindi and Ochieng, 2005).
- The initiation of the $118 US Climate Changes Spatial Planning Research program and the Adaptation Program for Spatial Planning and Climate in the Netherlands which will investigate "softer" strategies for climate proofing floodplains, the agricultural industry and water resources in the Netherlands (Kabat and Vellinga, 2005).
- The establishment of the Thames Estuary 2100 (TE2100) project, which has devised a Risk Management Plan (RMP) for testing the suitability of flood risk management options. It is comprised of different elements: *First*, it presents the strategic direction for managing flood risk in discrete policy areas across the Thames estuary; and *second*, it contains recommendations on what actions the U.K. Environment Agency and others will need to take in the short- (next 25 years), medium (the following 40 years) and long term (to the end of the century). The RMP is based upon current guidance on climate change, but it is adaptable to changes in future projections for sea level rise and climate change over the current century. Public consultations on the project held from April to June, 2011 (EA, 2011).

Furthermore, global insurance companies are presently looking for ways of mainstreaming climate change into their general strategies. Although the traditional approaches for managing exposure to natural hazards have been to limit risks, control damages, transfer risks or adjust product prices, companies are now shifting to a more holistic approach. This includes developing new insurance markets, setting insurance prices that reflect the degree of hazard for specific locations, providing guidance on emergency response and recovery processes and working with governments to promote community risk management (CII, 2005).

6. Concluding remarks

- Frequency of some extreme weather events are increasing and their severity is also on the rise. However, there are regional differences.
- Economic losses from extreme weather events non-linearly increasing due mainly to rapid rise in development activities in high risk areas (e.g., flood plains, coasts, deltas, etc.).
- Extreme weather events pose unique threats to engineering infrastructures. They have been saving human lives and property but their failures also facilitate disasters.
- Climate change can increase frequency and severity of extreme weather events that would put engineering infrastructures at additional risks.
- Mainstreaming of climate change risk into engineering plans, designs, maintenance and monitoring activities will reduce future vulnerability.
- To facilitate mainstreaming, there is a need of dialogue between climate researchers, engineering community, policy making authorities and other stakeholders.

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18

Impacts of Climate Change on the Power Industry and How It is Adapting

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1. Introduction

The Electrical Power and Energy Industry (the Power Industry) is facing great challenges with the transition to renewable energy options and sustainability (the Green Revolution) and the growing incidence of intelligent grid technology developments to encourage Customer-side responses (Smart Grid). At the same time, there is the definite need to meet continued demand growth (albeit slower) on top of the need for refurbishment and replacement of ageing assets and human resources (the looming Skills Gap) while coping with Climate Change and maintaining reliable and price competitive energy services in a safe and healthy environment and economy.

On the other hand, great challenges and needs bring with them great opportunities for radical thinking and innovation; "necessity being the mother of invention". For example the transition to a renewable and sustainable energy world needs to happen regardless of the Climate Change debate. If the desire to reduce greenhouse gas (GHG) emissions to mitigate climate change is driving **Mitigation Technologies** and market forces/programs such as Cap and Trade with a resultant speeding up of the green revolution then surely this is a good thing. Further information on the impacts of GHG mitigation programs and Markets can be found in the first Reference listed (*McConnach, Hammons & Duffey, 2009*). This reference paper provides an overview of the global responses to Climate Change and of the established and emerging GHG Markets and Programs arising from this. The impacts on the electrical power industry and how it is taking advantage of these programs and markets is discussed. This includes the impacts on policy, strategy and decision-making of major players such as governments, manufacturers, utilities, contractors and consultants and how they are leading by example within their own operations.

There is strong evidence of global warming and climate change that has already happened and that will continue to happen in future. Thus the Power Industry needs to focus efforts on technologies and measures for assessing, adapting to and coping with the risks of these climate changes (**Adaptation Technologies**). With Canada's vast land, water, infrastructure and natural resources, measures and initiatives for adapting to climate change and extreme weather are critically important for the protection and use of these resources. This makes sound risk management sense. The presentation of the second Reference listed reviews some of the programs, initiatives and measures being pursued by climate scientists, researchers and developers for forecasting and adapting to climate change, with particular attention to those impacting the electric power industry in Canada (*McConnach, 2010*). The review takes into account papers and presentations made at recent major Climate Change Technology Conferences held in Canada, notably "The 2nd Climate Change Technology Conference" held in Hamilton Ontario in May 2009 (CCTC2009 - see: www.cctc2009.ca) organized by the Engineering Institute of Canada (EIC) and the North American Symposium, "Engineering in a Climate of Change" held in Toronto April 29, 2010 and organized by the Ontario Society of Professional Engineers (OSPE). See: www.ospeclimatechange.ca

This Chapter of the book focuses on how the Power Industry is adapting to the great challenges and changes it is facing and the measures, tools, processes and technologies that are available for coping with these challenges and changes. Of particular interest is the climate risk assessment protocol in development by the Public Infrastructure Engineering Vulnerability Committee (PIEVC) as part of the National Engineering Vulnerability Assessment Project (NEVAP) led by Engineers Canada (*Engineers Canada*, 2008). See the third Reference listed. The PIEVC Engineering Protocol has great potential as a tool for assessing the risks of Climate Change to the Electrical Power Industry Infrastructure and progress to date with development of the Protocol is described in this Chapter.

2. Need and definition of adaptation

Mitigation measures to reduce the emissions of Greenhouse Gases (GHGs) into the atmosphere will simply slow the changes in Global Climate. Changes have already occurred and the Fourth Assessment Report: Climate Change 2007 (AR4) of the Intergovernmental Panel on Climate Change (IPCC) forecasts steadily increasing temperatures and increased frequency and magnitude of: - (See: http://en.wikipedia.org/wiki/IPCC_Fourth_Assessment_Report)

- Precipitation and flooding
- Droughts
- Severe wind intensities (cyclones, hurricanes, tornadoes, etc.)

All have significant impacts on public infrastructure and communities, including power grids and these impacts need to be either addressed or steps taken to prevent them from happening.

For example, where rising peak ambient temperatures impact the maximum ampacity loading capability of overhead lines, underground cables, transformers, switchgear and other equipment and components of the electrical power grid, this needs to be recognized and appropriate steps taken to establish the revised lower ampacity of these components for the higher ambient temperatures. On the other hand, where events such as extreme wind storms and hurricanes cannot be avoided, then the adaptation measures need to focus on enhancing emergency response and disaster management capabilities to mitigate the impacts on communities, physical infrastructure and human life.

Of course not all climate changes are necessarily detrimental. For example, there will be parts of the world and situations where warming will be welcome and mitigate the extreme cold temperatures and frost levels that need to be taken into account in infrastructure design.

Thus adaptation may be defined as any measure or activity that reduces the risk from negative impacts of climate change and/or takes advantage of the change for the benefit to society and/or the environment. Adaptation may be proactive, as in the example of de-rating the capability of electrical power grid elements, or reactive, as in the example of enhancing risk assessment and emergency response capabilities. Both may be planned, but reactive measures may sometimes have to be spontaneous.

Planned proactive adaptation measures and maintenance in general will incur less risk and result in lower long term costs over the life or service cycle of infrastructure.

3. Evidence of Canadian climate change and associated impacts

Some of the noteworthy evidence of Climate Changes in Canada are:

- Reduced mass and area of glacial cover
- Reduced extent and duration of snow and ice cover
- Deeper thaw of permafrost due to warming
- Changes in levels and timing of river high flows, with subsequent floods (e.g. recent floods in Manitoba and Saskatchewan)
- Increased frequency and intensity of extreme weather and storms
- Increased frequency of freeze-thaw and icing events
- More frequent and extended periods of high temperatures
- Earlier onset and longer season for plant growth
- Changes in fish species due to warming of water habitats
- Accelerated coastal erosion on eastern seaboard

The major impacts of these changes on power systems are:

- Warming peak and average temperatures impact on:-
    - Demand patterns and peak loading
    - Equipment plant ratings and grid security
    - Reduced equipment performance and reliability
- Increased frequency and severity of extreme weather events give rise to:-
    - Increased risk of failure of power grid, telecommunications and system control centers
    - Increased needs and costs for emergency response and disaster management capabilities
- Increased risks and costs to power grid infrastructure due to forest fires and floods
- Hydro-electric generation production impacted by changes in water levels and flows
- Increased ice accretion on power lines and transmission towers

4. Vulnerability and adaptive capacity

Engineering vulnerability to Climate Change impacts is the degree to which an item or system of infrastructure is susceptible to failure and unable to cope without some adaptation measures. Adaptive capacity is the extent to which modifications can be readily made or use patterns changed to cope with or take advantage of the impacts of Climate Change. In the earlier example of the impact of rising average and peak ambient temperatures on the loading capability of power grid system elements, the rated ampacity of the elements may need to be reduced to prevent failures. Where this is unacceptable, it may be necessary to install additional load carrying capacity to maintain reliability of supply.

Since 2005, Engineers Canada has led the National Engineering Vulnerability Assessment Project (NEVAP). This is a long-term project to assess the engineering vulnerability of infrastructure to the changing climate. Interim results from NEVAP were presented in the first assessment report (*Engineers Canada, 2008*) and concluded that adaptive capacity of infrastructure in Canada is generally high but unevenly distributed. Vulnerability of some regions and population groups is high, particularly where there is increased risk of flooding. On the other hand, some regions and populations may see opportunities to benefit from adapting to Climate Change, particularly where severe winter temperatures are moderated. Therefore a more complete definition of engineering vulnerability is the shortfall in the ability of public infrastructure to absorb the negative effects and benefit from the positive effects of changes in climate data and conditions used to design, operate and maintain public infrastructure.

The need for the NEVAP became evident when considering how to account for Climate Change in infrastructure design. Most notably, there was a low level awareness of climate impacts and vulnerabilities at the local level and the attendant gap between science, engineering and local planning. Available protocols, strategies and tools had focused on mitigation measures to reduce GHG emissions, while measures to increase adaptive capacity have been more limited and developed more slowly. Therefore there were few examples of comprehensive adaptation strategies and tools. This combined with uncertainties and competing priorities resulted in unwillingness to take action and no sense of urgency.

Engineers need to understand and assess the risks of Climate Change and account for it through changes in design and retrofitting of public infrastructure so as to minimize the risks of deterioration or failure and disruption throughout its lifecycle. There is the need to develop and/or revise policies, standards and tools to guide professional engineers in their day to day practice. In response to these challenges Engineers Canada proposed the NEVAP to the Canadian Federal government, specifically Natural Resources Canada's Climate Change Impacts and Adaptation Program. The primary objectives of the NEVAP were:

- To assess the risk of destruction, disruption or deterioration of civil infrastructure due to changing climatic conditions.
- To understand climate change and account for it in the design and retrofitting of public infrastructure.
- To develop or revise policies, standards, protocols, and tools to guide and help engineers in their day to day practice.

In this regard, public infrastructure (including the power grid infrastructure) is defined as those facilities, networks and assets, designed, installed and operated for the collective public benefit, including the health, safety, cultural and economic well-being of a country's population, whether operated by government and/or non government agencies.

Canada's engineers are on the front lines in helping ensure infrastructure adapts to the impacts of anticipated climate changes. Reliable studies, including those by the United Nations-backed Intergovernmental Panel on Climate Change (IPCC), report statistical trends of global warming – evidenced by increasing global average air and ocean temperatures. These trends cast doubt on the validity of applying historic climate data when designing infrastructure. In the face of climatic changes, engineers may have to reconsider existing assumptions relative to infrastructure capacity and vulnerability.

Based on this concern, Engineers Canada has focused the NEVAP towards engineering vulnerability assessment of four categories of Canadian public infrastructure:

- storm-water and wastewater;

- water resources;
- roads and associated structures; and
- buildings.

While acknowledging that Canada's inventory of public infrastructure extends far beyond the four selected categories, this work stressed the importance of initiating the process of assessing the engineering vulnerability of infrastructure to climate change. These infrastructure categories were considered by the Public Infrastructure Engineering Vulnerability Committee (PIEVC) to be the ones where the impact of climate change poses higher risks to public health and safety. Moreover, examples of the four selected categories of public infrastructure are widely dispersed throughout Canada. Seven infrastructure case studies in the four categories were completed by April 2008 under Phase II of the NEVAP. In Phase III, to be completed by the spring of 2012, another 15 case studies will have been completed and additional ones sought in the four categories as well as other types of infrastructure.

A progress report on NEVAP summarizing the results of the work of Phase II was issued in June 2008 (*Engineers Canada, 2008*). It includes the seven case study reports as well as recently completed literature reviews for each of the initial four categories of infrastructure covered by the project. Preliminary findings and conclusions, based on a limited number of case studies and expert opinion from a national workshop, comprise the first assessment report.

The work presented in the report was started in January 2007 and completed in March 2008. Further assessments, including further infrastructure systems, were to follow from the findings, conclusions and recommendations of this report. and the work was continued in Phase III which commenced in April 2009. Subsequently the PIEVC has extended the scope to include other categories of infrastructure now that the PIEVC Engineering Protocol has been successfully applied to the four different categories of infrastructure. There is full confidence in its application to other infrastructure categories, and the electrical power industry infrastructure is a prime candidate.

The PIEVC Engineering Protocol (the Protocol) was one of the pivotal outcomes of the Phase II work. The five-step protocol provides a procedure for sifting through data for developing relevant information on specific elements of the climate and characteristics of a given infrastructure. The Protocol then considers how this information might interact and result in the infrastructure being vulnerable or adaptive to climate change. A general description of the Protocol is provided below.

5. The importance of vulnerability and risk assessment

There are many uncertainties in assessing the effects of Climate Change. Forecasting future climate conditions is a very inexact science fraught with unknowns and complications, particularly when trying to forecast local conditions. The impacts of climate change on public infrastructure such as the power grid are better known but still leave room for doubts in vulnerabilities depending upon the original design, ageing effects and level of maintenance throughout its life-cycle. Socio-economic conditions can vary and impact the ability of communities to respond to climate induced disasters.

Sound risk management strategies and assessment tools can help decision makers to deal with these uncertainties, prioritize the risks and make prudent decisions on preventive or adaptive measures against Climate Change. A proven vulnerability and risk assessment tool has been developed and tested as part of the Canadian NEVAP and is described in the following sections. These sections closely follow the details of a presentation by Joel R.

Nodelman, P.Eng. at the May 2011 PIEVC Training Workshop, jointly organized by Professional Engineers Ontario and Engineers Canada.

5.1 Principles of infrastructure vulnerability and risk assessment due to climate change

Three basic beliefs held by design engineers are:

- The past predicts the future
- Scientific principles always apply (e.g. Thermodynamic laws don't change; Newtonian physics are constant.)
- Problems can be solved with logical reasoning

However, in the case of Climate Change we can no longer rely on past climate data and records to predict future conditions on which to base designs. The current trends in temperatures and the frequency and severity of extreme weather events are following a significantly different track to a simple extrapolation of historical records. The wide variation in possible outcomes between historical norms and the extrapolation to the future is a large un-quantified risk.

Scientific principles, although constant, must be applied in the proper context and this cannot always be predicted with certainty. Solving problems using logic and scientific principles only works when our assumptions are correct.

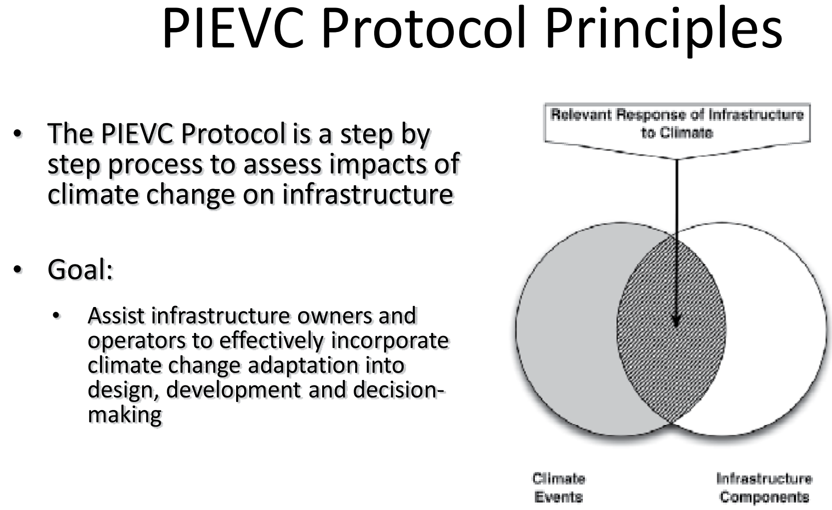
Another key observation when considering the impacts of climate change on public infrastructure is the fact that small increases in the forces/loads due to weather and climate extremes have the potential to result in large increases in failure and damages. The engineering resiliency of an infrastructure element is the safety margin between the forecast capability or capacity of the element and the loading imposed on it by climate extremes. This safety margin is susceptible to erosion from both sides. Ageing of the infrastructure and poor maintenance practices can reduce the capability/capacity of the element. On the other side, the increased loading on the element can occur due to warming temperatures or more extreme weather forces. The small increases in climate conditions can push the element from positive engineering resiliency to negative engineering vulnerability and possible failure.

The process to determine the resiliency and vulnerabilities of infrastructure elements was developed by the Public Infrastructure Engineering Vulnerability Committee (PIEVC) of NEVAP. The PIEVC Engineering Protocol leads practitioners through a formal, documented process and applies standard risk assessment tools to this new concern. Vulnerability assessment is predictive – it is contemplating **potential** risk of failure modes based on forecast information. Therefore in order to effectively address the risk issue with confidence we need to assess the likelihood of the event occurring and the level of service disruption. Risk assessment tools and techniques help to quantify the risk level. In the PIEVC Protocol, Risk level (R) is defined as the product of Probability (P) of an event occurring and the Severity Level (S) of disruption of an event given it has happened. **R = P x S**

Since risk is the combined effect of probability and severity both elements must be considered. Very low likelihood and high severity can still be a serious risk. Very high likelihood and low severity may be a low risk. Most people have an intuitive understanding of risk but need guidance to sort out and assess the relevant significance of Probability and Severity. The Protocol guides practitioners through the process of assessing both Probability and Severity in a rigorous manner.

5.2 The PIEVC engineering protocol

Figure 1 illustrates the overlap between infrastructure elements and climate parameters. There will be a subset of both that will interact and this is the focus of the vulnerability assessment. The Protocol is a five step evaluation process derived from standard risk management methodologies but tailored to climate change vulnerability. Data quality and availability is assessed throughout and it is recognized that there may often be gaps in the data, records, models and technical expertise available to a specific study. This need not deter practitioners from completing an assessment. The Protocol identifies which questions to ask and does not dictate the method to be used to answer those questions. Figure 2 shows the five steps and their sequence. There are a number of loops that may be necessary as the need for information and data becomes better understood.



PIEVC Protocol Principles

- The PIEVC Protocol is a step by step process to assess impacts of climate change on infrastructure
- Goal:
  - Assist infrastructure owners and operators to effectively incorporate climate change adaptation into design, development and decision-making

Fig. 1. The PIEVC Engineering Protocol Principles

To fill gaps it must be recognized that engineering vulnerability assessment is a multidisciplinary activity. A team approach is essential to filling gaps in data and resources. The combined resources of the team must have:-

- Expertise in risk/vulnerability assessment
- Directly relevant engineering knowledge of the infrastructure under study
- Climatic and meteorological expertise relevant to the region under study
- Operational experience and knowledge
- Hands on management knowledge of the infrastructure under study
- Local knowledge

The last item, local knowledge, filtered through the expertise of the team, can often be critical in compensating for data gaps and provide a basis for professional judgment of the vulnerability of the infrastructure.

The PIEVC Engineering Protocol has been rigorously and successfully applied with success to engineering vulnerability assessments of over 20 infrastructure case studies across Canada. Details of these case studies are available upon request to Engineers Canada. While the categories of infrastructure in these examples did not include Power Grid Infrastructure, the protocol is equally applicable. However, the availability of power was always considered as a part of the impacts of climate on an infrastructure. Without power a public infrastructure may not operate reliably, safely or within prescribed levels of service without back-up power generation.

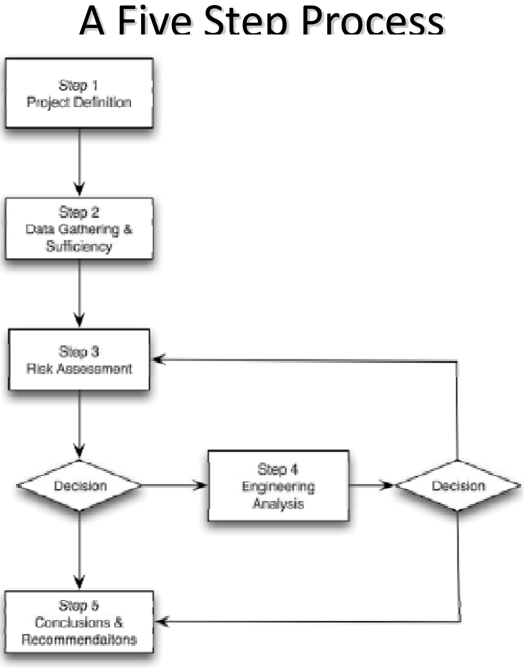


Fig. 2. The PIEVC Engineering Protocol Five Step Process

The evolutionary nature of the process must be stressed. Innovations and improvements to the process will be added as more and more experience is gained in its broader application, including to Power Grid Infrastructure.

6. Other studies and considerations

In addition to the research and developments in Canada relating to adapting to Climate Change, there are many such activities being undertaken in other countries and via international groups. A prime example is the study work by the Australian Government reported in the Position Paper on Adapting to Climate Change in Australia (*Australian Government, 2010*). The abstract from the Position Paper states:-

"This paper sets out the Australian Government's vision for adapting to the impacts of climate change and proposes practical steps to realise this vision. Adapting to the impacts of climate change will be a substantial ongoing challenge for all Australians well into the future. Meeting this challenge will require contributions from governments at all levels, businesses, communities and individuals. Individuals and businesses will adapt to developments as they unfold. However, governments have an important role to play in creating the right framework and in providing appropriate information to allow the private sector to make well-informed decisions. To this end, the Australian Government proposes to work through the Council of Australian Governments (COAG) to develop a national adaptation agenda. This agenda will clarify roles and responsibilities for adapting to the impacts of climate change and identify priorities for collaborative action between governments to position Australia to manage the unavoidable impacts of climate change."

Two of the authors of this Chapter reviewed international activities and presented a Paper providing an overview of the international response for mitigation and adaptation to climate change at the 2006 General Meeting of the IEEE Power & Energy Society (*Zobaa & McConnach, 2006*). This identified considerable international effort aimed at adaptation to climate change already occurring.

The risks of climate change are not limited to public infrastructure, communities and societies. Another major consideration is risks to private companies, the financial sector and the global economy. Extreme weather events can ruin companies and destroy asset values. The sixth Reference listed is an IEEE Paper which provides an overview of the risks that climate change can pose for the financial sector and the global economy (*Zobaa, 2005*).

7. Some adaptation measures for the energy sector

The following are a few examples of the adaptation measures available to the Power Industry.

- Applying risk assessment tools such as the PIEVC Engineering Protocol to quantify the risks from Climate Change.
- "Hardening" of grid systems to increase their capability to withstand extreme events. This includes developing grid equipments resilient to extreme environments and weather.
- Coping with changed loading patterns and reduced equipment ratings due to climate change.
- Strengthening and enhancing grid emergency response and restoration plans.
- Improving back-up telecommunications and grid control (as part of Smart Grid developments).
- Extending and incorporating climate monitoring and recording stations.
- Undergrounding critical circuits and interconnections.
- Revising codes and standards to reflect harsher climate conditions.
- Adaptation strategies for Energy Utilities and Municipalities
- Engineering in Extreme Climates – Policy Considerations
- Building climate changes into infrastructure Codes & Standards
- Extreme Weather Management: Planning, Preparation and Operations
- Using Smart Grid technology developments to adapt/respond to Climate Change.
- Strategies for adapting to the vulnerabilities and interdependencies of critical infrastructure facilities such as energy, transportation and telecommunications.
- Hydro Power and Climate Change
- Thermal protection of transmission line foundations against thawing of permafrost.
- Improvements to Disaster Management responsiveness and capabilities.

With regard to the latter item, the World Conference on Disaster Management (WCDM) was held in Toronto, Ontario, Canada in June 2011 (*WCDM, 2011*). The WCDM is the pre-eminent conference of its kind - providing the opportunity to gain valuable education, training and best practices to assist disaster management professionals, organizations and communities to mitigate, prepare for, respond to and recover from emergencies and disaster.

Many other adaptation opportunities exist in the Power Industry and this is a ripe area for further study.

8. Conclusions and recommendations

Significant impacts of Climate Change are evident across Canada and their frequency and severity are forecast to increase. Planning and development of adaptation measures in the Power Industry is needed and urgent.

Fortunately Canada has a high capability to assess, adapt to and deal with the impacts and consequences of Climate Change. There are many opportunities for the Power Industry to show leadership in developing technology, tools and processes for coping with Climate Change. In particular vulnerability and risk assessment processes, tools and strategies and associated technical expertise have a major role to play in this work.

Barriers and knowledge gaps to adaptation actions need to be addressed. This includes addressing limitations in awareness and availability of information and decision-support tools, such as vulnerability assessment and risk management tools. However, existing knowledge and capabilities are sufficient to undertake adaptation studies and activities in most situations.

Finally, the Power Industry and Governments must work together to address barriers and knowledge gaps in adaptive capacity and so reduce the impacts of climate change by applying sound risk management strategies and practices. The Conclusions and Recommendations from **Canada's First National Engineering Assessment Report** (*Engineers Canada*, 2008). are very relevant in this regard and are quoted here:-

Conclusions: A central finding from the first National Engineering Assessment of the Vulnerability of Public Infrastructure to Climate Change is that the Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment works (now referred to as the PIEVC Engineering Protocol). As such it has great potential for application to Climate Change risk assessment of the Electrical Power Industry infrastructure.

In its general conclusions and recommendations, this work also draws attention to the Interdependence of infrastructure in Canada. Generally, that infrastructure is designed to withstand extreme events. However, that does not mean the impact of climate change can be ignored. The conclusions from this study break out into seven themes.

Theme 1: Some infrastructure components have high engineering vulnerability to climate change. In the case studies a number of components demonstrated high vulnerability to climate change. More work is required to confirm the applicability of these conclusions to infrastructure located elsewhere in Canada(and which is now underway since the first assessment report was published).

Theme 2: Improved tools are required to guide professional judgment. Better consensus is needed regarding the definition of what is considered critical loss of infrastructure as well as what constitutes a catastrophic failure. These definitions are needed for each of the four infrastructure categories assessed.

Theme 3: Infrastructure data gaps are an engineering vulnerability. Many of the case studies reported significant gaps in the availability of infrastructure data. Thus engineers, operators and decision-makers have no clear definition of the capacity and resiliency of the system. These data gaps contribute to the overall vulnerability of infrastructure.

Theme 4: Improvement is needed for climate data and climate change projections used for engineering vulnerability assessment and design of infrastructure. The seven case studies revealed significant gaps in the types and nature of historical climate data needed to conduct engineering vulnerability assessments. The historical data establishes the baseline to compare future changes derived from the climate change projection models.

Theme 5: Improvements are needed in design approaches. There is a need to systematically document the climatic data that has been used to establish climatic design values in existing codes and standards in the four infrastructure categories. It is much easier to apply results of an engineering vulnerability assessment during design than to existing, mature facilities. It is important to apply assessment of climate change vulnerability to new technologies, many of which have unknown performance capabilities relative to the effects of climate change on infrastructure.

Theme 6: Climate change is one factor that diminishes resiliency. In recent years, concerns have been raised in Canada about present level of maintenance and future needs for infrastructure. Factors affecting the resiliency of infrastructure may include the age of the asset; level of maintenance and monitoring of facilities; changes in populations; and the amount of use the infrastructure receives. Climate change is likely to intensify the engineering vulnerability if current levels of maintenance continue. Properly maintained infrastructure enables the infrastructure and its components to function as designed, which includes accounting for changing climate events. A holistic approach is needed to deal with the issue, including consideration of financial, managerial and social factors as well as climate change.

Theme 7: Engineering vulnerability assessment requires multi-disciplinary teams. Assessment of vulnerability to climate change requires interdisciplinary approaches involving a range of expertise, including, but not limited to, engineers, climatologists, architects, hydrologists and others. Ideas on the vulnerability of a piece of infrastructure may differ between engineers and managers, on the one hand, and personnel involved in day-to-day hands-on operation of infrastructure on the other.

Recommendations: Five recommendations arise from the work completed to date:

Recommendation 1: Revise and update the engineering vulnerability assessment protocol.

During the execution of the case studies, a number of minor issues were identified with the current version of the Engineering Vulnerability Assessment Protocol (Rev 7.1, 31 Oct. 2007). (Note: Version 9 of the PIEVC Engineering Protocol is the one currently in use (from April 2009 to present) as of the date of this publication, and another revision will be available through Engineers Canada in the spring of 2012)

Recommendation 2: Conduct additional work to further characterize the vulnerability of Canadian public infrastructure to climate change. There is a need to conduct further engineering vulnerability assessments to more fully characterize the vulnerability of Canadian public infrastructure to climate change (This includes power industry infrastructure.)

Recommendation 3: Develop an electronic database of infrastructure vulnerability assessment results. The analysis provided in this report is based on analyzing limited data. As more information accumulates, an electronic database will significantly aid in the analysis of vulnerability trends within a category of infrastructure, regionally and/or nationally.

Recommendation 4: Assess the need for changes to standard engineering practices to account for adaptation to climate change. Some of the case studies determined that the current design codes and practices applicable to the infrastructure under consideration could be improved. In some cases, this was related to dated information used within a standard and in others it was based on the view that climate change should be factored into new designs. In light of this experience, further work is needed to:

- review codes and standards applicable to the four categories of infrastructure that are the current focus of the Public Infrastructure Engineering Vulnerability Committee (PIEVC) and determine specifically where dated climatic information is used;

- maintain a dialogue between engineers, scientists, modellers and climatologists to clarify the climate data needs and formats to support the design and management of engineering;
- maintain a dialogue with codes and standards organizations to communicate the outcomes from this engineering vulnerability assessment in order to evaluate the need to update codes and standards; and
- investigate incorporating the use of the Engineering Protocol for Climate Change Infrastructure Engineering Vulnerability Assessment, or similar assessment processes, into design processes for new infrastructure and major infrastructure rehabilitation in Canada.

Recommendation 5: Initiate an education and outreach program to share learning from this assessment with practitioners and decision-makers. Public infrastructure systems do not function in total isolation. Multiple stakeholders have a role to play in ensuring robust and resilient public infrastructure for assurance of serviceability and public safety. Key learning from this initiative should be shared with other constituencies in order to promote effective infrastructure design, operation and management.

9. Acknowledgements

The authors wish to acknowledge the kind permission of Engineers Canada to include material from their First National Engineering Vulnerability Assessment Report, in particular for the description of the PIEVC Engineering Protocol. The Protocol has great potential as a Climate Change risk assessment tool for the Electrical Power Industry. Further information on the Protocol, including its use for infrastructure engineering vulnerability assessment can be obtained by contacting Engineers Canada (David Lapp, P.Eng.) at the following email address: david.lapp@engineerscanada.ca

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Protected Landscapes Amidst the Heat of Climate Change Policy

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1. Introduction

The arguments in favour of maintaining, improving and extending the global Protected Area network, which includes Protected Landscapes, statutory nature reserves, biosphere reserves and other designated sites, are rehearsed regularly (Bass et al., 2010; Boitani et al., 2008; Brooks et al., 2010; Dudley et al., 2010; Jackson et al., 2009; Janssen, 2009; Kharouba and Kerr, 2010; and Leroux et al., 2010). Protected Areas are increasingly designated in places that maintain a significant proportion of national biodiversity, protect watersheds, soil carbon stores and indigenous food production. Consequently they maintain livelihoods and communities where resilience is linked to environmental goods and services. Where evidence emerges that biodiversity conservation is a central tenet of efforts to mitigate and adapt to the effects of human-induced climate change (EASAC, 2009, TEEB, 2010), a natural and logical conclusion is that Protected Areas themselves have a significant role to play in national climate change mitigation and adaptation strategies.

The Protected Landscapes in Britain (National Parks and Areas of Outstanding Natural Beauty), have a provenance that is based upon landscape and access to the countryside. The demand for open access to the countryside and protection of it grew during the nineteenth century as the Industrial Revolution produced a rapid urbanisation and industrialisation of the British landscape. Campaigns and demonstrations in favour of access to the countryside, of having access to large open spaces to experience the freedom and exhilaration provided by regions now designated as National Parks, lead to a landmark Act of Parliament[1]. During subsequent decades this saw the designation of ten National Parks in England and Wales, an additional Act of Parliament to designate the Norfolk and Suffolk Broads as an equivalent status landscape, the establishment of lobbying bodies and the passing of further legislation[2] to give National Park Authorities autonomy within local government.

There are now fifteen National Parks in Wales, Scotland and England covering about 10% of the land by area. Being relatively large areas within the context of Britain, and having been designated in order to preserve the majesty and beauty of some of the most rugged landscapes and coastal areas, it is no coincidence that they are dominated by upland and mountainous terrain. They therefore support significant tracts of biodiversity (ENPAA,

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[1] 1949 National Parks and Access to the Countryside Act.

[2] 1995 Environment Act

2010), which are also present in the lowland and coastal National Parks. Their geographical positions mean that they possess examples of most or all of the principal habitats and species of importance for biodiversity conservation in Britain, as well as the highest and lowest areas above sea level, the warmest and coldest, wettest and driest climates. This combination of significant tracts of land rich in biodiversity, exposure to meteorological extremes and additionally the coincidence of the upland National Parks in Britain with the Less Favoured Areas[3], mean that they are ecologically and economically at least as vulnerable as other regions in Britain, if not more so, to the adverse effects of climate change. Rural resilience and the ability to respond effectively to the effects of climate change are put under still greater strain by the inherently high ecological footprint[4] of rural life in National Parks (Dawkins et al., 2008).

Just as it is for Protected Areas elsewhere in the world, it is equally logical that National Parks in Britain have a significant role to play in national climate change mitigation and adaptation strategies. Being less urbanised and maintaining larger tracts of open hill, contiguous agricultural land, forestry, wetlands and undeveloped coastline than elsewhere in Britain, they can serve as 'environmental barometers of change' and test beds for new approaches to mitigating and adapting to climate change. This argument is repeatedly well made by the bodies representing National Park Authorities in Britain, yet it is largely unheeded at a national policy level. This Chapter examines the policy tensions that now impinge upon the National Parks and the Authorities charged with overseeing their management. These tensions stem from the historic purposes of the Parks and the modern purposes to which they can be put and which are being asked of the National Park Authorities but for which they are not yet well-enough equipped or supported to do so. It takes the reader 'under the bonnet' of the struggle to maintain the National Parks whilst at the same time meeting the new challenges whilst encumbered with tools of the trade from a post-war era. The Chapter is written from the viewpoint of a professional ecologist who has observed the conservation agenda evolve rapidly, from within an organisation and institutional framework that changes more slowly.

As a policy issue, climate change has seemingly rushed in on protected landscape management priorities, which gives rise to uncertainties over whether the current issues such as biodiversity conservation are being met satisfactorily (National Assembly for Wales, 2011) whilst new issues threaten to push them aside. National Park Authorities face the same challenge during the coming 50 years as they faced in the past, namely to retain the quality and value of the Park landscapes as their character evolves and new pressures arrive. Additional challenges arise from the emerging evidence of the cross-cutting societal value of biodiversity conservation and the cross-cutting societal risks posed by climate change, requiring a wider and deeper skill set to be deployed in National Park management than has traditionally been required. A question is ever-present, that of whether such skills

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[3] Less Favoured Areas are mainly upland regions within the European Union that are designated for special economic attention under the Common Agricultural Policy by virtue of their natural characteristics (geology, altitude, climate, etc.), which put farmers at an economic disadvantage.

[4] Measured as global hectares per capita, the biological ecological footprint (i.e., the amount actually available on the Earth per person) is 1.8 global hectares per capita (Dawkins et al. 2008). The actual figure for the USA is 9.6, for China 1.6, for Brazil 2.1 and the global average is 2.2. For Wales it was 5.16 in 2003 and rose (at a 1.5% annual rate in line with trends elsewhere in Britain) to 5.25 in 2005. Based upon figures listed for the counties in which the National Park sits, it is 5.3 to 5.46 global ha/capita in the Brecon Beacons National Park.

can or must be provided within and by the public sector or whether there is more to be gained by forging new partnerships within the commercial and private sectors and more significantly still, within the communities that live and work within the Parks?

This Chapter does not aim to discuss the technical issues surrounding the physical and biological receptors of climate change such as conserving carbon-rich peat, managing wetland ecosystems, understanding upland carbon budgets and fluxes, adjusting habitat management in response to climate change or the societal benefits from doing so. This is elegantly discussed elsewhere (Clark et al., 2010). The potential value to society from defining a stronger role for National Parks in adapting to the effects of climate change in Britain has been discussed (Sinnadurai, 2008) and is revisited here.

2. Invisible landscape sentinels; Britain's national parks

In accordance with categories established by the International Union for the Conservation of Nature (IUCN), National Parks and Areas of Outstanding Natural Beauty (AONBs) in Britain are Category V Protected Landscapes (Lucas, 1992; Phillips, 2002). As such, they are managed for their contribution to landscape and seascape; conservation and recreation are especially dedicated to the protection and maintenance of both biological diversity and natural and associated cultural resources; and they are managed through legal and other effective means (local action, projects and policy). The aim throughout the world where Category V Landscapes have been designated is to spread the value and achievements of management to areas beyond their boundaries, ensuring that the people who live and work within them are fully involved and benefiting from their management. This aim is underpinned by Category V management principles set down by the IUCN (Phillips, 2002), which in summary are as follows:

- Landscape, biodiversity and cultural values are at the heart of conservation
- Management should occur at the intersection between people and nature
- People are stewards of the landscape
- People should be central to all management
- Management should be co-operative and multi-stakeholder
- Good management requires good political and economic support
- Enhancement is as important as protection
- In cases of irreconcilable conflict, priority should be given to retaining the special qualities of an area
- Economic activities not essential to the area should take place outside it
- Management should be highly professional and business-like
- Management should be flexible and adaptive
- Successful management should be measured in environmental and social terms.

All of these principles lend themselves to developing effective local and regional responses to climate change. They encompass all aspects of landscape management, require local people to be closely involved in and wherever possible leading management, they seek to avoid activities that are inappropriate in nature and scale, they require professional and flexible business management, they require improvements as a consequence of management and they account for social as well as environmental benefits. They are suited to influencing the behaviour of people in a positive and progressive, self-helping way so that rural resilience to the potentially undermining effects of climate change is nurtured and enhanced. As well as the physical raw materials within National Parks, the management principles provide the building blocks for successful responses to climate change. However, they post-date the statutory purposes for which National Parks were designated:

The first purpose is to conserve and enhance the natural beauty, wildlife and cultural heritage of the National Parks.

The second purpose is to promote opportunities for the understanding and enjoyment of the special qualities (of the Parks) by the public.[5]

In pursuance of these purposes, National Park Authorities have a duty to seek to foster the economic and social well-being of local communities within the National Parks by working closely with the agencies and local authorities responsible for these matters. This duty brings the purposes closer to the management principles but it does not 'drill down' to achieving the self-help and self-determination that is expressed by them. Consequently, conservation work tends to resemble that undertaken by other conservation organisations working to different but overlapping remits centred on biodiversity conservation. Within National Park Authorities, ecologists and biodiversity officers work within the broad family of conservationists that includes statutory agencies, national and regional trusts and non-governmental organisations. This perhaps represents an absence of a distinctive approach within National Parks (where the other organisations are also active) and leaves room for adjustment in closer pursuance of the management principles. Currently, species and habitat conservation projects, farm-based conservation, historic landscape conservation and built environment conservation work are interchangeable with that undertaken by other organisations, with National Park Authorities providing an extra pool of staff to fulfil a common end.

In their responses to the inquiry undertaken by the Sustainability Committee of the National Assembly for Wales in failures to meet the Convention of the Parties 2010 target to halt the losses of biodiversity (National Assembly for Wales, 2011), the Welsh National Park Authorities submitted a list of over 200 biodiversity conservation projects undertaken by them during the past decade. This was in response to criticism of the contribution made by the Welsh National Park Authorities to biodiversity conservation, indicating an apparent lack of awareness at a Government level of the range and depth of such work undertaken by them. Similarly, ENPAA (English National Park Authorities Association) published a report (ENPAA, 2010) summarising the major contribution made to biodiversity conservation within National Parks in England. This helped to raise the profile of the hitherto 'invisible' biodiversity conservation work (Robins, 2008) and indicates the strength of achievement within these small organisations, in addition to the conservation work of other organisations.

The stand-out feature within National Parks about biodiversity conservation work that can be achieved there is one of scale and focus, owing to the range, size and quality of habitats present in these large rural areas, together with the range of conservation organisations at work. The challenge is not only to achieve outcomes at appropriate scales but also to provide national and regional solutions to climate change mitigation and adaptation based upon integrated landscape management within the National Parks.

2.1 Defining a way forward

The vision for the Welsh National Parks has been stated as follows (Welsh Assembly Government, 2007):

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[5] Section 61 of the 1995 Environment Act.

- *The Welsh National Parks are protected landscapes of international importance which capture much of what is distinct and special about rural Wales, environmentally and culturally. Although predominantly rural in nature, the Parks contain a resident population of over 80,000, are close to important urban communities and have significant potential to enrich the lives of the people of, and visitors to, Wales and to contribute positively to public health and well-being and to the Welsh economy. They are living landscapes, moulded by their communities over thousands of years. They are places where sustainable development is promoted for the benefit of the environment, the economy and for Park communities. They are places that experiment with new approaches in sustainable development and environmental conservation, providing exemplars of best practice for wider Wales, and helping to shape and lead future rural policy and practice. They are also places where all who can influence the future of the Parks work together to conserve and enhance their natural beauty, biodiversity and cultural identity, in line with sustainable development principles. Guided by the Park Authorities, these special areas are becoming progressively richer and more diverse in terms of landscape, wildlife and heritage and are enjoyed and cherished by a full cross-section of society.*

This vision has pulled the National Park purposes closer still to the IUCN management principles and invites National Park Authorities to play a lead role in rural resilience. By referring to "*sustainable development principles*", which are not included in the Park purposes and duty, it hints at a changing role for National Park Authorities and the National Parks. This is the beginning of the policy and legislative groundwork that may be necessary to redefine the role of National Parks and their Authorities, in Wales at least: towards landscapes that make an explicit contribution to climate change mitigation and adaptation, and biodiversity conservation, as well as the food production, access and recreation that they are already recognised for.

Redefinition is easier said than done. Public consciousness views National Parks in their historic context, providing free access for people to roam through wide open spaces, to adventure and to relax; biodiversity conservation and climate change responses are unlikely to be uppermost in the minds of most visitors, despite the primacy of biodiversity conservation within the Park purposes. During this Internet era when the world is changing rapidly, when ozone depletion, acid rain deposition within the British uplands (Batterbee, 2004), uncertainties about the impacts of genetically modified food crops on the environment and on public health, increasing public discomfort over the market distortions and environmental degradation produced by the Common Agricultural and Fisheries Policies, and the attention that sustainable development and biodiversity conservation have drawn beyond the boundaries of National Parks, it has not been obvious that these relatively large, relatively undeveloped but modified agricultural and afforested landscapes serve a wider role than is reflected in their purposes.

For example, the Brecon Beacons National Park is the source of more than 25 rivers and streams affecting south Wales. It also includes many decaying peat-rich and water storing wetlands, which need to be restored to continue to provide the long term benefits that agriculture and settlements have relied upon for centuries. Drinking water for south Wales, the largest conurbation in the country, is supplied from the reservoirs and catchments in the Brecon Beacons. These resources are likely to come under increasing resource management pressure as a consequence of rising demand and rising consumption on the one hand and uncertain supplies during prolonged dry summers or wet and stormy winters on the other (Environment Agency, 2008). So strategic investment in catchment management in the Park is essential, to provide these ecosystem services and lasting public benefits. Most of the carbon-rich peat soils and organo-mineral soils are situated in the British uplands (Clark et al., 2010) and most of the British National Parks are upland or montane, co-incident with much of the soil carbon resource. The priority must be to restore and conserve these 'carbon banks' (Welsh Assembly Government, 2010). Water and soil carbon conservation are new tasks that must be achieved within National Parks, thereby modifying their role and increasing their significance to the nation.

2.1.1 Growing consciousness of climate change in national parks

The Intergovernmental Panel on Climate Change (IPCC) published its first assessment report on global climate change in 1990, leading to the publication of the United Nations Framework Convention on Climate Change (UNFCCC). Whilst this produced some ripples at an intergovernmental level, it failed to register as an issue at the local conservation level, where sustainable development and biodiversity conservation had arrived as the take-home messages from the Rio Earth Summit in 1992[6]. During the following decade, the UK conservation organisations invested significant resources in preparing and publishing national biodiversity action plans and steering group reports (DoE, 1994) and tranches of habitat and species action plans, as well as the formation of partnership local biodiversity action plans (LBAPs) at the county level. The National Park Authorities of Wales and England published their respective LBAPs and set about trying to implement them. Throughout this process climate change was not included as a relevant issue; this Chapter hazards a guess that most, if not all biodiversity action plans failed to include the effects of climate change on the conservation targets set for the habitats and species involved. By 2010, the net result was that together with other nations, the UK failed to fulfil its commitment to meet the European Union target for halting the loss of European biodiversity by 2010. The process had been high on published strategies and plans, high on hyperbole, but low on achievement.

This same period between the mid-1990s and 2010 saw the publication of three sets of climate change scenarios by the UK Climate Impacts Programme (Hulme and Jenkins, 1998; Hulme et al., 2002; UKCP, 2009). These led to a number of modelling studies on the effects of climate change on biodiversity (for example Berry et al., 2006; del Barrio et al., 2006; Harrison et al., 2001, Honnay et al., 2002; Hossell et al., 2000, 2003; Hossell, 2000; Hulme et al., 2003; Perry et al., 2003; Thomas et al., 2004). By now, climate change consciousness was growing within the conservation professions and devolved governments (DETR, 2000a, 2000b; Welsh Assembly Government, 2000a, 2000b; 2001) and twenty years after the Rio Earth Summit, climate change began to influence local policy setting.

The National Park Authorities slowly started to pay attention to the impacts of climate change, with the Brecon Beacons National Park Authority undertaking a literature review in order to provide information notes for circulation between the Authorities and preparing the first position statement for the Association of National Park Authorities in 2004. These signalled that climate change was firmly at the heart of European and UK policy and that National Park landscapes were likely to be affected significantly by climate change in the future. There was general acknowledgement of the important role that National Parks can play in helping Wales and the UK to adapt to climate change, for example as vehicles for promoting integrated planning responses to and assessment of climate change, though there

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[6] United Nations Conference on Environment and Development 1992.

were not (and still are not) specific national policy drivers to support this. For example, whilst the Welsh Assembly Government supported the development of regional climate models (Welsh Assembly Government, 2000b), such a model has yet to be provided for Wales 11 years later.

The expectation in disseminating this information was that it would stimulate the National Park Authorities, and their sponsoring bodies, into a flurry of activity to develop a co-ordinated leading role in mitigating and adapting to climate change within the landscape; this did not happen. Local Government Associations in Wales and England published Declarations on Climate Change to which the Welsh and English local authorities, and National Park Authorities, signed up. Whilst actions responding to the effects of climate change are now underway in National Parks (Table 1) this work is supported by position statements issued by the Associations of National Park Authorities (ANPA, 2008; ENPAA, 2009) rather than guided or co-ordinated by an overarching national objective for Protected Landscapes.

In the lead up to issuing their own statements, the National Park Authorities have invested increasing effort in debate and discussion on the best options for National Parks, summarising the main impacts likely to affect them, identifying common issues affecting all of them, developing principles to guide work, and identifying opportunities within existing work plans to deploy these principles. These can be summarised as follows:

Issues

- National Parks are sparsely populated places that have been designated for specific purposes. As a consequence of this they are generally not taken into consideration when developing strategic and policy responses to climate change.
- The collective size of Parks together with their dispersed location throughout Britain means that they offer the potential for significant strategic responses to climate change and can play a lead role in demonstrating the value of a natural resource-led approach. They cover ~10% of Britain (~7% of Scotland, ~20% of Wales and ~8% of England), are the source of several major river systems and watersheds (for example the Rivers Dart and Exe in Dartmoor and Exmoor, Rivers Forth, Tay, Earn and Endrick in Loch Lomond, the Usk in the Brecon Beacons, the Derwent in the North York Moors, The Broads catchment is the sink for several major river systems including the Waveney, Yare, Wensum and Bure), as well as the highest peaks and most low lying areas. Together with the suite of Areas of Outstanding Natural Beauty, this strategic role expands further still.
- Whilst the geology, geomorphology, boundaries and distribution of National Parks are permanent features, the quality, robustness and patterns of landscapes and land uses within them are alterable by human intervention and by natural responses to human and environmental factors.
- The people-centric nature of the Category V Protected Landscape designation means that local people and wider society can be given every opportunity to be part of the decision making process in response to climate change. Involving new people beyond the realms of macro-economics and the natural sciences can help to ensure that communities are open minded to the changes ahead (Hulme, 2007).
- National Parks contain [parts of] ecosystems and [entire] human communities; in these fragile but also extreme environments natural resources and people are affected equally by the elements.

- At the same time, National Parks are especially vulnerable to the physical impacts of climate change given their upland and montane, wetland, riverine, woodland, floodplain and coastal habitats and biomes.
- Whether the long term prognosis remains one of longer, drier summers and warmer, wetter, stormier winters or colder, more severe winters as a consequence of changes to North Atlantic circulation systems, these habitats and biomes are still strongly affected.
- National Parks are at risk from a wide range of impacts including:
  - loss of snow (which affects Arctic alpine flora and moisture availability for insects and birds)
  - reduction in freezing and seed vernalisation
  - decline in heather (*Calluna vulgaris*) and other dwarf shrubs
  - increased winter survival of heather beetle (*Lochmaea suturalis*), affecting the viability of heather moorland, as well as the spread of other invasive species and plant pathogens
  - increase in bracken encroachment (*Pteridium aquilinum*)
  - dry moorlands at risk from increased incidence of wildfires
  - increased survival of agricultural pathogens and parasites
  - increased erosion, run off and flash flooding
  - low river flows for prolonged periods each year
  - coastal squeeze, accelerated coastal erosion and coastal and inland flooding
  - saline intrusion into freshwaters
  - increased leisure demand on natural resources
  - risk of lost income to habitat-related enterprises (shooting, angling, water recreation, farm-based tourism)
  - decay and loss of limestone features in karstic landscapes.

Cross-cutting themes that emerge from the issues

- Using natural processes to achieve reduced surface water runoff within river catchments, providing flood control within and ‘downstream’ of National Parks;
- Improving water quality and water conservation within and downstream of National Parks
- Restoring ecological connectivity between sites by restoring hydrological connectivity
- Focusing habitat connectivity within ecosystems on larger and more robust habitat patches, whilst reducing the incidence with other incompatible land uses
- Conserving and restoring soils
- Tolerating and understanding changes within landscapes in response to contemporary societal and environmental needs
- Changes to human use of natural resources and landscape patterns
- Insufficient understanding of the issues affecting National Parks and effective action required to address them
- Changing landscapes will affect the special qualities of the Parks, the aesthetic, experiential, spiritual and sense of place elements that people come to enjoy.

Principles that could guide responses to cross-cutting themes

- Britain should have expectations of what can be achieved within National Parks in response to climate change

- Given the vital importance of enlisting public support and engagement, Category V Protected Landscapes, where human biogeography is integral to the ecosystems within them, have a significant role in the national response to the impacts of climate change
- Where localised land abandonment occurs as a consequence of socio-economic changes, it is a short-term, temporary phase in the ever changing history of land use
- Farming has an expanded role through integrated land management and high nature value farming alongside food production
- As well as habitats and species, ecosystems need to be understood and conserved
- Ecosytem services cannot be provided if the infrastructure for healthy biodiversity is not there or is functioning poorly
- Air, soil and water quality are the backbone of all ecosystem management
- In the short term every effort must be made to maximise the quality and extent of current biodiversity in order to maximise opportunities for survival of species and maintenance of ecosystem services, 'buying time' for wildlife and conservation to adapt
- In a changing climate, the role of site-based conservation for biodiversity is essential in the short term but needs adjusting for the mid- and long term (Edward-Jones et al., 2007) to include conservation of the wider countryside
- There must be a willingness to make tough choices; in the short term (next 20 years) maximum effort should be made to conserve 'at risk' habitats such as upland hay meadows and lowland raised bogs until a better solution emerges or adverse impacts of climate change overtake best possible efforts
- The wildlife corridor that is really required is the wider countryside itself; anthropogenic climate change underlines the extreme urgency of the need to concentrate on encouraging farmers and other land managers through real incentives, to produce good quality food and other products (such as timber) in a high quality landscape. This is arguably the biggest and best adaptation to climate change for biodiversity purposes (and also a mitigation measure, since it would imply sympathetic management of soil and water and achieving lower food miles etc.) and it has always been the only sustainable way to manage land.

However, twenty years since the Rio Earth Summit and nearly 10 years since climate change became a mainstream policy issue, National Park Authorities still lack the national policy or legislative provision to play a lead national and regional role in responding to climate change through landscape management. In 2008, the former co-Chair of the IPCC, Professor Sir John Houghton explained that the world has only 100 months, that is only 8 years, to avoid the global average annual atmospheric temperature exceeding 2^{o}C, i.e., until 2016/2017, beyond which point there is a strong risk of runaway climate change. Jane Davidson Welsh Assembly Minister for Environment, Sustainability and Housing repeated this 100 month deadline during her speech to the Welsh Association of National Park Authorities on November 5th 2008 and also in her speech to the Royal Architects Association on November 20th 2008[7]. At the current rate of progress, the author of this Chapter is

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[7] http://www.architecture.com/Files/RIBAProfessionalServices/Regions/Wales/JaneDavidsonspeech.pdf.

uncertain that Britain and the global community will do enough in time to avoid this outcome.

There is still concern within National Park Authorities that focusing on climate change distracts conservation effort from other issues such as biodiversity conservation and that the job to conserve biodiversity is far from over (National Assembly for Wales, 2011). It would be naive to assume that all actions to address climate change will also benefit biodiversity, though undoubtedly some, such as blanket bog restoration (to conserve water and carbon-rich peat), wetland habitat restoration (to retain water and improve water quality) and woodland management (to improve woodland structure, carbon sequestration potential, retard surface runoff and provide biofuel) can do so. However, National Park Authorities possess limited knowledge of the 'climate status' of habitats and species within the Parks and, being small organisations, possess limited means to influence their management. The strategic importance of the British uplands has generated significant research into the different issues affecting the uplands (for example Clark et al., 2010) but leaves National Park Authorities relying on collaborations and external expertise to be able to keep up with and take advantage of research findings; there is no UK-based organisation doing this on their behalf. Despite the involvement of National Parks as study areas and case studies in the 'national discussion' about the strategic importance of the British uplands in a changing climate (for example Reed et al., 2009; Natural England, 2009a, b; 2010, b; National Assembly for Wales, 2009), there is still a failure to recognise the modified and enhanced role that National Parks and National Park Authorities should make, based upon modern purposes and duties.

3. Policy consultation fatigue

During the development of national policy responses and the improving integration of climate change and biodiversity conservation policy (Natural England, 2009a, b; Welsh Assembly Government, 2011), National Park Authorities have found themselves responding repeatedly to overlapping and seemingly repetitive consultations (Table 1). Whilst on the one hand the welcome attention to environmental matters since the emergence of climate change as a leading issue has given the conservation profession a stronger voice, on the other hand the volume of consultation perhaps has betrayed a national uncertainty over what to do for the best, as well as a lack of sufficient political will across all sectors. Despite the publication of IPCC reports in 1990 (and three subsequent reports) and three UKCIP reports since then, there still is not a comprehensive land-based mitigation and adaptation action plan being implemented in Britain.

In attempts to rationalise the consultations, the National Park Ecologists of the 15 Park Authorities published a joint statement on climate change (Association of National Park Authorities, 2008). In this, they highlighted that despite the space available within the Parks to experiment with mitigation and adaptation plans, generating the critical mass for public responses to climate change may be limited by their small populations and low economic base. They state that climate change has both accelerated the speed at which biodiversity conservation needs to take place and expanded the complexity of the task. The biodiversity within designated sites and in the wider countryside has developed in response to historic farming practices; therefore maintaining and enhancing it is equally dependent upon maintaining suitable farming practices. The increased numbers of people that may visit the

Parks during prolonged warm and dry spells will increase the footpath erosion pressure on upland habitats, meaning that additional investment in erosion control measures will be required. In the short term, information needs include better inventories on soil carbon and water resources. In the mid-term, there may be value in undertaking habitat zoning exercises to identify core biodiversity zones and there is a need for joint working by the National Park Authorities and for closer working relationships with the statutory conservation agencies.

Consultation	**Improving resilience and self-sufficiency**	**Green-house gas emissions**	**Localised renewable energy generation**	**Improving civic involvement and responsibility**	**Soil carbon, water catchment management**	**Enhancing the role of farming for climate change**	**Use of public buildings to provide district heating**	**Reducing food miles, increasing local supplies**	**New rail infrastructure required**	**Changes in and losses to seasonal water supplies**	**Inland re-ailignment**	**Developing the role of National Parks**	**Habitat fragmentation already a major issue**	**Biodiversity conservation and climate change measures**	**Peak oil and climate change**	**Regulatory assesments of national policies**	**Ecological footprints of rural areas and National Parks**	**Land use planning**
Welsh Assembly Government Climate Change Adapation Action Plan 2007	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Sustainability Committee Inquiry on the Future of the Uplands in Wales		●	●	●	●	●						●						
Wales Climate Change Group: adaptation sub-group		●	●	●	●	●		●		●		●						
Land Use Climate Change Group 2010	●	●	●	●	●	●		●			●	●			●			
Welsh Assembly Government Climate Change Strategy 2009		●	●		●							●			●			
Welsh Assembly Government Axis 2 consultation (Common Agricultural Policy) 2008		●	●	●	●	●				●	●	●			●	●	●	

Table 1. A summary of points made in selected consultations by the Welsh Association of National Park Authorities[8].

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[8] A full list of consultation responses provided by the Welsh National Park Authorities is available on http://www.nationalparks.gov.uk/wanpa/wanpa-policy/wanpa-consultation_responses.htm.

In its climate change position statement, ENPAA (2009) set a range of objectives shared by the English Authorities. These covered sustainable land management including conservation and restoration of peat lands and woodlands and the carbon reserves they contain; increasing natural carbon storage and supporting 'low carbon farming'; using the town and country planning process to help develop low carbon rural communities including renewable energy generation appropriate for a protected landscape; adaptation to climate change within the landscape including identifying habitat networks and safeguarding access to the countryside; and communicating climate change issues and solutions to Park residents and visitors, including working with young people, influencing behaviour and increasing engagement and volunteering.

In its position statement on climate change, the Welsh Association of National Park Authorities (WANPA, 2010) stated that the contribution made by the Authorities is beginning to be recognised nationally. Through the Park Management Plans, land use development plans and Sustainable Development Funds, the Authorities possess the tools for integrated approaches to land management. Being relatively undeveloped areas, successful carbon dioxide emissions reduction in the Parks will mainly be achieved within the existing built and historic environment and through improved land management. Being people-focussed designations, National Parks enable recognition of the barriers to behavioural change required to address climate change. Suitable renewable energy systems can be developed on land and inshore whilst economic and environmental resilience are achievable through integrated, co-operative land management. Major contributions to biodiversity conservation will adjust as the climate changes, as will the continuing contribution made to the provision and management of access to areas for recreation on landscape features.

These sorts of policy initiatives show genuine intent by the National Park Authorities to be taken seriously in the national response to climate change. They are also in step with international recommendations for managing ecosystems in order to continue to meet human needs (EASAC, 2009; TEEB, 2010; World Resources Institute, 2005) and with the IUCN management guidelines for Category V Protected Landscapes.

3.1 Climate change making National Parks more visible

National Park Authorities are striving to develop coherent responses to climate change (Table 2), with numerous initiatives underway in the Parks, many led by the National Park Authorities themselves. The scope and detail of the projects illustrate a strong commitment to addressing climate change but requires an over-arching strategy or championing of this work, either by the Authorities or their sponsoring bodies. In the absence of overarching guidance however, perhaps diversity and variety, rather than unification, are strengths of this work. It has the potential to generate added value and diversity of approach and it provides further impetus to help redefine the role of National Parks in the eyes of the public.

To take two examples, the first a local initiative to make full use of natural resources and the second a regional initiative to identify how to reduce carbon emissions within the landscape. Based within the Brecon Beacons National Park, The Green Valleys[9] helps individuals and communities to survey for and install micro-hydro-electricity systems in order to generate renewable electricity. Profits earned from UK Government feed-in-tariffs can then be re-invested in further energy and community-based projects. The Green Valleys also supports

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[9] http://www.thegreenvalleys.org/

National Park	Habitat management	Improving habitat connectivity	Other biodiversity management	Management of private land	Grant giving	Land use planning	Other policy development	Partnership projects	Renewable energy generation	Education and information	Added value projects	Public access management	Catchment-sensitive farming	Reducing carbon emissions	Low carbon projects	Reginal climate change strategies	One planet/ecological footprint projects	Research
Brecon Beacons	●		●		●	●	●	●	●	●	●	●		●	●	●	●	●
Dartmoor	●		●		●			●	●					●	●		●	
Lake District	●		●		●	●		●	●	●					●			
New Forest	●		●		●			●	●					●				
Norfolk and Suffolk Broads	●		●		●		●	●		●								●
North York Moors	●		●		●		●	●	●	●					●			
Peak District	●		●		●			●		●					●			●
Pembrokeshire Coast	●	●	●	●	●	●	●	●	●	●	●	●		●			●	●
Snowdonia	●		●		●	●		●	●				●	●			●	

Table 2. A summary of actions led by nine National Park Authorities in response to climate change, based upon information provided. Whilst other habitat conservation and sustainable development projects underway might also contribute to climate change mitigation and adaptation (for example peat land restoration projects), the Table summarises only those that are underway in direct response to climate change. The absence of a particular project initiative does not necessarily indicate that this work is not underway but reflects the scope of information volunteered for this Chapter.

community woodland groups who purchase or lease woodlands in order to harvest the wood fuel, manage biodiversity, support woodland-based education projects and generate an income from wood and value-added products. Other community-related benefits include capacity-building and giving members of communities the confidence to try out new ideas such as local food growing, biodiesel clubs and other energy efficiency measures.

In the Lake District National Park, The Low Carbon Lake District Initiative[10] has committed to setting a carbon budget for the Park. This will be based upon an estimate of total carbon emissions, with measures implemented to achieve annual reductions in line with England-

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[10] http://www.lakedistrict.gov.uk/index/caringfor/policies/climatechange/lowcarbonlakedistrict.htm

wide targets. Notably, the missing element from all the projects summarised is an understanding of the management of soil carbon within Protected Landscapes. This complex issue, though a 'frontline' one in policy discussion, is only now being supported with relevant research on how to manage this resource (Natural England, 2009a, b; Clark et al., 2010).

4. Conclusions and way ahead

National Park Authorities are responding to the climate challenge in the absence of a UK national policy for climate change in Protected Landscapes. The pace of the national response to climate change lags behind that of emerging evidence and behind the pace called for in 2008 by Professor Sir John Houghton. The recognition of a revised role for National Parks lags further behind still. Pioneering projects within National Parks (Table 2) are achieved under existing resource constraints relying on a historic skill set, and they are largely unnoticed by the British people. The array of natural resources in the Parks offers a cost-effective means of investing in climate change mitigation and adaptation measures; working with the grain of nature will be more cost-effective than not doing so (Stern, 2006; Pitt, 2007).

The Category V Protected Landscape is a model designation for building resilient and adaptive approaches to life through integrated landscape management. Within the Brecon Beacons National Park for example, the National Park Management Plan is centred upon the theme of "managing change together," giving scope for the flourishing of nascent transition movements currently underway. Organisations like The Green Valleys lead the way in micro-hydro-electricty generation and local capacity building and increase the scope for National Park Authorities to assist local people to develop autonomous, sustainable and resilient solutions to future change. Given the slow pace of change at a national level, local collective effort and co-operation can help to speed up national responses as a consequence of the diversity of minds, energy and ideas at work. Just as conservation in the wider countryside, alongside the management of designated sites and nature reserves, is the only truly effective way to conserve biodiversity, so too the only effective response to climate change is through the diversity of thought and collective will achieved by local action, complimented by appropriate and responsive national strategies.

A puzzling omission from all national policy responses to climate change is the likely influences of spiralling fuel costs in the face of declining supplies, so-called peak oil (Pitt, 2009; ODAC & PCI, 2008). Fuel and energy costs are of particular importance within National Parks where the ecological footprint (Dawkins et al., 2008) is higher than the national average as a consequence of the poor rates of return on these resources. Mitigation and adaptation solutions that rely upon machinery and agriculture will be moderated by peak oil. On top of the effects of climate change, agricultural change is inevitable in response to the effects of peak oil and the energy descent that will follow. A possible outcome might be fewer or more targeted use of machines and increasing costs of plastic (for example silage wrap), lower petro-chemical inputs (pesticides and fertilisers) used in food production and higher costs of feedstuffs. This, and increasing water shortages in the face of climate change and unsustainable demand increases from all sectors, may have a negative impact on the scale and extent of farming, with production systems shrinking in size whilst intensifying in a smaller area overall, provided that fuel prices and water supplies support this. In other words, despite the current 'feed the world' mantra that is at large within agricultural policy circles, the heavy reliance of current farming practices on fossil fuel and water may inhibit this response. Consequently, as fuel costs take their toll, the area of land under productive farming may shrink, which may release more land for biodiversity by default, and which might or might not be managed. This land could enter into 'high nature value' systems within Less Favoured Areas (ELO & CLA, 2009) or within agri-environment schemes. It could also be promoted to communities as new open space to provide for local food production (allotments, small holdings, farm gardens etc), woodland growth and so on. The agricultural pressures that affect farmers will be the same in every competitive nation including those providing farm export markets, with a possible outcome that export markets shrink as countries focus on becoming more self-sufficient and resilient and the costs of imports and exports rise with rising fuel prices.

The gradual integration of national policy for biodiversity conservation and climate change is exemplified in two policy initiatives in Wales and England, "A Living Wales" (Welsh Assembly Government, 2011) and "Making Space for Nature" (Lawton et al., 2010). Looking just at the Welsh policy initiative, A Living Wales seeks to re-evaluate the current approaches to biodiversity conservation in follow up to the failures to meet the 2010 European commitment to halt biodiversity losses. The aim is to develop a *Natural Environment Framework* that achieves integrated environmental management incorporating biodiversity conservation, ecosystem management and mitigating and adapting to the effects of climate change. The Welsh National Park Authorities and the National Association for Areas of Outstanding Natural Beauty each submitted replies to consultation responses, with the Authorities also supporting the reply provided by the Welsh Institute of Countryside and Conservation Management[11] (Table 3). The Framework has the potential to embed environmental management within the governance and future economic development of Wales and to provide an overarching plan, within which a clear role for National Parks could be defined. With this comes an opportunity to redefine National Park purposes, for example:

Proposed first purpose:

- To conserve and enhance the ecosystems, biodiversity, cultural heritage and historic environment of the National Parks

Proposed second purpose:

- To achieve the sustainable use of the Park's natural resources and ecosystem services whilst enhancing the special qualities of the National Parks

Proposed third purpose:

- To promote opportunities for the understanding and enjoyment of the special qualities of the Parks by people

Proposed duty for the National Park Authorities:

- In pursuit of these purposes foster the environmental, social and economic resilience of local communities and individuals within the Park.

This sort of redefinition of National Parks would acknowledge the wider role that they play, and it would give the Authorities the freedom to push further ahead with the sorts of initiatives summarised in this Chapter. It would also emphasise the leading role that National Parks make towards biodiversity conservation within the Protected Area network (Robins, 2008, IEEM, 2010).

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[11] www.natur.eu.com

Finally, nurturing diversity of thought, innovation and capacity building in land management can be achieved through deploying agri-environment schemes (Axis 2 Common Agricultural Policy) in a more entrepreneurial way. In order to accelerate the emergence of a resilient farming industry that prizes natural resources, agri-environment schemes could be used to support both landscape-based and smaller farm business 'start up' projects based upon high nature value and natural resource management. Currently the approach is for a government to use agri-environment schemes to purchase ecosystem services (PES) from the land manager. Under an entrepreneurial scheme, the smaller projects would be invited to bid for a smaller start-up 'loan' (or other suitable arrangement) in a business incubation model. This would support land management-based enterprises in soil, water, renewable energy, woodland and biodiversity management, helping the manager to improve the marque value of his or her existing food and livestock enterprises. Local conservation organisations would offer support through an expanded and 'collegiate' farming advisory service to advise these start-up businesses, drawing in other advisors too. The marque value of these new businesses would be expanded through sustainable tourism and local businesses, which in turn would benefit from the outputs and outcomes of the new farm ventures.

The advising bodies and other stakeholders would also help to draw in external investment and corporate sponsorship from sectors that from now on will be willing to invest in carbon and water management and renewable energy, as a means of fulfilling their climate change obligations. Land-based resource management projects offer a long term and secure investment because land resources are always there, providing permanent and essential ecosystem services whilst they are well managed. Within a Natural Environment Framework, the quality of land-based resources will be more assured too. This sort of investment would be viewed as a 'sure thing' by investors because the supply would be renewable rather than finite; and the seed capital would have been provided by the agri-environment scheme. It is not inconceivable that the private sector might wish to collaborate in order to create additional agri-environment schemes in fulfilment of its public obligations and commercial advantage.

The national government would be guaranteed a 'return on its loan' because the start up businesses would be incentivised by the need to maximise and grow the high nature value of their products, i.e., they would want to put in the work to make it successful, calling in the advice and assistance offered when needed in order to help guarantee a positive outcome. Private sector input would also guarantee this because providing public benefits will become mandatory either through legislation or public demand; allowing the supported farm businesses to fail will not be an option for an investor. This would also ensure careful selection of the start up ventures to receive support.

The success of the start up venture would provide the government or private sector agri-environment funder with a market basis for monitoring the success of this element of the scheme; therefore detailed biological monitoring *might not always* be required because the higher the market value, the higher the return based upon the quality of the ecosystem providing the service. The funder might even require a guaranteed capital return on the start up capital above a certain threshold, to be re-invested in another start up, or they could require the customer to do this for them, thereby keeping the agri-environment money circulating and growing rather than dwindling in supply as the equity declines as it would in the PES model.

This approach would create diversified, resilient, adaptable and distinctive local markets in different parts of a country, whereas a single agri-environment scheme is constrained by its

	Fully supportive of A Living Wales, with provisos	Conserving wider countryside	Subserviance of environment to econoomy	A Living Wales will cost more and require additional skills	Unrealistic implementation timetable	All-Wales ecosystem management plan required	Ecosystem monitoring should build on existing approaches	Precautionary principle is important	Weaknesses of ecosystem evaluation methods	Conflicting policies undermine environmental management	Stronger duty required for biodiversity conservation	Must build on, not abandon the current approaches	Can build on existing social and natural capital	Ecosystem services mgmt not always compatible with biodiversity conservation	Protected landscapes and Areas provide appropriate implementaiton and evaluation for A Living Wales	A Living Wales must incorporate wider issues	A Living Wales risks developing a unilateral reporting process	A Living Wales should implement the existing CBD principles	Public education and understanding is fundamental	No reference to peak oil
WANPA	●	●	●	●	●	●	●	●	●	●	●		●	●	●					
NAAONB	●	●				●			●	●		●	●	●	●					
Natur[12]	●			●				●				●		●	●	●	●	●	●	●

Table 3. A summary of the main issues raised in response to A Living Wales consultation, to which Welsh National Park Authorities and Areas of Outstanding Natural Beauty contributed. The response by Natur was very comprehensive (see footnote).

'one size fits all' methodology. A diversified and localised market would be more likely to grow, based upon the expansion and multiplication of strong and successful models, the added value of recruiting new ideas and people locally and the increased localised confidence and positive feedback encouraging more people to become involved. It would also encourage new entrants to land management and farming, to help build the confidence and entrepreneurship that will be essential beyond the 2013 CAP reforms, as well as raise the profile of this modern approach to integrated land management.

Larger landscape-based projects could be developed as cluster projects to provide a framework involving other initiatives to maximise the benefits of natural resource management, for example localised food production, wood biomass, hydro-electricity generation, linking with smaller site-based projects, education and interpretation projects.

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[12] Natur is the Welsh Institute of Countryside and Conservation Management. Its full response to the consultation is available here http://natur.eu.com/cms_items/f20101204145237.pdf.

The smaller start up projects would find further support and gain contextualisation from the landscape-based projects. Initiatives such as The Green Valleys could be invited to assist with the development of community-based carbon neutralisation projects, where for example investment in small scale, community-based hydro-electricity generation produces a profit from feed-in tariffs, which is then invested in further energy projects, as well as local food production and upland and wetland habitat restoration. Creating this sort of independent social enterprise could be a very cost-effective model for investing agri-environment cash too, producing real socio-economic returns that have public value because they can be measured in terms of publicly beneficial outcomes, as well as cash.

This cost-effective and repeatable approach would help to ensure that a real, resilient and growing market is established for ecosystem services and public benefits. It offers real scope for agri-environment schemes to buy much more than a simple one-off transaction paid to individual farmers and landowners; it guarantees a real entrepreneurial market rather than a range of single PES 'events' based upon what is affordable. It keeps the money circulating.

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20

Planning for Species Conservation in a Time of Climate Change

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1. Introduction

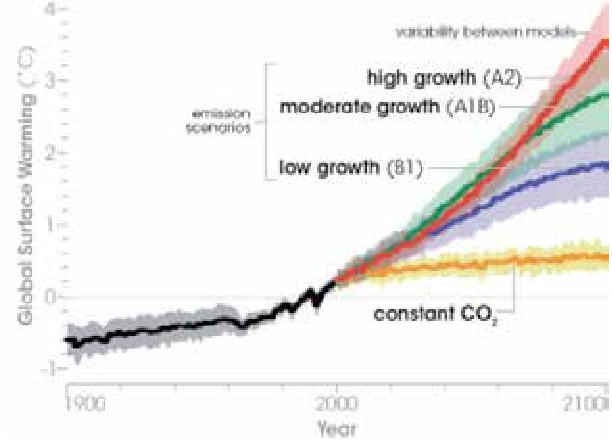
The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007) presented clear evidence that the global climate is changing because of human activities (Box 1). There is little doubt that this human-forced climate change event will become one of the main contributors to the global loss of biological diversity and has already caused accelerated rates of species' extinctions and changes to ecosystems across Earth (Sala et al., 2000; Thomas et al., 2004; Pimm, 2008). However, despite grim, almost doomsday-like, warnings in both the scientific literature and the general media for the best part of the last two decades (Peters & Darling 1985; Hannah et al., 2002), there has been little headway in the development of appropriate methodologies for integrating climate adaptation into conservation planning (Hannah et al., 2010; Poinani et al., 2011).

The purpose of this book chapter is to describe and classify some of the different methodologies governments and non-government organisations are using to integrate climate adaptation into conservation planning. By writing this book chapter, we hope to describe some of the benefits and limitations of the different adaptation planning approaches that are currently being espoused in the conservation arena. We conclude by describing some of the major hurdles human-forced climate change presents to conservation planners and some ways to overcome these. By no means is this an exhaustive review; rather, it builds on the work of others (e.g. Mawdsley et al., 2009; Dawson et al., 2011) by categorising some of the different adaptation planning activities being conducted within the conservation realm, so as to provide some clarity to national and international policy makers, private and public funding agencies, and practitioners, on what the best options are for conservation planning when climate change is considered.

Here, we focus on species-oriented conservation planning because it will ultimately be the reaction of species that define how ecosystems (and the services they provide) change because of human-forced climate change; species, as the basic evolutionary unit always need to be a focus of conservation planning. Although this chapter is species focused, many of the conclusions are also applicable to ecosystems, habitats, ecological communities, and genetic diversity, whether terrestrial, marine, or fresh water.

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as statistically significant changes in the mean or variability of climate properties that persist for long periods of time (decades or longer, IPCC 2007). Over the past few centuries, human activities, such as the burning of fossil fuels and agricultural practices, have increasingly contributed to climate change. Since the beginning of the Industrial revolution, the burning of fossil fuels has contributed to the increase in carbon dioxide in the atmosphere from 280ppm to 390ppm, despite the uptake of a large portion of the emissions through various natural "sinks" involved in the carbon cycle. Although climate has changed repeatedly over past millennia, for a variety of reasons, anticipated human-driven changes are likely to be unusually fast and large (Houghton et al., 2001). Global mean annual temperatures have already increased by 0.75 °C (1.3 °F) between 1901 and 2002, and are projected to increase by another 2 to 4°C (3.6 to 7.2°F) before 2100 with considerable changes in the timing and distribution of precipitation (IPCC 2007a). However, these changes in temperature and precipitation are occurring at different rates around the world (Girvetz et al., 2009).

While 0.75 °C rise in the global mean temperature may seem a small change, this increase has already had a demonstrable impact on natural resources as maximum high temperatures and droughts have become more pronounced and acute over the last 100 years. This trend is projected to continue over the next 100 years (Christensen et al., 2007). While the public generally appreciates that a world of rapidly changing climate is not desirable for nature or for people, most do not understand the gravity of the situation and the need to act now to mitigate emissions and adapt our conservation actions to a changing climate. If we remain on the current greenhouse gas emission trajectory, we are committed to no less than a global mean temperature increase of 3 °C (5.4 °F) by the end of the 21st century (see the figure below).



Source: http://www.epa.gov/climatechange/science/futuretc.html

Fig. Projected increases in global surface temperature as predicted by different models of the Intergovernmental Panel on Climate Change (IPCC).

Box 1. A summary of human-forced climate change.

2. What is being done to integrate climate adaptation into conservation planning?

A quick review of the conservation literature when searching on terms such as 'climate change', 'climate adaptation' and 'conservation planning and climate change' highlights two things. First, the vast majority of research conducted to date has focused on documenting the effects of climate change on species and ecosystems. Relatively few studies go into much detail about what should be done when planning for conservation in a time of rapid climate change. This is not unsurprising considering ecologists and conservation biologists have only just started to grapple with the threat climate change poses to biodiversity and it normally takes conservation scientists time to move from understanding a threat to planning to overcome it. Second, when strategies for conservation in light of climate change are developed, a myriad of approaches are raised, all under the guise of 'climate adaptation'. An soon to be published survey of all activities being undertaken by the African Biodiversity Collaborative Group (ABCG) in response to the impacts of climate highlights a number of distinctly different planning activities conducted by seven NGO partners over the past five years — for example, identifying where corridors needed to be restored, undertaking species vulnerability analyses, assessing agricultural production against different climate forecasts, and holding stakeholders conferences—all of which were labelled 'climate adaptation planning'.

It is our contention that despite some excellent work on describing different adaptation-relevant activities (see, for example, Mawdsley et al., 2009) there has been little critical review of what distinguishes some of the very familiar conservation approaches and actions (e.g. protecting corridors) touted as adaptation strategies as truly addressing the new or enhanced challenges faced by species in the context of rapidly changing climate conditions and their impacts. It is unclear which activities are appropriate and which are not. As the literature increasingly addresses climate change and conservation, we believe it is important to go beyond calling everything we do 'climate adaptation'. Without critically evaluating the different approaches identified as climate adaptation by planners and practitioners, the confusion around which actions are effective responses will only get greater.

To date, we argue that most conservation planning activities that have been labelled in some form 'climate adaptation' can be placed into three broad strategies:

1. Continuing 'best practice';
2. Extending on 'best practice' principles in consideration of species response to past climate change; and
3. Integrating assessments on species vulnerability to climate change into a conservation planning framework.

The following sections summarize these categories in more detail.

3. Continuing 'best practice'

The start of the 1980s marked a new era for spatial conservation planning. Since Kirkpatrick et al.'s (1983) groundbreaking work of using detailed biogeographic information and selection algorithms in the design of protected area networks, the days of ad hoc placement of protected areas and the focus on saving a few flagship species are (hopefully) in the past. Over the past thirty years we have seen an extraordinary growth in systematic conservation planning, and related tools are now used by all the major environmental organizations and many governments. From the publications of hundreds of peer-reviewed papers (see Moilanen et al., 2009; Watson et al., 2011 for summaries), a series of key principles have been identified as 'best practice':

- Identify and protect representative habitats (e.g. all habitats in a region are represented in conservation areas);
- Identify a persistence (adequacy) target of protection;
- Avert risk through replication (i.e. protection of multiple examples of each target);
- Protect critical habitats for threatened species; and
- Ensure the design is efficient, and aiming to reduce current threats to natural systems.

Until relatively recently, one of the most common beliefs held by governments and NGOs has been that continued planning using these principles will remain appropriate in a changed climate (Hannah et al., 2002). For example, the Australian government has stated that the first thing they need to accomplish when considering the long term impacts of climate change, is to ensure that a comprehensive, adequate and representative reserve system is achieved (Steffen et al., 2009).

While achieving these best practices principles are important aspects of an overall conservation agenda aimed at overcoming existing stressors that are creating the current extinction crisis, they should not be the sole basis of a climate adaptation strategy. The reason for this is the strategies that come from these 'best practice' principles are based on two problematic assumptions: (1) a relatively stable climate, and (2) that biological attributes are inextricably linked to place. We are not living in a period of a stable climate (see Box 1) and there is increasing evidence to show that the paradigm of 'place' (i.e. each site or region has its own suite of species, ecosystems, and genetic attributes that can be conserved without thinking of wider spatial or long-term temporal considerations) is very rare, regardless of climate change (Whittaker et al., 2005, Anderson and Ferree, 2010). When the problematic logic to these assumptions is ignored, the 'best practice' conservation paradigm is largely predicated on static spatial planning, and focused almost entirely on the establishment of protected areas and the identification of 'gaps' of important habitat. This type of planning does not consider the long-term implications of climate change and is not, as Game et al., (2010) observe, "approaches to climate change adaptation, despite commonly being cited as such in conservation literature; they are all things that we should be doing anyway."

4. Extending on 'best practice' principles

A goal of simply trying to achieve an adequate and representative system of reserves based on current species and ecosystem distributions and conditions has been rejected by most planners as insufficient to overcome the climate change challenge, and its use is in decline (Mackey et al., 2008). It has been replaced by the identification of a series of extensions of these principles, all of which are based on the fact that climate change is a natural phenomenon. Research over the past two decades has shown that there have been severe climatic oscillations for at least the last 500,000 years (Petit et al., 1999). Importantly, the ice core record shows that the transition out of glacial troughs may have been extremely rapid; arguably involving as much as 5°C warming in 20 years in some localities (Taylor, 1999). Almost all the species that persist today have gone through at least one of these glacial-interglacial cycles (Dawson et al., 2011), and a key question is – how did they survive past (often rapid) climate change events?

Five adaption strategies have been derived based on past climate and biological response (see Box 2), and Mackey et al., (2008) argue that these strategies distil into a set of 'common sense' general, inter-related principles for conserving species and ecosystem viability in light of future climate changes (Heller & Zavaleta, 2009; Mackey et al., 2010; Watson et al., 2009). These principles are:

- Significantly expand the current protected area estate to maintain viable populations of species and maximize adaptive capacity;
- Significantly expand the current protected area estate so as to capture refugia;
- Assign priority to protecting large, intact landscapes; and
- Ensure functional connectivity is maintained beyond protected areas.

These 'extending on best practices' principles are summarized below.

Evidence from marine sediments and polar ice cores has revealed the severe climatic oscillations that have occurred over the last 500,000 years (Petit et al., 1999). About every 120,000 years, average planetary conditions have oscillated between long glacial periods with low levels of atmospheric CO_2, low temperatures and dryness to shorter inter-glacial 'highs' that experienced high levels of atmospheric CO_2, higher temperatures and wetness. These glacial-interglacial oscillations revealed in the marine and ice core records are considered to be driven by long term periodic 'wobbles' in the Earth's orbit which changes the balance of solar energy reaching each hemisphere (Muller et al., 1997). The transition from glacial to interglacial is accelerated by positive feedbacks from ice melt and oceanic discharge of greenhouse gases (Hansen et al., 2007). Importantly, it is not a linear transgression with the ice core record showing that the transition out of glacial troughs may have been extremely rapid; arguably involving as much as 5°C warming in 20 years (though not all species have been confronted with changes of this magnitude) (Taylor, 1999). Almost all the species that persist today have gone through at least one of these glacial-interglacial cycles.

Five adaptive strategies have been identified, all of which help guide generic planning (Mackey et al., 2008):

(1) Micro-evolution. Evolution is heritable genetic change within populations. It is commonly understood to refer to only long term directional genetic change leading to speciation, that is, the evolution of new species. However, also evident is the evolution of new, fitter traits that represent local adaptations to changing conditions, including climate change, that are not necessarily directional and lead to speciation. There is increasing evidence that micro-evolution is far more rapid, common and widespread than previously recognized (Thompson, 2005) and is now occurring in response to rapid climate change (Bradshaw & Holzapfel, 2006).

(2) Phenotypic plasticity. The phenotype is the physical expression in an organism of its genome. Phenotypic plasticity refers to the range of genetically controlled permissible responses with respect to a species' morphological, physiological, behavioural or life history strategies and traits (Nussey et al., 2005). An example of phenotypic plasticity is the ability of a plant to change its growth form from a 'tree' to a 'shrub' in response to reduced water availability. Phenotypic plasticity differs from micro-evolution in that the adaptive response is found within the existing genome and is not the result of new, heritable genetic

change in the population.

(3) Dispersal. The dispersal of juveniles and seasonal migrations are common ecological activities. However, dispersal – in the sense of long distance movement – to locations that meet a species physiological niche and habitat resource requirements is a common adaptive life history strategy in many species, especially birds (Gilmore et al., 2007). In Australia, this is a necessary adaptive response for many species given the great variability in year-to-year rainfall and associated fluctuations in plant growth and the supply of food resources (Berry et al., 2007).

(4) Refugia and range reductions. Species can also persist by range reduction to micro-habitats that retain the necessary niche and habitat requirements; so called refugia (Mayr, 2001; Lovejoy & Hannah, 2004). Locations can function as refugia as a result of species responses to long term or short term environmental change. In Australia, refugia have been documented in the arid zone (long-term climate change related refugia; Morton et al., 1995), in temperate forests (fire refugia with respect to fire intervals of decades to centuries; Mackey et al., 2002), and monsoonal Northern Australia (annual seasonal refugia; Woinarski et al., 2007). The recognition of locations or networks of locations as refugia also invokes issues of spatial scale. For example, Soderquist and MacNally (2000) identified the role of mesic gullies embedded within dominantly drier forested landscapes. Remnant patches in a fragmented landscape can also function as refugia from which organisms can disperse to re-populate habitat as it regenerates following broad scale ecological restoration efforts.

(5) Wide fundamental niche. It is also possible for species to persist simply because they have evolved very wide fundamental (that is, physiological) niche requirements (*sensu* Hutchinson, 1957) and are able to survive, compete and reproduce under a broad range of climatic conditions. For example, many of Australia's forest and woodland birds occur in temperate, subtropical and tropical climatic zones, with the common determinant being vegetation-related habitat resources rather than fundamental niche response to temperate regimes.

Box 2. Five different adaptive strategies that species may have employed to overcome past climate change events (adapted from Mackey et al., 2008).

4.1 Principle 1: significantly expanding the current protected area estate to maintain viable populations of species and maximize adaptive capacity

A primary principle for conservation in a time of climate change is to maintain viable populations of all extant species across natural ranges in order to maximize intra-species genetic diversity and thus options for local adaptation and phenotypic plasticity (adaptation responses (1) and (2) in Box 2). A fundamental focus is thus replicating habitats in the reserve system so as to protect multiple source-populations across the environmental gradients occupied by the species (Watson et al., 2011).

4.2 Principle 2: significantly expanding the current protected area estate so as to capture refugia

A related goal is the identification and protection of refugia, or macro- and micro-habitats that supported relict species during past episodes of climatic warming (e.g., during interglacial periods) (Morton et al., 1995; Pressey et al., 2007; Ashcroft, 2010). Past climate change has resulted in some species experiencing dramatic range shifts and/or in-situ reductions; many species now only occur in networks of scattered locations that retain suitable conditions at a micro-scale because of this. It is thought that protection of refugia may prove critical in assisting certain species to persist through future rapid climate change (Mackey et al., 2002). If information on the specific locations of refugia that supported cooler-climate species during past times of warming is lacking, then a logical extension of the idea presented in section 4.1 is to significantly expand the protected area estate in the hope that this will increase the likelihood of capturing important refugia.

4.3 Principle 3: assign priority to protecting large, intact landscapes

As discussed in the 'Continuing best practices' section (3), conservation biologists and planners have reacted to the biodiversity crisis that is currently caused by, among others, rampant vegetation clearance and the introduction of invasive species by identifying priority areas to manage for conservation (Margules & Pressey, 2000; Fuller et al., 2010). Many of these approaches prioritize areas using criteria such as maximizing the number of threatened species and/or ecosystems (Myers et al., 2000; Dietz & Czech, 2005). While this threat-based approach to spatial prioritisation, targeting a snapshot of vulnerable biodiversity and landscapes, is logical in the short term given accelerating anthropogenic threats and past impacts (Brooks et al., 2002; Spring et al., 2007), it is not likely to be sufficient to ensure the long term persistence of biodiversity in the face of climate change. A reactive, threat-based approach does not take into consideration the impacts of climate change on the degree of threat and vulnerability of species.

Therefore a key principle is to proactively conserve large intact areas, often termed 'wilderness', alongside hotspots of threatened biodiversity (Mackey et al., 2008; Watson et al., 2009), as these landscapes sustain key ecological and evolutionary processes outlined in Box 2 (Soulé et al., 2006; Mackey et al., 2008). The high level of natural connectedness and climatic gradients driven by variability in elevation and aspect in intact landscapes improves the likelihood of survivorship of species by supporting large populations and a range of microhabitats. The ecosystems of extensive and intact lands will play a vital role in facilitating natural adaptation responses by species to human-forced climate change (Soulé & Terborgh, 1999). In particular, mobile species will have more habitat options as they disperse to find suitable locations in response to rapidly changing climate.

4.4 Principle 4: ensure functional connectivity is maintained beyond protected areas

A strategy based solely on the first three principles (e.g. expanding the protected area estate to increase species' adaptive capacity and protect past climate refugia, and ensuring large intact landscapes remain large and intact), is not likely to be sufficient to protect all biodiversity in a time of climate change (Rodrigues et al., 2004a; 2004b). This is because many of the most biologically productive landscapes around the world have been converted to agricultural uses, are privately owned or are in demand for more lucrative land uses (Mittermeier et al., 2003; Recher, 2004). As such, there is a general shortage of large intact areas to preserve in many landscapes (Lindenmayer, 2007). For these reasons, it is also important to undertake conservation management in the lands around formal protected areas to buffer them from threatening processes originating off-reserve and ensure 'connectivity' between protected areas.

Until recently, ensuring 'connectivity' in fragmented landscapes was focused entirely on the spatial arrangement of different types of habitat patches in the landscape and assessing ways to connect them (Tischendorf & Fahrig, 2000). Landscape connectivity was measured by analysing landscape patterns (McGarigal et al., 2002). In recent years, 'increasing ecological connectivity' has moved away from assessing the best design for vegetation corridors between protected areas, and towards achieving 'functional connectivity', which refers to protecting the spatially dependent biological, ecological and evolutionary processes within a landscape that will ensure long term persistence of biodiversity (Crooks & Sanjayan, 2006; Mackey et al., 2010). Examples of 'functional connectivity' processes include: maintaining ecologically functional populations of highly interactive species in the landscape (i.e. trophic regulators), understanding the habitat requirements of dispersive fauna, and maintaining natural disturbance (e.g. fire) and hydro-ecological regimes (Soulé et al., 2004; Mackey et al., 2007). The move towards ensuring functional connectivity does not preclude the creation of corridors, but rather it ensures a more holistic set of considerations that will be critical when considering the more dynamic connectivity needs of species during times of rapid climate change.

As noted above, the habitat loss, fragmentation and degradation now present in many productive landscapes presents significant impediments and barriers to species that may need to disperse and find new habitats (Bennett et al., 1992; Mansergh & Cheal, 2007). Therefore, an important component of ensuring functional connectivity is the protection and/or restoration of large-scale migration corridors that operate at regional and continent scales (Mackey et al., 2008). Where habitat connectivity has already been largely disrupted through broad scale land clearing, it is imperative that large scale rehabilitation of land cover conditions and land use between existing nature reserves becomes an integral part of the conservation framework. These intervening lands need to become more conducive to biological permeability and associated ecological and evolutionary processes. In this context, restoration will include development of regional networks of habitat patches, habitat corridors and habitat 'stepping stones'.

Some off-reserve 'connectivity conservation' actions that have been identified in the literature include:

- halting and reversing land clearing as this will help prevent further loss and fragmentation of core habitats and migration corridors (Soulé et al., 2004);
- developing policies that lead to removal of unsustainable extractive land use activities (primarily livestock grazing and logging (Woinarski et al., 2007; Lindenmayer, 2007) thereby preventing further habitat degradation;
- halting further large scale impoundment and diversion of water (Mackey et al., 2007);
- restoring migration corridors and stepping stones between intact protected areas (Donlon et al., 2006);
- re-vegetating riparian systems so as to provide corridors and at the same time ensure waterways remain cool (Seavy et al., 2009);
- restoring (or protecting) altitudinal and latitundinal gradients (Hodgson et al., 2009);
- controlling invasive weeds and animal pests (Woinarski et al., 2007); and
- restoring ecologically appropriate fire regimes (Soulé et al., 2004).

5. Integrating assessments on species vulnerability to climate change into a conservation planning framework

While it is widely accepted that the principles based on past climate responses outlined in the previous section are useful as they provide a 'rule of thumb' set of activities to guide conservation planning, it must be remembered that this the current anthropogenically-driven climate change event is different. All extant species are going to be exposed to climate changes of a rate and magnitude that they have most previously experienced, or that they have not experienced for thousands of years. Paleoecological data suggests the majority of the last 800,000 years was considerably cooler than today and the lowest or near-lowest global temperatures were reached at the last glacial maximum, 20,000 years ago. It is therefore thought that there has been much stronger selection for cold tolerance than heat-tolerance for nearly a million years (and possibly much longer), with the implication that the most heat-tolerant genes and species will already have been eliminated (Corlett et al., 2011). Moreover, the rate of change is going to be extremely rapid when compared to much of the warming that has taken place in the past (Box 1), and species are already coping with landscapes that have been significantly altered by human activities. As a consequence, simply adhering to the principles outlined above is unlikely to capture a coherent conservation adaptation agenda and it is therefore necessary that conservation planning and action explicitly account for this unique human-forced climate change event, and the vulnerabilities and impacts it will cause.

5.1 Assessing species vulnerability

To develop a plan that identifies strategies that will help species overcome this human-forced, and unnatural, climate change event, it is first necessary to understand how species differ in their vulnerability to projected future climate (Foden et al., 2009). As elaborated in Box 3, the vulnerability of species to climate change is generally assessed as a product of its: (i) susceptibility/sensitivity (defined by its intrinsic biological traits), (ii) exposure (does the species occur in a region of high climatic change?) and (iii) adaptive capacity (Box 3; Foden et al., 2009; Hole et al., 2011).

Vulnerability is the extent to which a species or population is threatened with decline, reduced fitness, genetic loss, or extinction owing to climate change. Vulnerability has three components: exposure (which is positively related to vulnerability), sensitivity (positively related), and adaptive capacity (negatively related).

Exposure refers to the extent of climate change likely to be experienced by a species or locale. Exposure depends on the rate and magnitude of climate change (temperature, precipitation, sea level rise, flood frequency, and other hazards) in habitats and regions occupied by the species. Most assessments of future exposure to climate change are based on scenario projections from GCMs often downscaled with regional models and applied in niche models.

Sensitivity is the degree to which the survival, persistence, fitness, performance, or regeneration of a species or population is dependent on the prevailing climate, particularly on climate variables that are likely to undergo change in the near future. More sensitive species are likely to show greater reductions in survival or fecundity with smaller changes to climate variables. Sensitivity depends on a variety of factors, including ecophysiology, life history, and microhabitat preferences. These can be assessed by empirical, observational, and modeling studies.

Adaptive capacity refers to the capacity of a species or constituent populations to cope with climate change by persisting in situ, by shifting to more suitable local microhabitats, or by migrating to more suitable regions. Adaptive capacity depends on a variety of intrinsic factors, including phenotypic plasticity, genetic diversity, evolutionary rates, life history traits, and dispersal and colonization ability. Like sensitivity, these can be assessed by empirical, observational, and modeling studies.

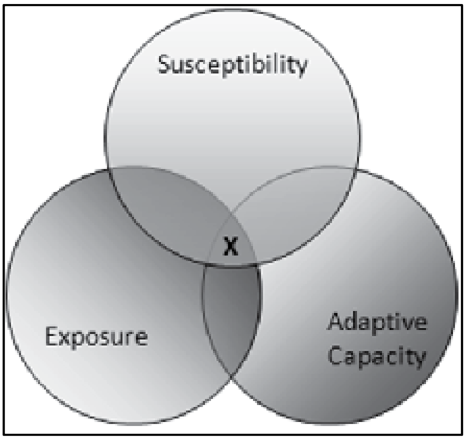


Fig. A schematic representation of a species vulnerability to climate change, where each component varies from 'low' to 'high' according to the shading gradient, such that 'X' represents greatest vulnerability (i.e., the intersection of the three components – high susceptibility, high exposure and low adaptive capacity; see also Box 3) (Source: Hole et al., 2011).

Box 3. Species vulnerability in the context of climate change (Source: Dawson et al., 2011).

There are a number of methods that assess species vulnerability and integrate this into conservation planning (Hole et al., 2011). Arguably the most commonly used methods utilize some variation of climate-envelope (or empirical niche) models (Guisan and Thuiller, 2005). Climate-envelope models use current distributions of species to articulate the range of climatic conditions that suit them. Climate model projections for the future are then examined to determine where on the landscape the optimal 'envelope' of climate conditions may be located in the future. For many species, these models have shown that large geographic displacements and widespread extinctions will take place (e.g Araújo et al., 2006).

Despite their frequent use, climate envelope models are contentious, not least because they omit a number of factors that may be as or more important than climate in controlling species distributions. For example, these models generally exclude consideration of human activities, interactions with other species and random events. They are also not comprehensive, since they focus almost exclusively on exposure to climate change and do not incorporate other aspects of vulnerability such as acclimation, interspecific interactions, dispersal limitations and adaptive capacity (Corlett in press, Dawson et al., 2011, Rowland et al., 2011).

A recent paper by Dawson et al., 2011 outlined a new framework for assessing how vulnerable a species is to climate change, based on the integration of mechanistic, empirical and observational methodologies (See Figure 2). While this framework has not yet been utilized (as far as we are aware), it is likely to be useful because it overcomes the shortfalls of climate envelope models.

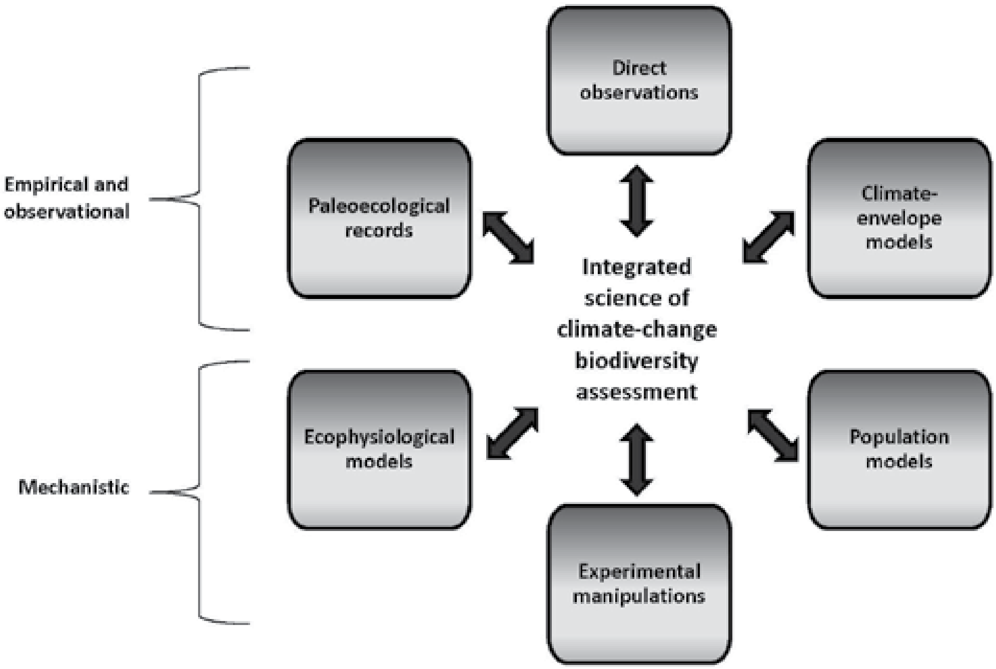


Fig. 2. Dawson et al., (2011) argue that an 'integrated' climate-change biodiversity assessment will overcome the shortfalls of climate-envelope modeling by drawing from multiple sources and approaches. Each provides useful information on exposure, sensitivity, and adaptive capacity, and integration of these approaches will provide a more robust basis for vulnerability assessment and allocation of resources for conservation and adaptation.

While the integrated methodology outlined by Dawson et al., (2011) has never been used, there exist expert opinion driven methodologies that capture all the aspects of vulnerability (exposure, sensitivity, adaptive capacity). For example, NatureServe has developed a *Climate Change Vulnerability Index* (see http://www.natureserve.org/) that uses a scoring system that integrates a species' predicted exposure to climate change within an assessment area and three sets of factors associated with climate change sensitivity: 1) indirect exposure to climate change, 2) species-specific factors (including dispersal ability, temperature and precipitation sensitivity, physical habitat specificity, interspecific interactions, and genetic factors), and 3) documented response to climate change. NatureServe argues that assessing species with this Index facilitates grouping taxa by their relative vulnerability to climate change, and by sensitivity factors, which NatureServe expects will help users to identify adaptation options that could benefit multiple species. Further, while it is still new, they hope that this tool will help land managers develop and prioritize strategies for climate change adaptation that lead to actions that reduce the vulnerability of species to climate change. A limitation to the NatureServe methodology is that it is not spatially explicit; however, vulnerability results associated with species distributions have potential to be used in large scale planning exercises.

5.2 Integrating species vulnerability into a conservation planning framework

Adaptation, as defined by the IPCC (Schneider et al., 2007), is an *adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*. Accordingly, a key aspect of integrating adaptation into conservation is to ascertain what the future will look like (and accepting the uncertainties around this), and then integrating this knowledge into all activities (and not just conservation-oriented planning) that are currently in place. Therefore while undertaking species' vulnerability assessments is an important first step in developing an adaptation plan, it can only be considered a first step, and there needs to be a process of integrating this data into a holistic planning framework.

While still in its infancy, there are now a number of tools aimed at overcoming the considerable uncertainty and complexity of climate change by tailoring adaptation strategies to particular species, human communities and geographies (e.g. Groves et al., 2010; Cross et al., in review). Common to many of these tools are the following steps:

1. Identify features targeted for conservation (e.g., species, ecological processes, or ecosystems) and specify explicit, measurable management objectives for each feature.
2. Build a conceptual model that illustrates the climatic, ecological, social, and economic drivers of each feature.
3. Examine how the feature may be affected by multiple plausible climate change scenarios. This can be a threats-based analysis of current and future states, and often takes the form of a vulnerability assessment (see section 5.1).
4. Identify intervention points and potential actions required to achieve objectives for each feature under each scenario.
5. Prioritize potential actions based on feasibility and tradeoffs.
6. Implement priority actions, monitor the efficacy of actions and progress toward objectives, and re-evaluate to address system changes or ineffective actions.

The Adaptation for Conservation Targets (ACT) Framework is one such tool that was developed by a team of conservation planners and practitioners (affiliated with the National Center for Ecological Analysis and Synthesis in Santa Barbara, California, and including NGO, government agency and university participants) (Cross et al, in review; Figure 3). The ACT Framework is a participatory and iterative process for generating adaptation strategies that is practical, proactive, place-based, and helps to overcome the reluctance to take actions due to uncertainties inherent in future projections. Working with multiple stakeholders and partners, the Wildlife Conservation Society is using the ACT Framework to identify and implement priority climate change-informed wildlife conservation and management strategies across a number of landscapes in the United States (see Table 1). The framework draws on collective knowledge to translate climate change projections into a portfolio of adaptation actions. These actions can then be evaluated in the social, political, regulatory, and economic contexts that motivate and constrain management goals and policies.

While planning processes such as the ACT Framework may end up recommending some of the same actions outlined in section 4 (e.g create and/or restore corridors, increase the size of protected areas etc), the key difference is the process by which those actions are identified. Rather than simply relying on 'rules of thumb', structured adaptation planning explicitly considers the long term impacts of climate change when determining appropriate and necessary conservation actions. Targeted climate change planning also attempts to strategically direct where adaptation actions are needed most.

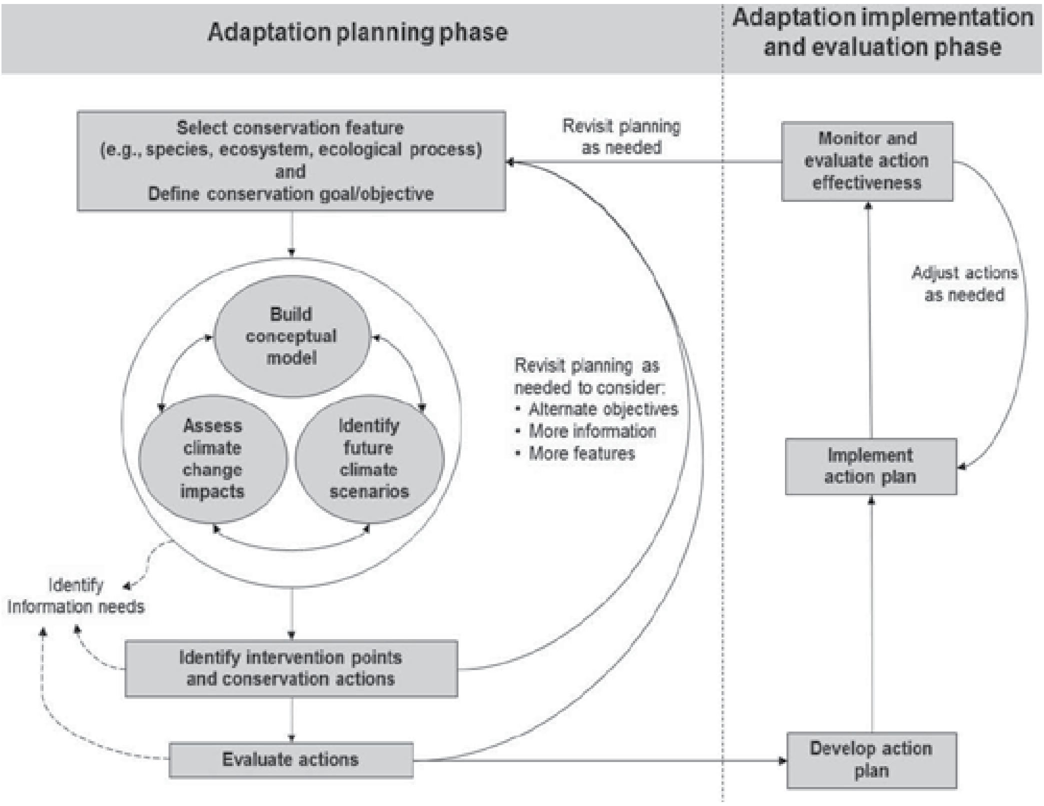


Fig. 3. The Adaptation for Conservation Targets (ACT) framework (adapted from Cross et al., in review). An online description of this framework is available at the Climate Adaptation Knowledge Exchange (CAKE; http://www.cakex.org/virtual-library/2285)

7. Several challenges for effective climate change planning

This review provides a first attempt to classify some of the different climate adaptation approaches being undertaken around the world. While all the approaches are important for conservation, we argue that we need to move from a conservation paradigm dominated largely by static spatial assumptions (i.e. the *Continue 'best practices'* approach described in section 3) to one that incorporates spatial and temporal dynamics of climate change and their attendant uncertainties. Given the absence of precedent for this multifaceted (and globally distributed) threat, the conservation community has largely been caught off balance in determining what the best courses of action are to address it (Moser & Ekstrom 2010). While there has been some movement away from generic principles towards explicit species impact assessments and planning frameworks that integrate climate change (such as the approaches outlined in section 5), a few remaining challenges to effective climate change planning are outlined below. These challenges are the focus of a burgeoning area of research that deserves much attention in the near future if these challenges are to be overcome.

Project Location	**Conservation Features Addressed**	**Project Leads**
Jemez Mountains, New Mexico	Wildfire regime; Jemez River flows	Southwest Climate Change Initiative[1]
Gunnison River Basin, Colorado	Alpine wetlands; Gunnison River headwater flows; Gunnison sage-grouse	Southwest Climate Change Initiative
Four Forest Restoration Initiative area, Arizona	Ponderosa pine wildfire regime; Ponderosa pine watershed function; Mexican spotted owl	Southwest Climate Change Initiative
Bear River Watershed, Utah	Abandoned oxbow wetlands; Bonneville cutthroat trout	Southwest Climate Change Initiative
Adirondack State Park, New York	Lowland boreal wetlands	Wildlife Conservation Society
Northern U.S. and Transboundary U.S.-Canada Rocky Mountains	Grizzly bears; Wolverines	Wildlife Conservation Society and U.S. Fish and Wildlife Service
Great Plains Landscape Conservation Cooperative region (parts of Colorado, Nebraska, Kansas, Oklahoma, Texas and New Mexico)	Grassland structural and compositional diversity (to support sustainable bird populations)	Wildlife Conservation Society

[1] The Southwest Climate Change Initiative is led by The Nature Conservancy in partnership with the Climate Assessment for the Southwest, Wildlife Conservation Society, National Center for Atmospheric Research, Western Water Assessment, USDA Forest Service, and the University of Washington.

Table 1. On-going efforts to test and refine the Adaptation for Conservation Targets (ACT) Framework in landscapes across the United States.

7.1 Forecasting the impacts of climate change at scales that are relevant to planners

While the general physics of global warming can be easily explained and understood (e.g. more greenhouse gases in the atmosphere will lead to radiative forcing that will, in turn, lead to the Earth warming; see Box 1), the science of how climate change will affect landscapes and seascapes at the spatial scales at which conservation is normally planned for and conducted is far more complex. Current limitations in the different global circulation models (GCMs) and downscaling techniques, and the variability of forecasts that are derived from these exercises has resulted in considerable uncertainty (and sometimes scepticism) in how to best plan for climate change in different landscapes and seascapes (Wiens & Bachelet, 2010). For example, while most GCMs show consistent rainfall and temperature trends in east Africa over the next century, they are vastly inconsistent in their predictions throughout Southeast Asia (IPCC, 2007). Integrating future climate scenarios in conservation plans will mean very different things to conservation planners in Southeast Asia, as the degree of uncertainty is immense. A lack of information on what future climates are possible in different regions has hampered climate change adaptation planning to an extent that most conservation action undertaken across the globe is completely blind to the challenge that climate change presents. This challenge can only be overcome with increased efforts in understanding how the current climate system works. However, it is important to recognise that some of these problems outlined above may not be overcome for many years or decades. Therefore, while improving climate-change projections and downscaling techniques is important, planners must recognize that there will continue to be unknowns – we need to become comfortable planning for conservation within realms of uncertainty (Watson et al., 2011).

7.2 Addressing climate variability in addition to climate change

There is considerable confusion over what can be attributed to climate variability (at inter-annual and multi-decadal time scales) and what can be attributed to long-term climate change. This confusion can hamper the process of conservation planning. Regional variation in temperature and precipitation is sensitive to fine-scale topographic features that affect weather patterns (e.g. mountain ranges) as well as other larger-scale climate features (e.g. the El Niño-Southern Oscillation), some of which are not well understand and therefore not captured by the GCMs on which current projections are based (CSIRO, 2007, Sheridan & Lee, 2010). For example, for the continent of Australia, Prowse and Brook (2011) identify four modes of climate variability that are particularly important for the Australian climate: the El Niño Southern Oscillation (ENSO), the inter-decadal Pacific Oscillation (IPO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM), none of which are accurately captured in the current generation of climate models, but all of which have significant impacts on biodiversity.

When assessing the effects of climate change, we need to move away from simply taking into account the long-term changes in mean climate variables (e.g. temperature increases or decreases in seasonal rainfall occurring over many years or decades). A thorough planning exercise needs to consider discrete impacts, principally extreme weather events (e.g., storms, droughts, fires, extreme temperate or rainfall events) that can have dramatic implications for the persistence of many species. Conservation planners need to formulate vulnerability assessments that integrate the impacts of both climate variability and climate change (and how climate change may impact climate variability), and integrate this knowledge into spatially explicit planning tools. This may only be achieved with a more thorough understanding of species thresholds to climate events, which is relatively unexplored in the climate – biodiversity literature at the moment (Corlett, 2011).

7.3 Incorporating the myriad of threats climate change presents into planning

Although most planners are likely to be aware of frequently discussed changes such as sea-level rise, melting of sea-ice and permafrost, or the impacts of severe droughts or storms, there are many less obvious impacts to ecosystems around the globe that are more difficult to predict and plan for. As the climate changes, so will key abiotic characteristics that are the basic building blocks of a species' fundamental niche (e.g. temperature, rainfall, cloud formation, rates of evaporation, evapotranspiration etc). The distribution and abundance of many species are likely to be affected by climate change induced alterations of the length of the growing season, the timing of seasonal events (e.g. phenology), and the length of the stratification period in lakes, to name but a few examples (see Figure 4; Parmeson & Yohe, 2003; Root et al., 2006). These impacts of climate change are relatively hard to predict and require a depth of knowledge of a species' ecology, which is rare for 99.9% of species (Whittaker et al., 2005). A recent paper by Geyer et al., (2011) highlight the issue that climate change impacts are complex: in their analyses of 20 conservation sites they classified and grouped climate change induced stresses on biodiversity and found that there were at least 90 different specific stresses could be attributed to climate change.

A related challenge is ascertaining how processes that currently effect species persistence will be indirectly affected (and often exacerbated) by climate change. When considering the impacts of climate change, it should not be forgotten that we are in the midst of an extinction crisis. Global species extinctions currently exceed the background rate by several orders of magnitude (Pimm et al., 1995; Woodruff, 2001) and the most recent International Union for Conservation of Nature (IUCN) Red List describes an ever worse situation for the world's biodiversity, with at least 38% of all known species facing extinction in the near term (Vie et al., 2009). Habitat loss is the most pressing threat to species persistence globally (Baillie et al., 2004); however, a range of other threats also drive species endangerment, including spread of disease, increase in frequency and intensity of fire and the relative importance of particular types of threat varies across taxonomic groups (Ceballos & Ehrlich, 2002; Davies et al., 2006; Ehrlich & Pringle, 2008). For certain species overexploitation and loss of habitat are immediate threats- so actions such as enforcement need to be undertaken regardless of the predicted impacts of climate change on the species. Most of these other threats will ultimately be dictated by how humans respond to climate change, which leads to a further complexity. To overcome this challenge, more research needs to be focussed on both developing methods that assess (quickly) what the impacts of climate change will be for particular species and how current drivers of extinction will change as a consequence of climate change.

7.4 Mainstreaming adaptation

One of the main obstacles with conservation planning is that many of the products of planning, while well thought through, are never implemented because they do not consider how humans will be affected by the plan. To be successfully implemented, systematic conservation plans must be complemented with social, political, and institutional tools and processes (Knight et al., 2009). Planned adaptation involves societal intervention to manage systems based on the knowledge that conditions will change, and actions must be undertaken in order to reduce any risks that may arise from that change, and particularly within vulnerable systems. While often talked about, this is rarely achieved when conservation planning is conducted.

The linkages between the impacts and responses of people and biodiversity to climate change are very strong and in recent years a concept known as 'ecosystem based adaptation' (EBA) has been developed which aims to use biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (Secretariat of the CBD, 2009). Such an approach aims to take into account the role that ecosystem services can play in human adaptation, while at the same time helping people to adapt in equitable and participatory ways that avoid bringing short-term benefits but in the longer term place additional pressures on natural systems, threatening the very systems that people depend on. We believe that this while in its infancy, the tenets of EBA can be integrated into the framework outlined in Figure 3 and be used to find optimum solutions to balance the needs of both humans and biodiversity.

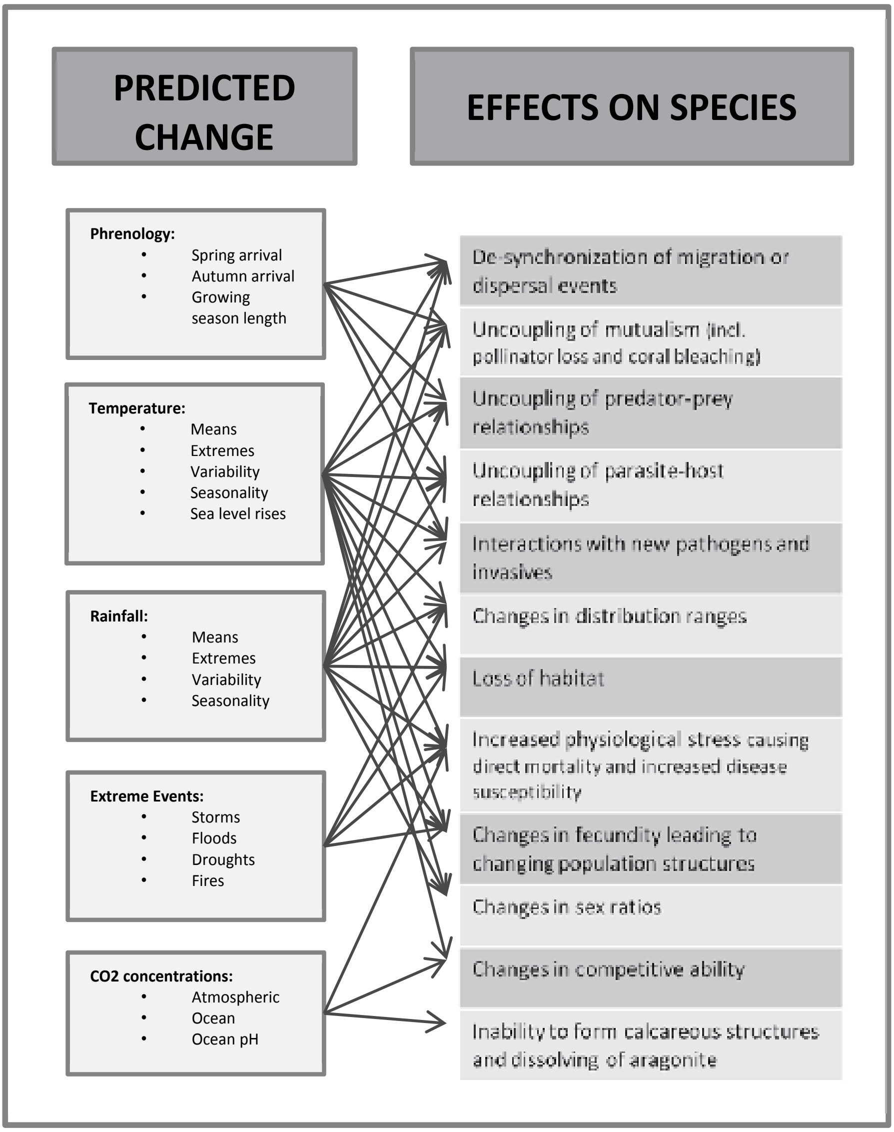


Fig. 4. Climate change impacts and their predicted effects on species (from Foden et al., 2008).

8. Conclusion

Climate change is a fact of our times. It is already altering species from the poles to the tropics (Root et al., 2005; Parmesan, 2006) and because greenhouse gas emissions to date commit the Earth to substantial climate change, will do so for decades or centuries to come regardless of the mitigation efforts we undertake. This change is happening faster than originally expected and faster than most managed systems have experienced previously. The potential for the loss of biodiversity, termination of evolutionary potential, and disruption of ecological services must be taken seriously. Averting deleterious consequences for biodiversity will require immediate action, as well as strategic conservation planning for the coming years and decades.

In this chapter, we have identified a number of broad strategies being used by conservation planners to overcome the challenge presented by climate change. We are critical of an approach that blindly relies on status quo and *Continue 'best practices'* as we think it is inappropriate and in the long-term, could lead to conservation activities that are maladaptive. Planners must adapt to deal with the new reality that climate change presents, and abandon the current focus on the preservation and restoration of 20th century reference conditions, as they will no longer be relevant in a changing world. We believe that a refocus on *Extending 'best practice' principles* is a more appropriate response as the set of 'common sense' general principles outlined in section 4 for conserving species and ecosystem viability that are based on adaptive responses to past climate changes are important and should always be considered and enacted, especially if there is limited access to data on future climate changes and associated impacts (Heller & Zavaleta, 2009; Mackey et al., 2010; Watson et al., 2009). However, integrating future climate change forecasts and scenarios into conservation strategies is going to be vital for long-term biodiversity protection as this human-induced climate change event is different from past climate changes (Heller & Zavaleta, 2009). This is especially true in the context of the many other current threats to natural systems that will also be affected by changes in local climate (Sala et al., 2000; Orr et al., 2008). Structured climate change planning needs to consider not just how species will be affected by climate, but also how humans are going to be affected. Many species are likely to go extinct because of the direct and indirect consequences of climate change unless we develop pro-active planning frameworks within a new, more dynamic conservation paradigm.

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21

Adaptation of Boreal Field Crop Production to Climate Change

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1. Introduction

The average annual global temperature increased by 0.76°C during the past century (Intergovernmental Panel on Climate Change (IPCC), 2007) and climate modelling results show an increase in annual temperature in boreal regions of 0.1 – 0.4°C/decade over the 21st century, depending on the scenario and model. Warming will be unevenly distributed, being greater in summer in lower and middle latitudes but greater in winter at higher latitudes, and this differential will increase. Mean annual precipitation is projected to increase in the North and decrease in the South, and winter precipitation will increase in northern and central Europe, continuing the trends established in the 20th century of a 10 – 40% increase in northern Europe and a decrease of up to 20% in southern Europe (IPCC, 2007). The increase in winter precipitation is due to the increased water carrying capacity of the atmosphere resulting from the higher temperature.

Global warming will increase the frequency of soil freeze-thaw cycles (FTCs) in cool-temperate and high-latitude regions previously subject to prolonged winter soil frost (Kreyling et al., 2007; Henry, 2008). Warmer winters will result in fewer soil freezing days and in boreal Europe, lowland permafrost is expected to eventually disappear (Harris et al., 2009). The length of the frost-free season has already increased in most mid- and high-latitude regions of both hemispheres over the values established in the middle of the 20th century. In the Northern Hemisphere, this is mostly manifested as an earlier start to spring, which will arrive progressively earlier in Europe by 2.5 d per decade (Menzel et al., 2006).

Increased precipitation in winter, when there is little plant growth, increases the probability of leaching, runoff and erosion from unprotected boreal soils. Climatic warming can paradoxically lead to colder soil temperatures in winter when it reduces the thickness of the insulating snow cover (Henry, 2008 and references therein) leading to root injury (Kreyling, 2010). Increased soil freezing when snow was removed led to root injury, increased leaching of C, N and P, and decreased soil microarthropod abundance (Groffman et al., 2001; Weih & Karlsson, 2002; Henry, 2008), but it is unclear what impacts FTCs and lower soil temperature will have on soil biological and physical processes. Observed nitrate losses to the groundwater after deep soil frost events are attributable more to reduced root uptake due to root injury than to increased N net mineralization (Matzner & Borken, 2008) (Figure 1).

The intensity and frequency of summer heat waves is likely to increase (IPCC, 2007). Between 1977 and 2000, these trends were more extreme in central and north-eastern Europe and in mountainous regions than in the Mediterranean region. Temperatures are increasing more in winter than summer. Furthermore, an increase in variability of daily temperatures was established during 1977 – 2000 due to an increase in warm extremes, rather than a decrease of cold extremes. Thus Nordic summers are predicted to show more frequent heat waves, while the summer rainfall comes in less frequent, heavier intervals, and the net effect for crops will be more frequent heat and drought stress.

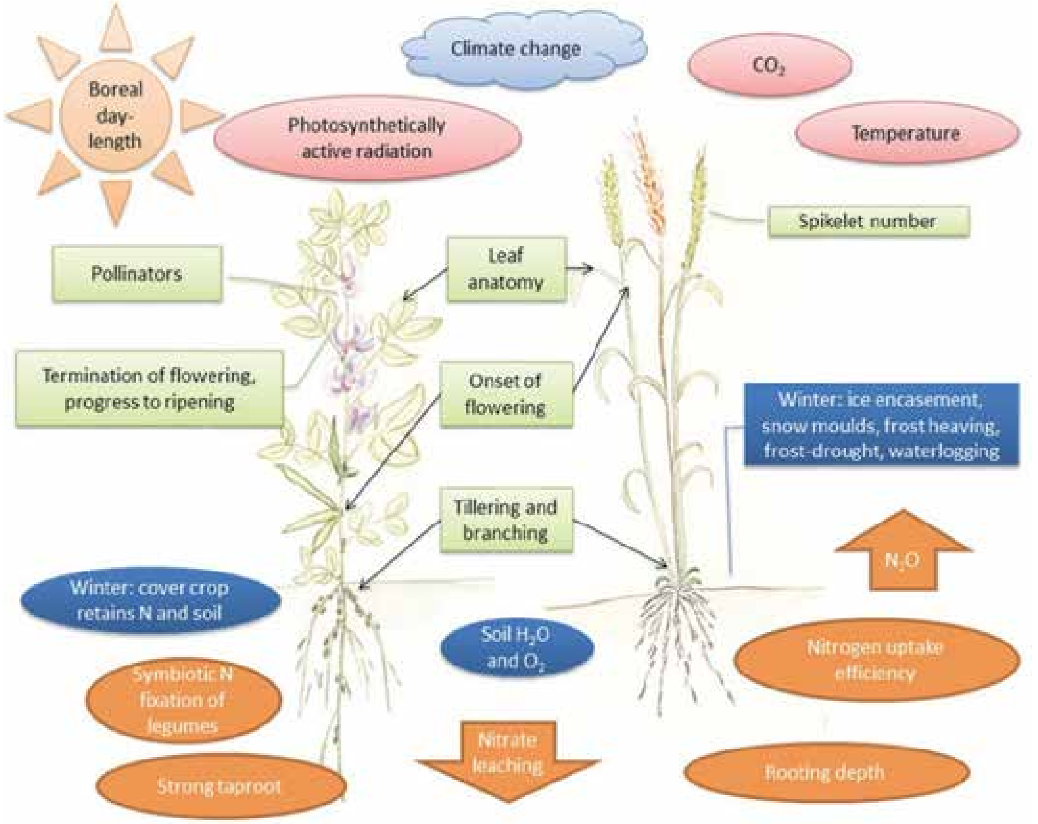

Fig. 1. Climate change alters the inputs of photosynthetically active radiation while CO_2 and temperature both rise and boreal daylength is long. These factors affect leaf anatomy, branching and flower development. Indeterminate crops need to stop flowering in order to ripen in time. Autumn-sown crops are subject to several winter-related stresses. Rooting depth is important to withstand drought , and broadleaf crops usually have a strong taproot. Key aspects of the N cycle include nitrate leaching when snow melts, release of N_2O from soil after summer rains, the use of N-fixing legumes in the rotation, and the potential to improve N uptake efficiency in cereals and oilseeds to counter the increased C:N ratio that results from the higher availability of CO_2.

These cycles of wet and dry could also lead to increased releases of N_2O from the soil, as the intervals of anaerobiosis following the heavy rains, combined with the warmth of the soil, increase the activity of denitrifying prokaryotes (Philippot et al., 2007). In an *in situ* ecosystem manipulation experiment, short-term N_2O-N losses slightly increased when elevated CO_2 was combined with warming and drought (Cantarel et al., 2011). Potential management strategies include slowly released N sources, such as plant residues, along with rapid N uptake, promoted by cover crops in autumn and well managed crop stands in summer (Figure 1).

Heavy precipitation in the autumn occurring at the time of yellow ripeness and maturity will decrease the quality of grain crops by increasing alpha-amylase activity, leading to starch damage and pre-harvest sprouting, and by promoting the growth of fungi including toxin-producing *Fusarium* species (Porter & Semenov, 2005; Clarke et al., 2005).

Crop physiological responses to temperature largely determine plant adaptation to different climatic zones and seasons; the level of photosynthetically active radiation and the length of the growing season determine the upper limit of productivity, and the phenological development of crops is influenced by temperature and light quality. Porter & Semenov (2005) highlighted the non-linear relationship of photosynthesis and respiration with temperature, in contrast to the linearity of the overall rate of crop development and progression through the life cycle.

1.1 High temperature

Plant responses to temperature and their sensitivity to temperature changes differ during ontogeny. Growth and development are accelerated by an increase in ambient temperature up to some optimum or maximum, whereafter rates decrease again. Generally crops are more sensitive to temperature changes at generative than at vegetative stages. In oilseed rape (*Brassica napus* L. ssp *oleifera* (DC.) Metzg.), high temperature resulted in shorter and thinner stems, smaller and thicker leaves, and also decreased stomatal conductance and thus transpiration (Qaderi et al., 2006). These morphological and anatomical changes could explain the decrease in plant biomass. High temperature during seed filling resulted in reductions in seed yield and oil content in this species, with strong differences among cultivars in the ability to adapt to a gradual increase in temperature (Aksouh et al., 2001).

Porter & Gawith (1999) divided the temperature responses of cereals based on four different developmental stages: sowing, terminal spikelet initiation, anthesis and grain filling. At the time of sowing, the soil temperature should be above 5°C, whereas optimum air temperatures range from 20 to 24°C. Winter crops are mainly sown when average air temperatures are already suboptimal, below 16°C, so an increase in autumn temperatures would not be detrimental to crop development or yield formation (Porter & Gawith, 1999). The sowing temperature has a marked role especially in crops that require vernalization before flowering. In the worst case, temperatures over 21°C after vernalization fulfilment may reverse the vernalization process and hinder flowering, as shown in meadow fescue (*Festuca pratensis* Huds.) (Heide, 1988). Base temperatures for vernalization range from -1.3°C to 15.7°C and in wheat (*Triticum aestivum* L. emend Thell.), spikelet initiation begins above 1.5°C and deteriorates above 25°C. Floret, pollen and grain sterility increase when temperatures decrease below 9°C or exceed 31°C during early stages of anthesis (Porter & Gawith, 1999), so the major yield component affected by high temperature is harvest index due to decreased grain number (Porter & Semenov, 2005). The grain filling stage is the most resistant to changes in temperature, the main effect usually being on starch synthesis (Porter & Gawith, 1999). The occurrence of high temperature during grain filling and drought during stem elongation has decreased wheat yields in France (Brisson et al., 2010). An increase in night temperature has been found especially detrimental for grain filling processes (Prasad et al., 2008).

Root growth is even more sensitive to temperature changes than shoot growth. Root growth responds to diurnal temperature changes in the upper soil layers. The optimal temperature for root growth seems to be around 20°C, whereas under 2°C and above 35°C root growth is reduced or stopped, and roots die under -20°C (Porter & Gawith, 1999). However, when Patil et al. (2010) tested the effect of soil warming by 5°C, no significant difference was observed in wheat grain yield, even though the crop growth period was shortened by 12 days. Since the developmental stage in cereals is determined by the apex, soil warming might affect the developmental rate only when the apex is close to the soil surface (Patil et al., 2010).

Flowering needs to occur in the window between risk of late spring frosts and risk of summer heat, both of which affect ovule and pollen viability and embryo growth. An adjustment to flowering date needs to be compensated by a corresponding adjustment to the grain-filling period, in order to allow timely harvest while maintaining the duration of light interception. If earlier-flowering cultivars are selected, the risk of low temperatures during spring can cause yield reductions by slowing growth (Figure 2A), affecting fertility, or killing the young plants (Figure 2B). When frost occurs during the flowering time of winter rye or another cereal with a determinate growth habit, the harvest fails.

Pests and pathogens decrease yield either by depressing the formation of reproductive branches and hence reducing both photosynthetic green area and grain number, or by destroying the photosynthetic green area and thus decreasing energy capture (Duveiller et al., 2007). In rainfed systems, such as Nordic areas, where short periods of drought are common, soil-borne pathogens are frequent. Increasing temperatures, irregular precipitation together with longer growing season will add to the risks of severe infestations of pathogens in boreal agriculture (Luck et al., 2011).

1.2 Drought

Drought, a temporary inadequacy of water supply to a plant, is widely considered the main limitation to crop yields (Boyer, 1982). Spring drought is already a part of the cropping season in many Nordic regions, restricting imbibition and establishment of spring-sown crops, and affecting the formation of generative organs of cereals, since the change from vegetative to generative stage occurs early, close to the two-leaf stage. Thus, the number of sterile florets and abortion increases in cereals. These changes are irreversible and decrease the final yield. Transient summer drought is predicted to increase and drought resistance of the cool-temperate crops suitable to the boreal region is important. The effects of drought are mainly due to limitation of gas exchange until relative water content is reduced to a certain point, after which biochemical changes become more important. Net photosynthesis of turnip rape (*Brassica rapa* L. ssp. *oleifera* (DC.) Metzg.) (Mäkelä et al., 1999b) and oilseed rape (Qaderi et al., 2006) decrease under drought conditions, due to stomatal closure and metabolic impairment of photosynthetic tissues.

Oilseed rape adjusts readily to prevailing growing conditions through morphological and anatomical changes. Water deficit causes reductions in its stem height and diameter as well as in leaf number and area and thus, in total dry matter (Qaderi et al., 2010). Drought-stressed oilseed brassicas form short, thick roots that, after rewatering, rapidly elongate, exploring large soil volumes (Deleens et al., 1989; Mäkelä et al., 1999a). Water deficit also increases the amount of epicuticular wax in oilseed rape (Qaderi et al., 2010).

Sugar beet (*Beta vulgaris* var. *altissima* L.) root biomass and sugar content were reduced approximately 20% under transient drought stress developed at an early growth stage, due to decreases in leaf life span and net photosynthesis, but plants recovered from the stress rather quickly and almost completely (Monti et al., 2007).

Elevated CO_2 can override some of the yield decreasing effects of drought. The water status of barley (*Hordeum vulgare* L.) under drought conditions was better under elevated CO_2 than in ambient CO_2, on account of the decrease in stomatal conductance under elevated CO_2 (Robredo et al., 2010). In elevated CO_2, photosynthesis was, surprisingly, also stimulated more under drought than under well watered conditions, and photorespiration decreased. The electron transport chain and utilization of ATP and NADPH were stimulated by elevated CO_2, thus making them more tolerant to water deficit, and photoinhibition decreased (Robredo et al., 2010).

Fig. 2. Spring frosts damage crops at early growth stages. A, spring barley leaves are damaged by spring frost, decreasing the photosynthetic leaf area and slowing biomass accumulation. The apical meristem is at this stage below soil surface and does not get damaged. B, the apical meristem of sugar beet is sensitive to frost and sometimes the seedlings die, as shown around the surviving seedling in the picture

1.3 Waterlogging

The expected increase in autumn and winter precipitation in the boreal zone will increase the incidence of waterlogging, which will affect the overwintering ability of winter crops, although waterlogging damage is more severe, around 70% yield decrease, at 25°C than at winter temperatures (Luxmoore et al., 1973).

Oxygen deficiency is typical for both ice encasement and waterlogging, since the plants consume O_2 while entry of O_2 is prevented. Thus, metabolic anoxia tolerance plays a major role in short-term anoxia, whereas in long-term anoxia, aerenchyma formation is important. The central strategy for the plant is coping with the energy crisis (reviewed in Colmer & Voeseneck, 2009), and although the soil is in a reducing state, waterlogging itself results in oxidative stress (Blokhina & Fagersted 2010). In overwintering plants, often the problem is starvation during winter when the C reserves are utilized. Timothy (*Phleum pratense* L.) maintains higher C reserves than, for example, lucerne (*Medicago sativa* L.), red clover (*Trifolium pratense* L.) and cocksfoot (*Dactylis glomerata* L.), and this is considered one of its survival strategies (Bertrand et al., 2003).

Winter waterlogging in wheat decreased the size of the root system and leaf area as well as grain yield due to decreased number of spikes per plant, since the number of tillers produced was reduced (Dickin & Wright, 2008; Dickin et al., 2009). Winter waterlogging also decreased the supply of nitrogen to the shoot in the early spring. This was later seen as decreased grain protein content at maturity and slightly delayed development of shoot, spikes and maturity (Dickin & Wright, 2008). The reduced size of the root system and leaf area limits the ability of the crop to take up nutrients and intercept radiation, and later, make it more vulnerable to drought. The root system is restricted since the nodal roots located in the top 20 cm of soil are predominant, whereas the seminal roots located at deeper soil layers are killed due to waterlogging (Dickin et al., 2009). Thus, waterlogging is even more detrimental to yield potential than drought, and reduced canopy density during winter months could enhance formation of tillers and nodal roots, which could play an important role in yield formation in waterlogged conditions (Dickin & Wright 2008).

Sairam et al. (2008) proposed that reactive oxygen species (ROS) and nitric oxide (NO) have messenger roles in the waterlogging stress response in plants. Formation of NO could be related to maintenance of ATP levels and energy charge, providing time for development of adventitious roots (Sairam et al., 2008), since roots can only form aerenchyma within the first 100 mm of growth (Dickin & Wright, 2008). Moreover, NO could be involved in aerenchyma formation in waterlogged roots by means of apoptosis (Sairam et al., 2008).

1.4 Carbon dioxide

The CO_2 concentration in the atmosphere is well known to be increasing, being at the moment 394 ppm (May 2011, http://co2now.org/) and predicted to increase to 700 ppm at the end of the century (IPCC, 2007). While CO_2 is considered as a greenhouse gas that contributes to climate change, it is also essential for photosynthesis and hence plant growth. Numerous Free-Air CO_2 Enrichment (FACE) experiments around the world have tested hypotheses on the effects of altered CO_2, in conjunction with other stresses, on the growth of various plants. In general, elevated CO_2 stimulates photosynthetic carbon gain and net primary production over the long term, despite increasing the saturation of Rubisco (Ribulose-1,5,-bisphosphate carboxylase/oxygenase) and the intracellular CO_2 concentration increases due to smaller stomatal aperture (reviewed in Haverkort & Verhagen, 2008). High CO_2 down-regulates Rubisco activity in C3 plants (including wheat, oilseed brassicas, and legumes) that are the main crops in the boreal region, stimulates dark respiration via transcriptional reprogramming of metabolism, and decreases photorespiration (reviewed in Leakey et al., 2009). The photosynthesis of C3 plants, such as potato (*Solanum tuberosum* L.), however, acclimatizes to elevated CO_2, which results eventually in reduction in Rubisco content (Haverkort & Verhagen, 2008; Leakey et al., 2009). Even though assimilation is stimulated, partitioning is not, and yield increases are sink-limited unless additional N is supplied (Leakey et al., 2009). Elevated CO_2 concentration has also been shown to attenuate the effects of water deficit and to improve the efficiency of water use at both the leaf and canopy scale by maintaining the stomatal conductance, carboxylation rate and RuBP (Ribulose-1,5-bisphosphate) regeneration (Robredo et al., 2010). When the photosynthesis is limited by RuBP regeneration capacity, the increase in photosynthesis results mostly from decrease in photorespiration (Leakey et al., 2009). Even though water use efficiency (WUE) of most crops increases, this green leaf period may also lengthen, leading to an overall increase in use of water (Haverkort & Verhagen, 2008).

Elevated CO_2 increased the leaf thickness, leaf area, stomatal density and photosynthesis in potato, but decreased the stomatal conductance by reducing stomatal aperture (Lawson et al., 2002). Photosynthesis was increased and respiration decreased in potato in the same conditions and the decrease in respiration was attributable to the lowered protein content of the plant tissues (Fleisher et al., 2008). Moreover, the majority of additional photosynthate was partitioned to tubers and roots instead of above-ground biomass, and no marked differences were observed in the area, appearance rate, expansion rate, and senescence rate of leaves (Fleisher et al., 2008). When the irrigation rate under elevated CO_2 was increased, photosynthate was partitioned more to leaves and stems, decreasing the harvest index, and this was attributable to the increased respiratory costs of increased biomass. Under elevated CO_2, the increased tuber sink may play an important role in reducing the drought-induced feedback inhibition of photosynthesis. The radiation use efficiency (RUE) of potato was increased under elevated CO_2 (Fleisher et al., 2006). Glycoalkaloid, citric acid and nitrate concentrations decreased while phosphorus, starch and dry matter content of tubers all increased in elevated CO_2 (reviewed in Haverkort & Verhagen, 2008). Low glycoalkaloid and nitrate content represents better product quality, but lowered citric acid content allows greater discolouration after cooking. At the same time, the higher temperature that is part of global change causes a contrasting decrease in dry matter content, and irregular precipitation can cause secondary growth of tubers.

Similarly, in oilseed rape, elevated CO_2 resulted in taller plants with thicker stems and larger and thicker leaves (Qaderi et al., 2006), but there was no change in yield or seed oil content (Franzaring et al. 2008). Photosynthesis increased, as did chlorophyll fluorescence and content, contributing to the higher biomass production of plants grown under elevated CO_2 (Qaderi et al., 2006). In the vegetative stage, biomass was higher in elevated CO_2, particularly in old cultivars, but the difference between growing conditions disappeared at later stages, which was attributed to the lack of carbon storage (Franzaring et al., 2008).

When wheat was grown under high CO_2, its photosynthetic capacity was decreased, probably due to down-regulation of Rubisco activity (Alonso et al., 2008). Elevated CO_2 also increased the temperature optimum of the crop. Alonso et al. (2008) suggested that this was due to decrease of the Rubisco activation state at high temperature and concluded that in future conditions, the light-saturated photosynthesis will be limited by Rubisco, which could have explained the modest increase of the wheat yield obtained.

Hybrid cultivars have generally responded more positively than inbred lines to elevated CO_2, probably due to their larger sinks, in which carbon assimilation is less restricted by feedback inhibition (Sun et al., 2009). When sink capacity is insufficient, CO_2 elevation results in increased leaf carbohydrate concentration and down-regulation of photosynthesis (Leakey et al., 2009).

In contrast, the effects of elevated CO_2 on C4 photosynthesis are small, and generally significant only in drought conditions (Leakey et al., 2009), but this group is currently of minor importance in boreal agriculture.

In order to maintain the yield response to elevated CO_2, an increased supply of Rubisco is needed, and the plant's C:N ratio is increased by the enhanced supply of photosynthate (Porter & Semenov, 2005), so improved access to N is likely to be important in boreal systems under climate change. Crops under elevated CO_2 required more N than those under current ambient levels in order to produce optimum yield (Sun et al., 2009). Elevated CO_2 reduces N use efficiency, lowering the protein content of cereal grains and the rheological properties of wheat flour (Porter & Semenov, 2005), and it reduces the assimilation of nitrate in the shoots of both wheat and Arabidopsis (Bloom et al., 2010). Integration of agronomy, physiology, genetics and omics is necessary to identify novel ways to improve NUE of cereals and oilseeds in order that yield is maintained at lower N input levels or higher C:N ratios. Manipulation of glutamine synthase genes in maize had significant impacts on grain yield, whereas the genes underlying variation in root length, branching and soil volume exploration remain harder to identify and hence manipulate (Hirel et al., 2007). Strategies to improve the N economy of wheat, and applicable to other non-N-fixing crops, include maximizing N capture through effective root morphology, optimizing N uptake and assimilation by activity of glutamine synthetase and other enzymes, and optimizing N partitioning to grain by remobilizing stem N while maintaining leaf photosynthetic activity and N content with stay-green mutations (Foulkes et al., 2009).

The enhanced availability of photosynthate resulting from high atmospheric CO_2 concentration has been shown to increase N fixation in several legume species, so grain quality and protein content are generally maintained (Rogers et al., 2009), but there is weak evidence for this in some of the cool-temperate adapted species grown in the boreal region. Doubled CO_2 concentration (700 ppm instead of 350 ppm) resulted in higher photosynthetic water use efficiency in faba bean (*Vicia faba* L.), the increase depending on cultivar (Avola et al., 2008), and occurring only when the water supply was not limiting (Wu & Wang, 2000) and when solar UV-B irradiance was not increased (Tosserams et al., 2001).

The increased C:N ratio from elevated CO_2 concentration has implications for hay and silage cropping (Porter & Semenov, 2005), which are important components of boreal agricultural systems, and adequate protein content is a key factor determining forage quality.

CO_2 concentration is understood to have little or no direct effect on phenology (Craufurd & Wheeler, 2009). Nevertheless, at elevated CO_2, stomatal conductance is often reduced, so the canopy and tissue temperature increase, resulting in a thermal influence on phenological development. The apical meristem is the developing organ and it is the temperature nearest the apical meristem that affects the development (reviewed in Craufurd & Wheeler, 2009). In spring wheat, no changes in phenological development, rate of leaf emergence or final leaf number were observed following elevation of CO_2, but the number of shoots per plant and leaf area index were increased over 10% (Ewert & Pleijel, 1999).

Elevated CO_2, together with other global change factors, affects crop architecture and flowering time in a variety of ways. Tillering of wheat increased in response to elevated CO_2, with an old, tall cultivar being significantly more responsive than a young, semidwarf one (Ziska, 2008). The result was that the yield superiority of the modern cultivar disappeared at high CO_2 (Ziska, 2008). Depending on the species and cultivar, flowering time has shown accelerated, unchanged, and delayed responses to elevated CO_2 (reviewed by Springer & Ward, 2007). The primary mechanism involved is not known, but involvement of carbon metabolism has been suggested (Springer & Ward, 2007), because of its effect on flowering time (Rolland et al., 2002).

2. Consequences for agriculture

Climate change will lead to the intensification of agriculture in northern Europe and other boreal and nemoral zones. For example, it will lead to shifts in the northern limits of areas thermally suitable for the cultivation of soya bean and grain maize by several hundred kilometres, and lengthen the northern European growing season by 3-12 weeks by 2085, with a stronger effect at the end than at the start of the growing season leading to substantial increases in biomass production (Carter, 1998; Fronzek & Carter, 2007). Thus these regions are predicted to gain many benefits from climate change, as the areas suitable for crop production will expand and new crops can be introduced to production. Some of the greatest temperature increases are expected in the Nordic region. While this will reduce some incidences of chilling, it will increase the occurrence of heat stress episodes, to which current cultivars are not adequately tolerant. The increases in CO_2 concentration are expected to be beneficial to the crops with C3 metabolism that provide the basis for high-latitude agriculture, as long as temperatures remain in the moderate range that is predicted. The impacts on autumn-sown crops are more geographically variable. Yield is expected to strongly decrease in most southern areas, and increase in northern or cooler areas (e.g., wheat: +3 to +4% by 2020, -8 to +22% by 2050, -15 to +32% by 2080) (Olesen et al., 2007; IPCC, 2007).

The more uneven distribution of rainfall predicted by the models (Section 1), with longer droughts in the spring, heavier and less frequent downpours in summer, and more rain in autumn and winter with less snow cover, will decrease potential crop productivity, and more attention will need to be paid towards these factors and crop responses to them. The changes in temperature and rainfall patterns will bring an increased risk of pest attacks limiting or destroying the crop production. Plants can, however, adapt to the environment. The responses of plants to the environment influence the development of new cultivars, new cropping systems and crop management practices.

The phenology, or timing of growth, of the crop determines how much light it can intercept and thus the potential biomass accumulation. The phenology of modern crops is fitted to their growing environment; that is, different developmental stages occur at appropriate times, so oilseed crops or small grain cereals flower in midsummer rather than too soon or too late. The rates of developmental processes and growth are determined by temperature, and in some cases daylength. The threshold temperatures and rates of response to changing temperature differ according to the developmental processes, plant species, and often cultivar (reviewed in Porter & Gawith, 1999). Therefore, concepts such as growing degree days have been found useful for describing, modelling, and predicting crop growth. Growth and development are quantitative responses to temperature affected also by flux of carbon gains and losses (Porter & Gawith, 1999).

Crop growth is affected by genotype, environment and management practices, and the environmental factors include temperature, daylength, radiation, nutrient and water availability, and CO_2 concentration. Late spring and early autumn frosts limit boreal crop production, and climate change is not expected to alter this situation markedly, so there is limited scope for increasing crop yields in the future by extending the growing period.

The drawback for winter crops in boreal conditions has been poor overwintering, the main reason for which is not inadequate frost resistance but damage caused by pathogenic fungi (*Microdochium* spp., *Fusarium* spp., *Typhula* spp., and *Sclerotinia* spp.) that damage the crops during winter months under thick and long-lasting snow cover (Figure 3) when the soil temperatures are 0 – 5°C. Sometimes the plant stand is almost completely lost (Jamalainen, 1974). Moreover, ice encasement, frost-drought and frost-heaving as well as waterlogging can destroy overwintering plant stands. When snow cover lasts for several months without soil freezing, winter cereals in particular can die from starvation, as plants respire throughout the winter under the snow cover, utilizing carbohydrate reserves (Jamalainen, 1978). Since the duration of permanent snow cover has been forecast to shorten, the importance of snow mould should decrease, even though the rainy autumn and winter days that promote the disease are forecast to increase. Good management practises, such as timely sowing, appropriate fungicide applications, and avoidance of too dense canopies in the autumn will further decrease the incidence of snow mould. Good frost hardiness is already available in a range of winter-annual crops, including rye, wheat (Hömmö, 1994), turnip rape (Mäkelä et al., 2011) and faba bean (Link et al., 2010), so winter damage due to cold temperatures will be less frequent in future, but resistance to the other stresses needs to be improved.

3. Phenological changes due to climate change

Phenological change as a response to climate warming has been documented in crop plants and natural communities across the northern hemisphere (Walther et al., 2002; Parmesan & Yohe, 2003; Menzel et al., 2006; Estrella et al., 2007). The advances in timing of spring events, including earlier flowering, maturity, leaf unfolding, budburst, shooting, closure of the stands, and ear formation, correspond to patterns of human-induced climate change (Rosenzweig et al., 2008). The mean temperature of the month preceding onset was shown to have the most predictive value for timing, with effects also from the second preceding month and the month of onset (Menzel et al., 2006). Changes in timing of farm activities, including drilling, tilling, harvesting, were also strongly correlated with changes in temperature (Menzel et al., 2006).

Temperature, together with photoperiod, is a seasonal cue and a major determinant of the rate of plant development, and warmer temperatures that shorten developmental stages of determinate crops will lead to reduction of the yield. The optimal temperature for most crop plants in boreal agriculture is below 25°C (Porter & Gawith, 1999; Porter & Semenov, 2005) and this value will be exceeded more often in the future, warmer climate than it is now. Crop physiological responses to temperature largely determine their adaptation to different climatic zones and seasons; the level of photosynthetically active radiation and the length of growing season determine the upper limit of productivity, and the phenological stage of a crop is influenced by temperature and by light quality. Daylength has a further impact on development and as it increases in spring it can determine the transition from the vegetative to the reproductive phase. At the start of the high-latitude growing season, daylength is already longer than the critical value for many cultivars developed at lower latitudes. In cereals, this vegetative-reproductive transition limits biomass production, since there is no further vegetative development, whereas in pasture crops and other species with indeterminate habit, vegetative growth continues.

Fig. 3. Winter damage in rye. Snow mould kills the overwintering plants under snow cover and sometimes hardly any plants survive. (Antti Tuulos)

Autumn sowing in the boreal zone is currently restricted by the onset of autumn rains that make agricultural practices difficult. Autumn-sown crop establishment occurs during a period of cooling soil and air temperatures and shortening day length. Wetter, warmer autumn conditions are therefore likely to continue to restrict sowing, but to allow crops to develop further than they do now before the onset of winter, and thus to be at greater risk of winter damage. The effect of increased autumn temperatures on vernalization has not been studied, but clearly hardening will be delayed. Changes in timing of the emergence and establishment of autumn-sown crops (which are related to harvesting and subsequent drilling) are little related to temperature (Menzel et al., 2006).

The genetic and environmental moderation of the timing of flowering, by determining the season length, and hence the availability of radiation, water and nutrient resources for growth, and by affecting the exposure of the crop to climate extremes, is therefore central to the success of the crop.

3.1 Biomass production

The intensity and daily duration of solar radiation varies depending on elevation and latitude. At high latitudes, solar radiation has a high red content, on account of the lower angle of the sun in the sky, even in midsummer. Cloud further decreases the amount of available radiation. Thus only part of the incident radiation is intercepted by plants and available for photosynthesis (Sinclair & Muchow, 1999), particularly at high latitudes. Intercepted solar radiation is linearly related to dry matter accumulation. The level of solar radiation also defines the optimum leaf area index (LAI) (Stern & Donald, 1961). An earlier developing and later maturing crop thus has the potential to capture and utilize the radiation for a longer period, within the limits set by the risks of cold temperatures in the spring and autumn. Extreme temperatures, even though not yet harmful, increase the respiration of the crops and thus limit biomass accumulation. Primary production is determined by a function of available incident solar radiation across the season, the efficiency of light interception by the crop and the efficiency of conversion of absorbed energy into biomass (Sun et al., 2009). This last step, the RUE, is affected by crop developmental stage, leaf tissue structure, and location (level of solar radiation and diffuse radiation), and through photosynthesis temperature as well as N and water availability. However, RUE is almost insensitive to latitude and LAI. Leaves with a high N content have high photosynthetic activity and RUE, which is saturated at certain leaf N levels depending on species. Since water deficit affects photosynthetic activity, RUE is dependent on the severity of water deficit (Sinclair & Muchow, 1999).

RUE varies among species and developmental stages since there are differences in biochemical components of the plant products and in photosynthesis. During early stages of crop establishment when the photosynthetic capacity of the leaves is still limited, RUE is usually lower than at later stages. In potato producing starch-containing tubers forming early in the season, the conversion of photosynthate to starch can be higher than 0.83 g carbohydrate per g photosynthate, whereas in wheat it is 0.71. Wheat grains that develop later in the season contain up to 14% protein formed from N that is translocated from leaves. Species with C4 photosynthesis have generally higher RUE than C3 species, while legumes that use some energy for symbiotic nitrogen fixation have lower RUE than other crops. Interestingly potato has almost as high RUE when vegetative as maize, and the RUE is rather stable throughout the growing season (reviewed in Sinclair & Muchow, 1999). Careful analysis of RUE could reveal the growth- and yield-limiting factors that could be improved by management practises and breeding in an attempt to maximize biomass for partitioning into yield. RUE levels can increase as total radiation level decreases, and in those conditions there is usually an increased proportion of diffuse radiation, so RUE is further enhanced (Sinclair & Muchow, 1999).

Increased rooting depth and specific leaf area (SLA) could affect yield positively in warmer climates (Ludwig & Asseng, 2010). Increased rooting depth can be an advantageous trait under rising temperatures when crop demand for water is increased. Increased SLA is advantageous only in cases when the grain yield is restricted by too short a period of pre-anthesis growth, as found in boreal areas. On the other hand, increase in early vigour results in rapid use of water reserves in rainfed areas early in the growing season. Ludwig & Asseng (2010) also demonstrated that elevated CO_2 reduces the benefits of SLA.

3.2 Epigenetics and the thermosensing of flowering pathways

Flowering, which is essential for the partitioning of biomass into grain yield, is initiated in response to both environmental cues (temperature, daylength) and the autonomous pathway that is related to the developmental stage of plant. The relative contributions of the two pathways to flowering vary among species (Amasino & Michaels, 2010). Flowering is a major developmental pathway that is regulated by ambient temperature. The acceleration of flowering in Arabidopsis by higher temperature requires genes from the autonomous pathway (Blázquez et al., 2003), and is dependent on increasing expression of *FLOWERING LOCUS T* (*FT*) (Balasubramanian et al., 2006). This thermosensing response in Arabidopsis is due to the epigenetic regulation of chromatin structure that leads to changes in chromatin integrity (Kumar & Wigge, 2010). Epigenetic regulation also affects vernalization, another temperature-dependent pathway of flowering. *FLOWERING LOCUS C* (*FLC)*, the key gene in vernalization, is progressively repressed when plants are exposed to cold during winter. This repressed state later facilitates flowering induction in spring, and continues even when cold is not present, indicating that a long cold period confers a cellular "memory" of winter (Sung & Amasino, 2006). The transition from vegetative to reproductive growth in plants is now understood to be strongly influenced by epigenetic control mechanisms, and the effects of stresses on these mechanisms need to be investigated in order to allow better control of the onset of flowering in a changing environment (Mittler & Blumwald, 2010) (Figure 4).

In addition to flowering, epigenetic regulation has important roles in other developmental processes and responses to environmental cues, including abiotic and biotic stress (Jarillo et al., 2009; Bennetzen & Zhu, 2011; Deal & Henikoff, 2011). Warmer developmental conditions and maternal drought stress can decrease seed dormancy, allowing germination in non-optimal conditions (Qaderi et al., 2006). Hence, high temperature can also have an impact on seed lot homogeneity and stability.

Some environmentally induced changes in plant traits are transient, mediating acclimation response, while others are heritable epigenetic modifications that provide plants a (within- and trans-generational) stress memory that may help them cope with subsequent stresses more effectively (Chinnusamy & Chu, 2009; Bennetzen & Zhu, 2011). Berger et al. (2009) proposed three categories of signals that operate in the establishment of a stably heritable epigenetic state. The first is a signal from the environment, the second is a responding signal in the cell that specifies the affected chromosomal location, and the third is a sustaining signal that perpetuates the chromatin change in subsequent generations.

The heritability of environmentally induced traits has special relevance in the context of climate change, as it can have a role in long-term environmental adaptation. Several studies tested the existence of trans-generational epigenetic inheritance of environmentally induced traits and its stability (Paszkowski & Grossniklaus, 2011). The underlying mechanism involves altered DNA methylation and removal, as in the case of warm temperature response, and histone variants may be exchanged, but it is difficult to distinguish epigenetic marks that are inherited from those that are reset (Paszkowski & Grossniklaus, 2011). Epigenetic changes induced by abiotic stress may have an adaptive advantage for plants, but they may also prevent the next generation from growing to its full potential by affecting timing of the developmental phases (Chinnusamy & Chu, 2009).

Histone variants and post-translational modifications to histones are able to alter physical properties of nucleosomes and serve as a mechanism for regulating DNA exposure. Histone variant H2A.Z, and H2K4 and H3K27 methylation, are key elements in the regulation of genes involved in developmental processes of plants, including the vegetative to reproductive transition (regulation of *FLC*) and in stress responses (Deal & Henikoff, 2011). Histone variant H2A.Z is unstable in warm temperatures, and its nucleosome occupancy declines, so it is suggested to act as temperature sensor (Kumar & Wigge, 2010). The chromatin status at the *FT* locus responds to temperature and is altered in the absence of H2A.Z (Kumar & Wigge, 2010), allowing the expression of *FT* in response to higher temperature (independently of *CONSTANS*, CO).

Understanding the molecular basis of the temperature sensing mechanism is essential in order to predict the responses of plants to further increases in temperature and to use this information in breeding crops to cope with climate change. The rate of development is largely determined by responses to temperature and photoperiod, and it is possible to quantify and predict the effects both of temperature and of photoperiod at optimum and suboptimum temperatures (Craufurd & Wheeler, 2007). However the mechanism of action of the effects of temperature and photoperiod on developmental stages above the optimum temperature are not well understood (Craufurd & Wheeler, 2007).

In general, the phenological stages determining yield of autumn-sown crops occur earlier than in spring-sown crops, thereby avoiding heat stress, but also being slower and allowing a longer period for tiller and spikelet formation. An early beginning of the growing season and low spring temperatures increase tiller formation, whereas increasing temperatures between stem elongation and anthesis decrease the number of tillers. A slight increase in winter temperatures would increase the yield of winter cereals at high latitudes, since it would result in more head-bearing tillers and more grains per head (Chmielewski & Köhn, 2000). Winter crops have better access to water reserves in early spring and are thus less sensitive to drought (Chmielewski & Köhn, 2000). Tiller survival is, however, very sensitive to water deficit, which can have a marked role in some years. The crop canopy is leafy in early spring before the spring crops are sown and thus, the canopy can make better use of incoming radiation (Figure 5). Many of the same principles apply to autumn-sown broadleaf crops with an indeterminate growth habit, such as faba bean (Link et al., 2010) and turnip rape (Mäkelä et al., 2011).

Warmer soil temperature increased the green leaf area index, above-ground biomass, and nitrogen content during early developmental stages of winter wheat, without significantly affecting the generative stages and yield of the crop (Patil et al., 2010). Thus the crop had an opportunity to utilize the incoming radiation for accumulating biomass and nitrogen, which could at later stage be converted into grain yield.

Modelling of sorghum (*Sorghum bicolor* L.), a C4 plant, showed that in the presence of drought, increased rooting depth maintained or increased yield in spite of drought-reduced

RUE, and also reduced yield variability (Sinclair & Muchow, 2001). Utilization of carbohydrate reserves stored in the stem allows continuation of grain filling in drought- or heat-stressed cereal plants (Blum, 2005). Reduced plant size and leaf area mainly account for increased water use efficiency in crops, but they usually result in lower yield potential. Hence Blum (2009) developed the concept of "effective use of water", whereby emphasis is returned to maximized yield rather than to limited water use. Component traits included large leaf area with selective killing of older leaves under stress, and osmotic adjustment that allows fast recovery after stress relief (Blum, 2005, 2009). Temporary storage of carbohydrate reserves, as found in many cereal stems, allows a crop to adjust to fluctuation of assimilate supply by maintaining a viable sink, preventing sink-limitation and feedback inhibition of the enhanced potential photosynthesis following elevated CO_2 levels.

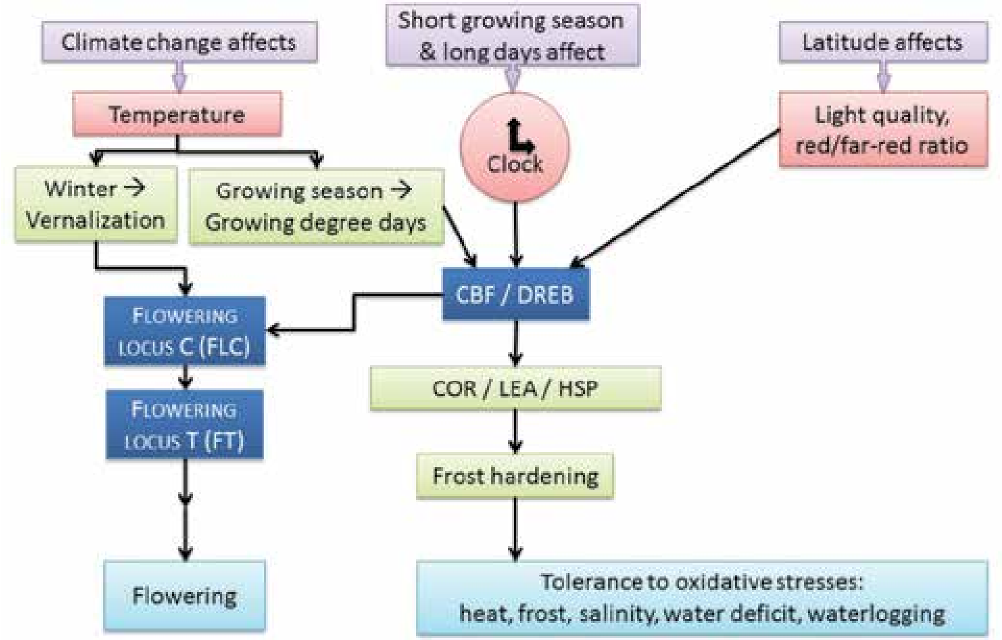

Fig. 4. Pathways affecting flowering and stress responses as influenced by climate change in the boreal region. CBF/ DREBs (C-REPEAT BINDING FACTOR/DEHYDRATION-RESPONSIVE ELEMENT BINDING FACTOR) have a central role in cold acclimation and responses to abiotic stresses and are regulated by temperature and light. CBF activates COLD-RESPONSIVE/LATE EMBRYOGENESIS-ABUNDANT (COR/LEA) genes that improve freezing, drought and salinity tolerance. Heat stress induces DREB2A that improves heat tolerance through the HEAT SHOCK TRANSCRIPTION FACTOR-HEAT SHOCK PROTEIN (HSF-HSP) pathway. Vernalization and CBF act in a coordinated fashion to regulate FLC that, in turn, regulates further downstream genes to induce flowering. (Adapted from Chew & Halliday, 2011)

4. Challenges and limitations for crop improvement

Abiotic stress is a primary cause of crop loss, reducing average yields of most crop plants by more than 50% (Boyer, 1982; Bray et al., 2000). In the future, increased episodes of abiotic stresses can lead to even more severe losses in yield. The production of crops with improved responses to wide-ranging environmental conditions is needed, for boreal agriculture as much as for that at lower latitudes. Adaptation options that may be explored to minimize negative impacts of climate change and to take advantage of positive impacts include changes in crop species, cultivar, sowing date, fertilization, irrigation, drainage, land allocation and farming system (Olesen & Bindi, 2002).

Breeding methodology should, as always, be effective. Increasing yield stability under different stress conditions is a challenge to breeders as it is difficult to synchronize the crop cycle with the most favourable environmental conditions. In boreal climates, crop plants have to be adapted to both the long photoperiod and low temperature, and the combination of timing, duration, intensity, and frequency of heat, drought, frost, flooding, disease and pest stresses cannot be predicted. The full suite of technologies, including traditional breeding, mutation breeding, marker-assisted selection, genomic selection, and cis- and trans-genic technologies, will be needed to improve crop performance and yield (Jung & Müller, 2009; Mittler & Blumwald, 2010; Varshney et al., 2011).

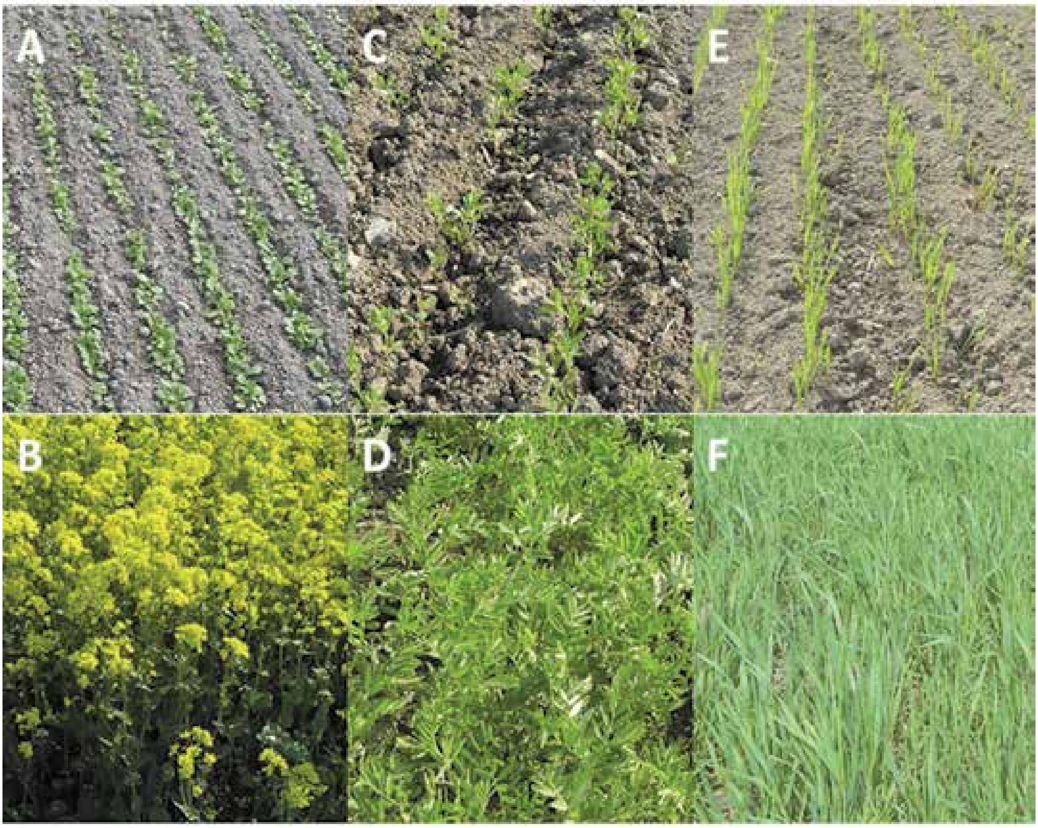

Fig. 5. Winter crops already cover the soil surface and efficiently utilize available resources, such as solar energy, when spring crops have just formed their first true leaves. A, spring turnip rape, B, winter turnip rape, C, spring lentil, D, winter lentil, E, spring cereal and F, winter cereal. All photographs were taken on 30 May 2011 (Antti Tuulos).

4.1 Biotechnology

Biotechnological manipulations can assist the development of sustainable crops for the boreal zone. The availability of the complete Arabidopsis genome sequence and the increasing number of complete genomic sequences and omics tools from crop plants (Langridge & Fleury, 2011) will reveal new candidate genes for future crop improvement and novel products. Advances in sequencing technologies have led to a rapid increase in the number of crop species for which the genome sequence is either complete or nearly so (GenBank, 2011). Together with advanced bioinformatics tools available, the integration of genome and functional omics data (transcriptomics, proteomics, metabolomics) with genetic and phenotypic information is leading to the identification and characterization of genes and pathways responsible for agronomically important phenotypes (Mittler & Blumwald, 2010; Tester & Langridge, 2010; Mochida & Shinozaki, 2010; Langridge & Fleury, 2011). Omics analyses, in which the expression of thousands of genes, changes in protein composition and metabolite profile are simultaneously examined, are crucial for understanding the whole processes of molecular networks in response to stresses, in order to improve crop resistance and productivity. Omics analyses of regulatory networks have cast light on plant abiotic stress responses (Urano et al., 2010). A relatively new omics technology is automated phenotyping or phenomics, which has progressed to the stage where even such large plants as maize can be automatically scanned, as long as they have been grown in containers in controlled conditions (www.lemnatec.com). For field-grown materials, the technology of precision agriculture, in which near infrared (NIR) scanners are placed in combine harvesters, has been adapted and tractor-mounted NIR scanners read the spectra from growing crops (Montes et al., 2007).

Genes of potential importance can be transferred into elite germplasm, through molecular breeding in the same species, or across species by using genetic engineering. When the naturally occurring variation is not enough, genetic engineering permits the generation of novel variation and traits. The potential of using genetic engineering for crop improvement in modern agriculture facing climate change has recently been reviewed by Mittler & Blumwald (2010).

Engaging multiple stress pathways by manipulating the expression of specific transcription factors has proven to be a useful approach for improving abiotic stress tolerance (Century et al., 2008; Yang et al., 2010; Long & Ort, 2010; Chew & Halliday, 2011). C-repeat binding factor (CBF) and abscisic acid-responsive element (ABRE) transcription factors (TF) confer tolerance to multiple abiotic stresses, including cold, drought, heat and oxidative stress (Hua 2009; Thomashow, 2010; Chew & Halliday, 2011; Dong et al., 2011). As these regulatory pathways are conserved among species, and are present in hardy crops as well in species that are chilling sensitive, it is possible to modify pathways in one plant using TF from another plant (Jaglo et al., 2001; Nakashima et al., 2006). Targeted genetic engineering using CBF/ABREs can result in improved survival rates in crops and also gives a chance to increase the number of crop species for cultivation (Figure 4).

4.2 Flowering

The synchrony of the life cycle of a plant to the changing seasons is particularly important in boreal environments where extreme changes in environmental conditions occur at different times of the year. Timing developmental events to coincide with favourable seasonal conditions is critical for plant growth, survival and reproduction, and in crop plants this means harvestable yield. Temperate plants respond to and often use the combination of daylength, vernalization and temperature to ensure optimal timing of flowering. The appropriate timing of flowering is pivotal for reproductive success in plants, and hence the transition to flowering is controlled both by endogenous developmental factors and environmental cues (Amasino & Michaels, 2010). This aspect of adaptation already limits the use of imported cultivars in the boreal zone and in the projected future climate, novel combinations of environmental and seasonal cues can have an effect on the flowering-time gene network with important consequences for plant life history.

The molecular biology of seasonal flowering responses has been elucidated in Arabidopsis (Amasino & Michaels, 2010), and in cereals the components involved in flowering and vernalization are well characterized (Alexandre & Hennig, 2008; Greenup et al., 2009; Kim et al., 2009). The basic photoperiod pathway appears to be conserved in flowering plants, converging on the activation of *FT* (Mouradov et al., 2002). *FT* encodes florigen, a small protein that is a strong promoter of flowering (Turck et al., 2008). In Arabidopsis, *FLC* represses expression of *FT* until this repression is removed through the silencing of *FLC* by vernalization, the process by which prolonged exposure to cold makes plants competent to flower (Kim et al., 2009). In cereals, *VERNALIZATION 2* (*VRN2*) acts as a flowering repressor that, like *FLC*, is turned off during cold exposure (Galiba et al., 2009; Greenup et al., 2009). Although the proteins coded by *VRN2* and *FLC* are not homologues, the functional role for repressors is the same, namely the repression of *FT* (called *VRN3* in cereals). Pin et al. (2010) demonstrated another strategy to regulate vernalization in sugar beet, a biennial crop, where the regulation of flowering time is controlled by the interplay of two paralogs of the *FT* gene, *BvFT1* and *BvFT2*, that have antagonistic functions. *BvFT2* is functionally conserved with *FT* and essential for flowering, whereas *BvFT1* represses flowering and its down-regulation is crucial for the vernalization response in beet.

The molecular biology of flowering is presently being intensively investigated in order to identify genes involved and their interactions in crop plants. The genetic basis of flowering is important for plant breeding and improvement strategies, as well as for predicting and managing responses to changing climates. The timing of flowering is important for adaptation to and avoidance of abiotic stresses. In many annual crops, brief episodes of hot temperatures (>32-36°C) or a single night frost are well known to cause severe damage at flowering, and as a consequence reduce crop yield. Faba bean ovules, for example, are susceptible to a fraction of a degree of frost (Link et al., 2010).

Delaying time of flowering can be used to optimize biomass production where the whole plant is used. Late-flowering cultivars of maize are chosen for boreal conditions in order to optimize whole-crop biomass and quality for forage or bioenergy use (Pakarinen et al., 2011). Similarly, transforming tobacco with an Arabidopsis *FLC* construct that delayed flowering resulted in a significant increase in dry matter production (Salehi et al., 2005).

Targeting genetic manipulation to increase freezing tolerance by using CBFs and/or genes involved in timing of flowering will produce crop varieties that are able to withstand or avoid sub-optimal growing conditions. Elegant work on poplar (*Populus tremula* L.) (Böhlenius et al., 2006) and sugar beet (Pin et al., 2010) shows that combining the information obtained from Arabidopsis with profound knowledge about flowering physiology can produce outcomes with high value in crop breeding. *PtFT1* (*FT* ortholog) controls both flowering and the growth cessation and bud set in the fall, indicating that *FT* orthologs have a more general role in regulating biological processes subjected to photoperiod than previously anticipated (Böhlenius et al., 2006). The increased knowledge about “critical daylength” is central for our ability to adapt plants to new climates. In addition, with the ability to manipulate *FT* activity, it is possible to either prolong or shorten the growing season of plant and to accelerate the breeding process (Böhlenius et al., 2006).

European attitudes and regulatory policies concerning GMOs are highly negative and restrictive. Creation of marker-free plants (antibiotic-free constructs) and the use of cis-genic vectors (www.cisgenics.com), in which only host gene sequences are used, go partway toward answering the criticism and may make it easier to licence GM crops.

5. Conclusion: building a resilient boreal agriculture

Warmer conditions will reduce some limitations to crop production in high latitudes. Taking full advantage of these opportunities, without losing too much to the countervailing stresses, will require new interdisciplinary interactions between soil scientists, microbiologists and crop scientists (including agronomists, breeders and pathologists). We propose that a resilient boreal agriculture can be built on three pillars: diversity, sustainability and technology.

5.1 Diversity

Crop diversity has many well known advantages, several of which have been undervalued by the Common Agricultural Policy of recent decades. First among these is that rotational diversity breaks a number of cycles, particularly soil-borne disease cycles of the primary crops, usually small-grain cereals. The weed, pathogen and pest fauna and flora of different crops are different, so the control measures differ, and rotation reduces the prospects that these populations develop resistance to the control measures. At the countryside scale, a patchwork of different crop species and cultivars can help slow the spread of diseases or reduce their impact on farm income. The different root morphologies of different crops lead to exploration of different soil layers and usage of a different balance of nutrients, and leave residues of different types, thus helping to maintain the structure and biological diversity of soil. Break crop effects have been quantified in a number of systems, with the benefits to the following wheat crop reaching 60% in some experiments in Saskatchewan and Sweden (Kirkegaard et al., 2008).

Crop diversity offers other opportunities. Fibre hemp (*Cannabis sativa* L.) can be used for industrial fibre or bioenergy, and provides reliable yields at high latitudes (Pakarinen et al., 2011). Flax (*Linum usitatissimum* L.) fibre commands premium prices in the fabric market, and the seed residue is valuable as a functional food. Microbiological diversity can be more productively exploited. In addition to appropriate rhizobium inoculants for legumes, inoculants of mycorrhizal fungi and plant growth-promoting bacteria are already on the market, although their value has yet to be demonstrated in many circumstances.

5.2 Sustainability

In the context of increasing knowledge about the releases of greenhouse gases from soil, leaching of nutrients from arable and livestock farms, and pollution of inland waterways, inputs to agriculture should clearly be managed in an appropriate fashion. This does not mean low-input or organic management, but an “ecological intensification” (a concept that has evolved in several directions since adopted by Cassman, 1999). Integrated management is a central part of this paradigm. Catch and cover crops take up nutrients in the autumn and hold them in tissues while their roots hold soil particles into the spring, thereby reducing both leaching and erosion. Grasses such as ryegrass, legumes such as clovers, and other crops including winter turnip rape, all have potential for use in this way.

Crop diversity contributes to sustainability. Legumes have several roles, including N fixation, support of H-fixing soil bacteria, release of bound soil phosphorus, and the supply of pollen and nectar to bees. Mixed clover-grass pastures require little or no N fertilizer, in contrast to the 300 kg / ha of N fertilizer that is applied to many grass pastures. Stockfeed can be produced from legume crops near the point of use, replacing soybean or other meal imported from overseas. Novel foods can also be produced from legume crops, and regionally novel legumes have been successfully introduced into boreal or nemoral agriculture, including blue lupin (*Lupinus angustifolius* L.) and lentil (*Lens culinaris* Medik.).
Oilseed brassicas are well adapted to boreal agriculture and make important contributions to sustainability that could be further enhanced, such as their potential for biofumigation of soil-borne pathogens and pests (Matthiessen & Kirkegaard, 2006). Similarly, hemp not only suppresses weeds through its ground-covering ability, shown in our experiments, but also is reputed to have allelopathic effects (Singh & Thapar, 2003).

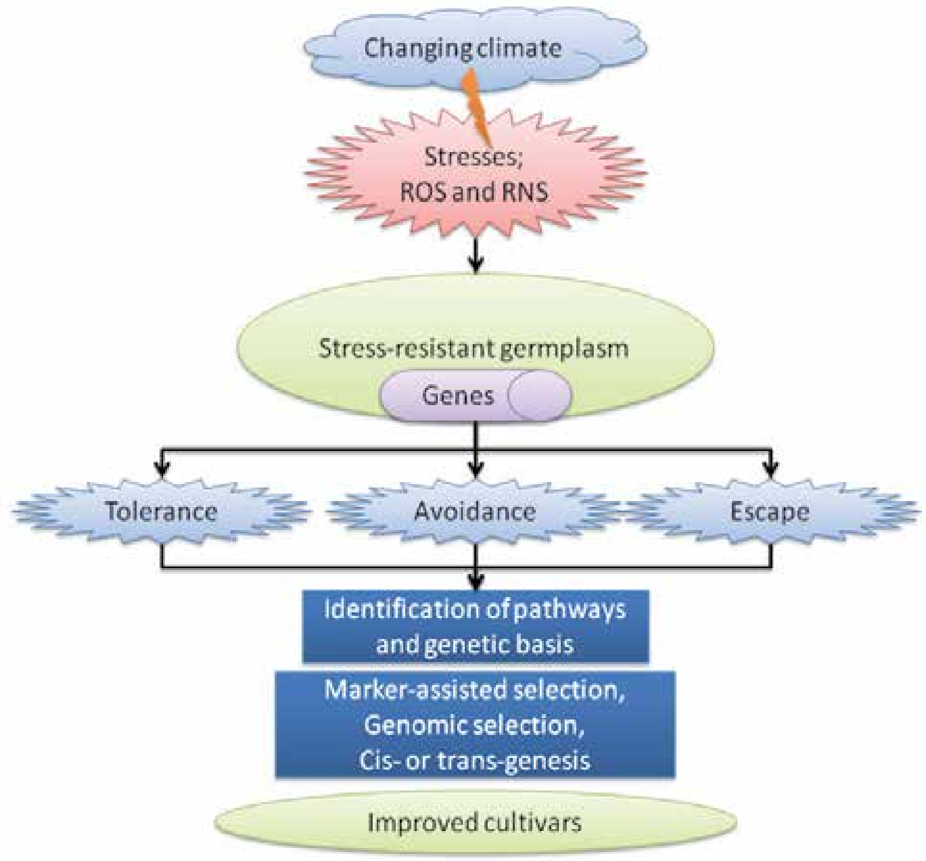

Fig. 6. Breeding of crops for the changed boreal climate requires information at different levels. Germplasm collections contain stress-resistant accessions, and the resistance may take the form of tolerance, avoidance or escape. The genetic basis of the resistance often needs to be elucidated. Modern, precise breeding technologies can then be used to produce cultivars with superior response to stressing environments.

5.3 Technology

Crop breeding has been greatly accelerated by the development and application of a range of technologies including doubled haploidy for rapid homozygosity, marker-assisted selection, genetic transformation, and comparative omics (Figure 6). Some of these technologies are expensive to implement and others are based on information such as complete gene sequences that are expensive to derive. These expenses can be prohibitive when boreal cropping is at the fringes of agriculture, with particular requirements regarding daylength and season length, and when some of the key crops, like turnip rape, are not globally important. International cooperation is necessary to ensure that progress on the regionally important crops, in the regional conditions, is made sufficiently rapidly that the region is able to capitalize on the changing climate. The development of hardier winter crops, with better tolerance to snow cover and resistance to snow mould, is a high priority.

Energy conversion technologies have a role in future boreal agriculture and will affect sustainability as well. Manure is often unproductively managed in boreal systems, but it contains both energy and valuable nutrients. Spreading of manure allows unproductive leaching of nutrients and release of methane to the atmosphere, whereas treating it in a methane digester captures the methane and some of the energy, while producing a nutrient-rich digestate that can be used as a fertilizer. Supplementing the methane digester with plant material allows capture of some of the energy from the cellulose while the lignin remains in the solid residue, potentially adding to soil carbon stocks. A high-biomass legume crop, such as annual white lupin (*Lupinus albus* L.) or perennial fodder galega (*Galega orientalis* Lam.) that can produce 14 t/ha of dry matter, can fix far more nitrogen than can be used for the following crop. By passing such a crop through a methane digester, energy can be gained, and enough nitrogen fertilizer for 3-5 times the original field area can be obtained.

Agriculture must be transformed. The rapid advances in technologies, including precision agriculture and omics sciences, can help bring the diversity required to add sustainability to boreal agricultural production in time to meet the challenges of climate change.

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Use of Perennial Grass in Grazing Systems of Southern Australia to Adapt to a Changing Climate

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1. Introduction

Grasslands and rangelands occupy over 70% of the earth's land area (Holechek et al., 2004; World Resource Institute, 2000), and are a major source of meat, milk and fibre production in the world. The rising demand for meat and milk in the past 30 – 40 years and the adverse impact from climate varibility have placed great pressure on the productive and sustainable use of grazing lands (Delgado, 2005; Nie & Norton, 2009). By 2020, it is predicted that developing countries will consume 72 m tons more meat and 152 m tons more milk compared to 2002/03 whereas developed countries' increases will be 9 and 18 m tons for meat and milk, respectively (Delgado, 2005).

Australia is the world's driest inhabited continent. Half of its total land area has an average annual rainfall (AAR) of less than 300 mm. Around 60% is used for agriculture, of which over 90% is used for grazing (Peeters, 2008). A particular feature of the continent is the high rainfall variability which makes selecting the right pasture species/cultivars, optimising pasture and grazing management and avoiding overgrazing very challenging. About 5% of Australia's grazing lands have been sown to introduced plant species and these improved pastures support a large proportion of the domestic livestock. The improved pasture species are productive and generally have high nutritive characteristics; however, their persistence is often poor due to the limited capacity to sustain a suite of varying soil, climatic and management conditions. A pasture survey in south west Victoria revealed that the majority of pastures were dominated by low-producing, 'unimproved' grass species (Quigley et al., 1992), and similar results were found in southern New South Wales (NSW; Virgona & Hildebrand, 2007).

The main perennial pasture grasses sown in southern Australia are perennial ryegrass (*Lolium perenne*), phalaris (*Phalaris aquatica*), tall fescue *(Festuca arundinaceum* syn. *Lolium arundinaceum*), and cocksfoot *(Dactylis glomerata*) (Reed, 1996). These grasses differ in their requirements of rainfall, temperature and soil type and fertility for growth, therefore have a varying degree of adaptation in different regions. Plant breeders have developed new cultivars to improve one or more attributes for each of the grasses. Agronomists working with other specialists such as animal and soil scientists have developed management systems to accommodate the expression of the attributes from the new cultivars. At present there are large variations between cultivars within each species, not to mention between species.

In rangelands and marginal land classes such as steep hill or stony country where improved perennial grasses cannot be sown or do not persist, Australian native grasses are often the dominant perennial species. Native grasses have grown and evolved in Australia for millions of years, and are generally well adapted to the soil and climatic conditions. While there has been debate on the yield and nutritive value of native grasses compared with improved exotic species, there is a general consensus that native grasses are better adapted to low fertility soils and low input farming systems that receive low and unreliable rainfall.

Climate change projections for Australia indicate increasing temperatures, varying rainfall patterns across regions, and elevated atmospheric carbon dioxide (CO_2) concentrations (CSIRO & BoM, 2007), which are likely to affect the productivity of pasture-based systems, although the overall effect is likely to vary regionally, depending on the combination of those changes (Harle et al., 2007; Howden et al., 2008; McKeon et al., 2009). The predicted long-term (up to 2070) rainfall patterns indicate a higher chance of rainfall reduction in southern than in north, central and eastern Australia (CSIRO & BoM, 2007). The rainfall reductions in southern Australia are projected to be largest in winter and spring.

Research into the responses of perennial grasses to climate, soil and management factors has long been a major target for agronomists, breeders and physiologists to improve the resistance/adaptation attributes and management of these plants. The challenge is how we can place these responses and improved attributes in a systems context and achieve production and sustainability goals in practice. This chapter discusses the past and current research on perennial grasses and their management systems that may lead to the development of adaptation strategies to climate change in southern Australia.

2. The role and performance of perennial grasses for Australian grazing industries

Historically, Australia's flora did not evolve under grazing by large groups of herbivores (Moore, 1970). Native species (predominantly native perennial grasses) were adapted to low fertility soils, periodic burning and infrequent grazing by soft-footed animals at low grazing pressures. The process of deterioration of native pastures started from the early 1800s when cloven-hoofed animals in closely managed groups were introduced. The failure of early European settlers to appreciate the consequences of the regular pattern of droughts, and the exploding rabbit population exacerbated the process. In the 1890s, severe droughts, livestock death and the demise of the pastoral resources attracted the attention of the press, governments, pastoralists and scientists, which were recognised as a major national problem. In the 1950s, widespread management change and introduction of new pasture species were made to halt pasture decline in many parts of temperate Australia. These included the introduction of temperate perennial grasses and subterranean clover (*Trifolium subterraneum*), the widespread use of phosphorus fertiliser, the formulation of policies to restrict stock numbers, and the development of economic means of rabbit control (Kemp & Michalk, 1993).

Australian native grass is a general term to describe a diverse range of grasses that have evolved in Australia for millions of years. There are about 1000 native grass species in Australia, which are well adapted to the harsh and varying climate, and play an important part in maintaining ecosystem health (Nie & Mitchell, 2006). The agronomic and environmental values of Australian native grasses were generally undervalued until recently when severe environmental problems such as dryland salinity were clearly demonstrated as being associated with the clearance of native vegetation. Studies (Dorrough et al., 2004; Eddy, 2002; Nie et al., 2005; Nie & Zollinger 2008; Waters et al., 2000) have found that native grasses not only have significant environmental value, but their agronomic characteristics such as dry matter (DM) accumulation, persistence and nutritive characteristics should also be given more objective judgement as many native species may better adapt to some environments and produce higher amounts and more nutritious feed for grazing animals than improved exotic species.

The introduction of exotic plants and animals with extensive clearing, heavy stocking and ploughing of fields led to the disappearance of most native grasslands, particularly in temperate Australia. However, this did not result in a massive increase in the coverage of grasslands by the improved species. Up to date, the proportion of Australia's grazing lands that have been sown to introduced plant species is still low (approximately 5%; Peeters, 2008), although these improved pastures support >40% of our domestic livestock (Hutchinson, 1992). Improved pastures were mainly sown in medium to high rainfall (>550 mm AAR) environments with high fertiliser and management inputs due to their lack of persistence in harsher environments.

Among the four major improved temperate perennial grasses in Australia, perennial ryegrass is most widely sown in high rainfall (>650 mm AAR) and high fertility zones (Reed, 1996). Most Australian dairy farmers operate in more heavily (compared with sheep and beef) fertilised, high rainfall or irrigated areas and rely almost exclusively on perennial ryegrass. The minimum rainfall required by the grass increases with lower latitudes (e.g. 650 mm AAR for Victoria, 700 mm for southern New South Wales, and 800 mm for northern New South Wales) and decreases with higher altitudes. Perennial ryegrass is highly nutritious, fast establishing and very productive over the growing seasons. It is well adapted to medium to heavy textured soils and generally will not persist on light soils. Drought tolerance and persistence are a limitation of the grass in comparison with other major perennial grasses (Nie et al., 2004; Slack et al., 2000).

Tall fescue and phalaris are commonly used where soils are heavy textured and waterlogging can be severe. Both species are deep rooted and generally tolerate soil moisture stress better than perennial ryegrass (Moore et al., 2006; Nie et al., 2008). They can grow and persist well in medium to high rainfall (>550 mm AAR) environments. Tall fescue has two types with distinct growth patterns, summer active and winter active, which can be used to balance the feed supply across seasons. Both types provide nutritious feed in late spring and early summer although their growth rates vary considerably between summer and winter (Moore et al., 2006). Phalaris is often sown to improve the balance of seasonal feed supply and increase stocking rate in wool and lamb production systems (Reed, 2006). It is sensitive to aluminium toxicity induced by soil acidity (pH in $CaCl_2$ < 4.2) and the use of lime is needed to aid persistence on acid soils (Reed, 2006).

Cocksfoot is well suited to free drained, light textured soils. It is useful in areas of lower rainfall, strong soil acidity and low fertility. There are three types of cocksfoot: temperate (or continental; ssp. *glomerata*), Mediterranean (or Hispanic; ssp. *hispanica*) and intermediate types (ssp. *glomerata* x *hispanica*) (Volaire and Lelièvre, 1997). Temperate and intermediate types of cocksfoot are summer active whereas Hispanic type (Spanish cocksfoot) is highly summer dormant. The Hispanic cocksfoot is one of the most drought tolerant among the perennial grass species and can grow and persist well in the Mediterranean regions which receive around 300 mm AAR (Harris et al., 2008).

Other perennial grasses such as tall wheat grass (*Thinopyrum ponticum*), perennial veldt grass (*Ehrharta calycina*), panic grasses (e.g. *Panicum maximum*) and kikuyu grass (*Pennisetum clandestinum*) are also sown in targeted regions or areas of southern Australia. For instance, tall wheat grass is tolerant of high levels of salinity and is used in saline soils where other improved perennial species will not grow (Reed, 2006). Kikuyu grass and panic grasses have been evaluated and sown on coarse-textured soils including deep sands in Western Australia (More et al., 2006).

3. Climate change and perennial pastures

Australia is the hottest and driest inhabited continent in terms of duration and intensity of heat. Temperatures above 45°C have been recorded at nearly all stations more than 150 km from the coast and at many places on the north-west and southern coasts (NATMAP, 1986). Half of Australia's total land area has an average annual rainfall of less than 300 mm and about 80% has less than 600 mm (Fig. 1). In southern Australia, whether in the Mediterranean or temperate environments, rainfall is often winter dominant and highly variable, with frequent droughts lasting up to several seasons.

The main climate change variables that are likely to be important in their impact on perennial grass growth and survival are temperature, rainfall and the concentration of CO_2 in the atmosphere (Cullen et al., 2009; Howden et al., 2008). Since 1910 the average maximum and minimum temperature in Australia have risen by 0.7°C and 1.1°C, respectively (Alexander et al., 2007) and this trend is predicted to continue at higher rates in the next 50 – 70 years (Hennessy et al., 2007). The average annual temperature is projected to rise between 0.4 and 2°C over most of Australia by 2030, with an accompanying increase in the likelihood of extreme hot and wet days (Harle et al., 2007). Potential evaporation (or evaporative demand) is also likely to increase with increasing temperatures.

Annual rainfall in southern Australia has dropped since 1950 (Smith 2004). Predicted further reductions in rainfall together with the increases in evaporation are anticipated to result in up to 20% more droughts by 2030 (Mpelasoka et al., 2007). Projected changes in seasonal rainfall by 2030 range from -20% to +5% for spring rainfall in the southwest high rainfall zone to -5% to +15% for autumn rainfall in the south-eastern wheat-sheep zone (Harle et al., 2007). The most pronounced decreases are predicted for winter and spring, although some coastal areas of the high rainfall zone may become wetter in summer, and some areas of the eastern sheep-wheat zone may become wetter in autumn.

The International Panel on Climate Change projections for the atmospheric CO_2 concentration in the year 2030 range from 400 to 480 ppm, compared to about 280 ppm in the pre-industrial era and 380 ppm currently (Cullen et al., 2009; Harle et al., 2007). The breadth of this range is due to uncertainties associated with different socio-economic assumptions in greenhouse gas emission scenarios, the carbon removal processes (carbon sinks) and the magnitude of climate feedback on the terrestrial biosphere.

The climate change that has been observed in Australia and the likely trend of further changes have shown significant impacts on the grazing industries and the need to develop pasture plants and grazing systems to address the issues (Cullen et al., 2009). While the changes in temperature and rainfall generally have a negative impact on perennial grass growth and survival, the elevated atmospheric CO_2 concentration could promote pasture growth in the absence of other climate changes (Wand et al., 1999). Cullen et al. (2009) predicted a 22 – 37% increase in dry matter (DM) production of temperate grass dominated pastures in southern Australia, simulated by raising the atmospheric CO_2 from 380 to 550 ppm. These increases will be affected by pasture species (e.g. C_3 vs C_4 grasses) and soil nutrients (Long et al., 2004; Lüsher et al., 2006).

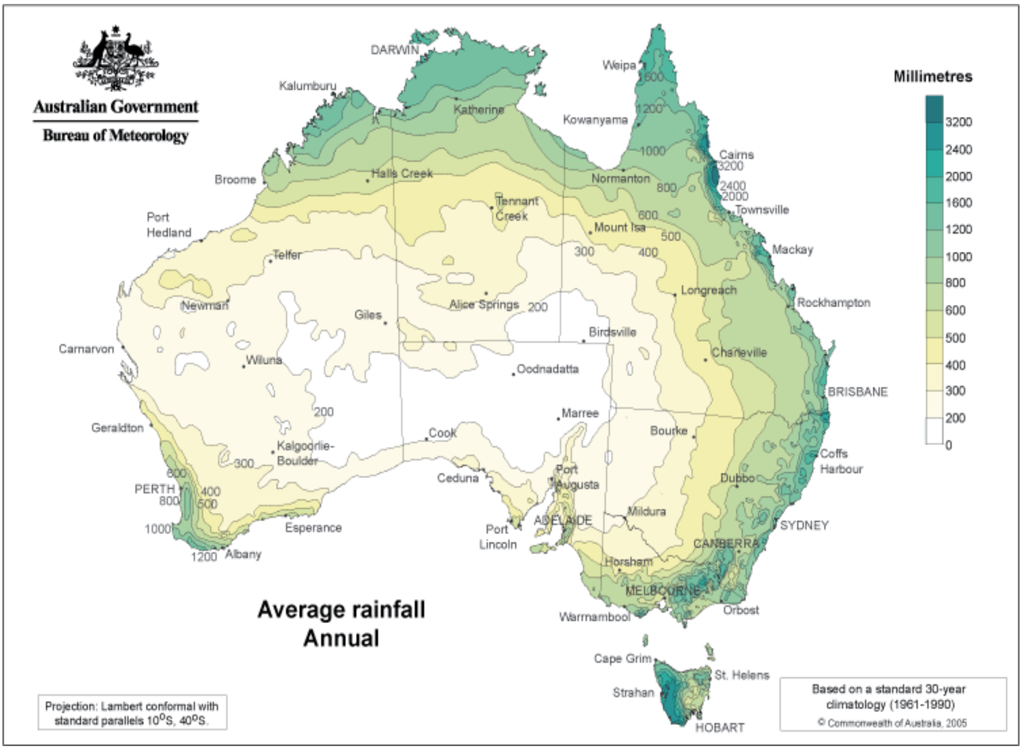

Fig. 1. Rainfall distribution in Australia (Australian Government Bureau of Meteorology Climate Data Online; copyright Commonwealth of Australia reproduced by permission; adapted from Nie & Norton, 2009).

The biggest concerns associated with climate change for Australian grazing industries are the negative impacts of changes in rainfall and temperature which have already been a long-term challenge to ensure sustainability in pasture and animal production. The more extreme temperatures and the reduced and more variable rainfall predicted in southern Australia are likely to shorten the growing season, reduce pasture yield and nutritive value (Harle et al., 2007), and more importantly impose a higher risk for the perennial species to survive and persist (Nie & Norton, 2009). It is therefore imperative to understand the potential role that perennial plants, particularly perennial grasses, can play in a changing climate and develop adaptive strategies and systems that can deliver sustainability as well as profitability for the livestock industries.

4. The adaptive traits of perennial grasses to moisture and heat stress

Rainfall reduction and more extreme temperatures are the two most significant features of the current climate change and projections for future change that could adversely affect temperate perennial grasses in southern Australia. Decline of sown grass species has already been common in most pastures, because of their poor adaptation to the more severe and more variable climatic conditions (Beattie, 1994). A pasture survey in south west Victoria revealed the majority of pastures were dominated by low-producing, 'unimproved' grass species (Quigley et al., 1992). Similar results were also found in southern New South Wales (Virgona & Hildebrand, 2007). In native pastures, perennial species are predominantly native grasses which are often low in botanical composition due to climate, soil nutrient and management constraints (Garden et al., 2001; Nie et al., 2005).

In response to soil moisture and heat stress, perennial grasses have developed adaptive traits in order to survive under stressful environment conditions. Major traits that have shown to increase the resistance of perennial grass plants to drought and hot weather include rooting depth and summer dormancy. Other traits such as water-soluble carbohydrate (WSC) concentrations in tiller bases may also be beneficial in improving drought tolerance (Volaire & Lelièvre, 1997). Research into these traits or other mechanisms to support plant resistance has been limited to a small number of the species/cultivars. Further research is needed to have a better understanding of these traits for a wider range of grasses and to find or develop more adaptive traits.

4.1 Rooting depth

Rooting depth is a trait that contributes to a species overall strategy of response to water stress. It determines the accessibility of a plant to moisture in the soil profile, which is particularly important for perennial species in avoiding dehydration and coping with environmental stress (water and nutrient deficiency) across seasons, years and landscapes (Levitt, 1980; Nie et al., 2008; White et al., 2003). Therefore, the benefits of deep roots in perennial grasses are expressed and become more critical when plants encounter severe moisture stress.

Rooting depth of perennial grasses are generally much greater than annual grasses (Lolicato, 2000), and can vary dramatically between species, and between the environments in which they are grown. In a study to investigate the performance of a range of perennial grasses in southern Australia (Nie et al., 2008), rooting depth of 11 temperate perennial grasses and one cultivar of kikuyu grass (*Pennisetum clandestinum* cv. Whittet) was measured at two sites (Hamilton and Warrak in western Victoria, Australia) contrasting in rainfall, soil type and slope (Table 1; Reed et al., 2008). The cultivar with the deepest root system (up to 2 m) was Whittet kikuyu grass, followed by phalaris and tall fescue cultivars (rooting depths between 1.12 and 1.5 m at Hamilton and 0.84 and 0.96 m at Warrak). Interestingly, cocksfoot was the lowest in rooting depth at Hamilton, but higher than perennial ryegrass at Warrak, a site with shallower soil and lower rainfall than Hamilton. Mean rooting depth across all species was 1.3 m at Hamilton (ranging from 0.9 to 2.01 m) and 0.9 m at Warrak (ranging from 0.75 to 1.27 m) (Table 1). The differences were associated with differences in rainfall, soil structure and fertility between the two sites (Nie et al., 2008). Hamilton had the higher rainfall over the experimental period and higher soil fertility, which allowed plants to develop roots under less moisture stress and lower nutrient deficiency. The compacted stony–gravel conglomerate layer in the subsoil at Warrak may have also contributed to a more shallow root system.

Field studies to quantify the relationship between rooting depth and persistence in perennial grasses are always challenging, not only because persistence can be affected by many factors (Nie et al., 2004), but also the survival mechanisms of different species vary between species and between cultivars within a species. Nevertheless, regression analysis

Species	Cultivar	Hamilton	Warrak	Mean
Phalaris aquatica	Australian	1.50	0.88	1.19
P. aquatica	Atlas PG	1.49	0.84	1.16
P. aquatica	Holdfast	1.12	0.94	1.03
P. aquatica	Landmaster	1.47	1.11	1.29
Dactylis glomerata	Currie	0.93	0.81	0.87
D. glomerata	Porto	0.90	0.92	0.91
Festuca arundinaceum	Fraydo	1.28	0.89	1.09
F. arundinaceum	Resolute MaxP	1.43	0.91	1.17
F. arundinaceum	AU Triumph	1.39	0.96	1.18
Lolium perenne	AVH 4	1.05	0.76	0.90
L. perenne	Avalon	1.24	0.75	0.99
Pennisetum clandestinum	Whittet	2.01	1.27	1.64

Table 1. Means of rooting depth (m) for various pasture cultivars at Hamilton and Warrak in March 2005 (Nie et al., 2008).

on the data collected over 4 years from the above experiment has shown a positive relationship between rooting depth of the perennial grasses and their persistence (expressed as %change of plant frequency from year 2 to year 4) for most perennial grasses tested except two cultivars, Atlas PG phalaris and Currie cocksfoot at the Warrak site (Fig. 2). However, there was no clear relationship between the two attributes for the same species and cultivar at the Hamilton site, presumably due to the large differences in rainfall, soil and topography between the two sites. The Hamilton site was flat with Brown Chromosol soil and mean annual rainfall of 640 mm (ranging from 523 to 750 mm) whereas the Warrak site was on a slope with Red Kurosol soil and mean annual rainfall of 480 mm (ranging from 438 to 525 mm) over the 4-year (2002 – 2005) experimental period (Reed et al., 2008). The harsher environmental conditions at Warrak allowed the expression of the deep rooting merits of the perennial grasses. Atlas PG phalaris and Currie cocksfoot did not fit well with the regression analysis of the Warrak data, probably because they have different survival mechanisms under water stress. For instance, Volaire and Lelievre (2001) observed that Currie cocksfoot had the ability to continue extraction of soil water at low levels of available soil moisture, suggesting this as a significant factor in its survival under prolonged drought.

Apparently increased rooting depth can also improve pasture growth rate and production due to higher accessibility to soil moisture/nutrients and dehydration avoidance under water deficit. Cullen et al. (2009) compared the pasture growth rate and yield between two rooting depths (0.4 vs 0.6 m) by modelling a high greenhouse gas emission scenario in 2070 in a high rainfall perennial grass-based pasture environment of southern Australia. The 2070 climate change projections for the site are 3.3°C increase in temperature and 22% reduction in rainfall in comparison to a 30-year (1971-2000) historical baseline climate. Mean predicted total annual pasture production increased from 10.5 t DM/ha at a rooting depth of 0.4 m to 11.6 t DM/ha at a rooting depth of 0.6 m, largely due to extended growing season and increased growth rate (an increase of 10 kg DM/ha.day) in spring (Fig. 3). The pasture yields were lower than the baseline simulation at a rooting depth of 0.4 m (12.9 t DM/ha). With the deeper root system, the predicted mean annual drainage was reduced from 270 to 252 mm.

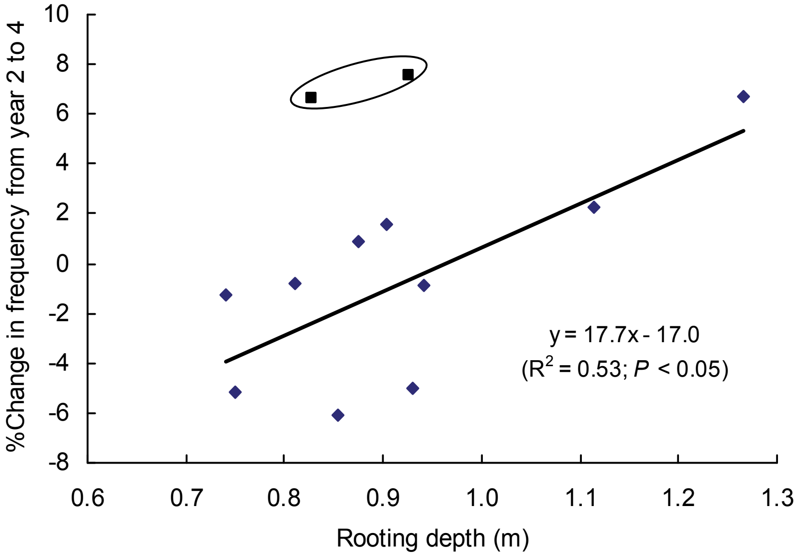

Fig. 2. The relationship between rooting depth and persistence expressed as percentage change in perennial grass frequency from year 2 to year 4 in a perennial grass (see Table 1 for cultivar list) evaluation experiment at Warrak, Victoria, Australia (circled dots are Atlas PG phalaris and Currie cocksfoot; data source: Nie et al., 2008).

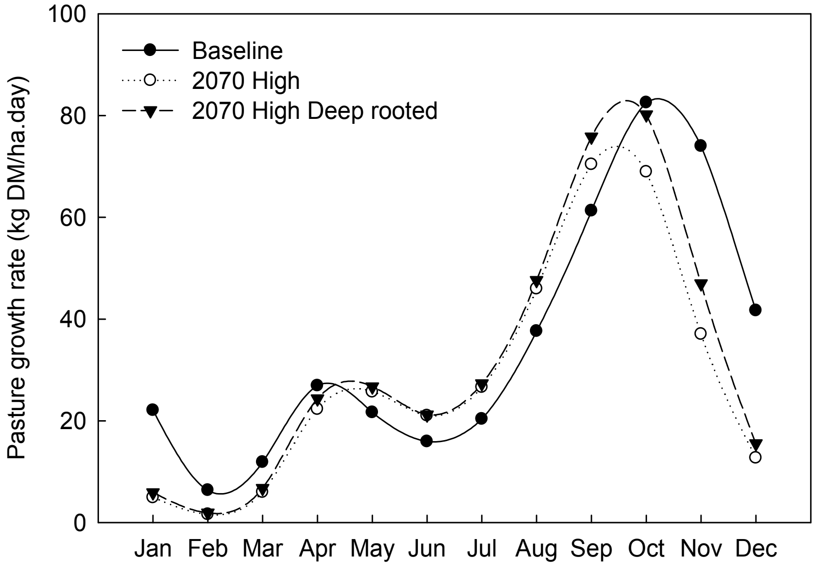

Fig. 3. Predicted pasture growth rate (kg DM/ha.day) at rooting depths of 0.4 m (2070 High) and 0.6 m (2070 High Deep rooted) in a 2070 High climate scenario, and at a depth of 0.4 m in the baseline climate scenario in a high rainfall environment of southern Australia (Adapted from Cullen et al., 2009).

4.2 Summer dormancy

Summer dormancy is an adaptive response of perennial grasses to water and heat stress over summer, which is believed to play a significant role in promoting drought resistance for temperate perennial grasses (Reed et al., 2004; Volaire & Norton, 2006). The mechanisms comprising the summer dormancy trait, the history of the concept and research into dormancy as well as an explanation of how summer dormancy are associated with survival have been reviewed by Volaire & Norton (2006). Based on a set of field protocols and four types of responses – leaf growth in summer, senescence of mature herbage, dehydration of enclosed bases of the youngest leaves and formation of resting organs, they grouped temperate perennial grasses into three distinguished populations: 1) population that maintain active growth under irrigation; 2) population that cease growth completely for a minimum of 4 weeks during summer and 3) population that exhibit reduced growth, associated with partial senescence of foliage, but no dehydration of leaf bases (Volaire and Norton, 2006). These classifications are more or less associated with the terms that are commonly used for temperate grasses – summer active, summer dormant and summer semi-dormant.

Many studies on summer dormancy trait have been focused on cocksfoot, which has relatively shallower roots, but persists well when grown on stressful soils (light textured) with frequent droughts. In the 1950s, Knight (1960) undertook early studies with a range of cocksfoots of Mediterranean and northern European origin to identify the characteristic signs (e.g. foliage senescence and cessation of growth) of summer dormancy in Mediterranean populations. The results showed that the Mediterranean germplasm had markedly better summer drought survival than the northern European genotypes (Knight, 1960 and 1966). Further studies by Biddiscombe et al. (1977) broadened the range of species and included perennial ryegrass, phalaris and tall fescue as well as cocksfoot. They assessed the effect of summer dormancy on growth and persistence of these species in south-western Western Australia.

Dormancy level in the studies (Biddiscombe et al., 1977) was measured by the ratio, number of new shoots per plant : number of live buds per plant, 12 days after removal of plants in the field and rewatering in late summer (February). The ratio indicated the level of live buds that became active after summer drought – the higher the ratio, the less dormant is the plant. The results from a drier site on a sandy soil showed a strong negative exponential relationship ($R^2 = 0.94$; $P < 0.01$) between summer dormancy ratio and plant survival in the final year (Year 4) (Fig. 4). All cocksfoot and phalaris lines had higher survival rates than the perennial ryegrass lines. Interestingly, the 3 tall fescue lines varied dramatically in final year plant survival, i.e. the cultivar Melik had > 70% of plant survival whereas the other two lines had < 35%. Melik is a highly winter-active cultivar of tall fescue (Reed et al., 2004) whereas the two other lines are summer active. Like rooting depth, summer dormancy did not show benefits on plant survival at a high rainfall site (annual rainfall 1120 mm) in this study.

There has been less information on summer dormancy in tall fescue. Norton et al. (2006) tested two contrasting cultivars of tall fescue, Demeter and Flecha, under drought, full irrigation and simulated mid-summer storm. Though not expressing as high a level of dormancy as was seen in the earlier research with cocksfoot, Flecha exhibited responses associated with partial summer dormancy and used less soil water over summer which helped it to fully survive a severe summer drought and produce a higher post-drought

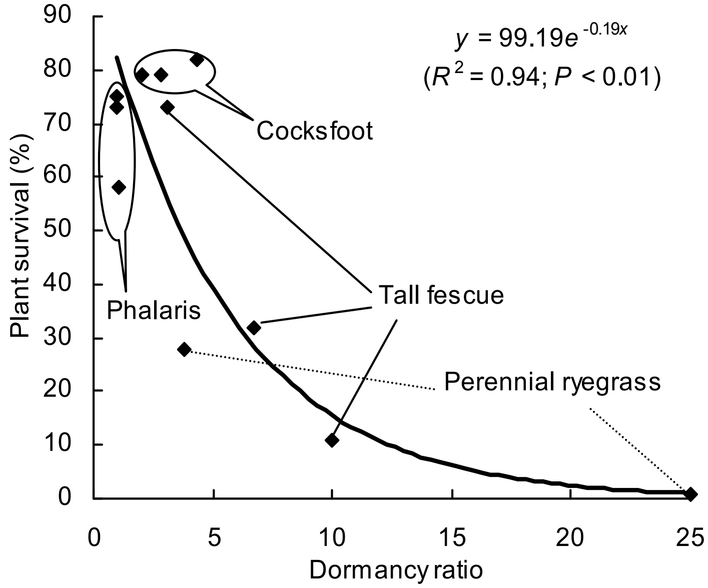

Fig. 4. The relationship between dormancy ratio and plant survival four years after establishment (Data source: Biddiscombe et al., 1977).

autumn yield. In contrast, the summer-active Demeter suffered a 25% loss in basal cover. Just as in the dormant cocksfoot, a high and stable level of dehydrins was observed in Flecha, which may be associated with a membrane stabilising role that these proteins play during drought. Information on summer dormancy in most other perennial grasses in Australia is severely lacking. There is also a trade-off between summer dormancy and herbage production since complete dormancy has been associated mostly with populations of low yield potential (Volaire & Norton, 2006).

4.3 Other traits and mechanisms

Water-soluble carbohydrates provide the most readily available source of energy for grazing animals, and increased WSC concentrations in herbage are considered as an option to alleviate the seasonal deficiencies in the nutritive value of perennial ryegrass (Smith et al., 1998). Apart from their role as nutrients, WSC may have a role in plants' response to drought. Volaire & Lelièvre (1997) found that the total WSC reserves in leaf bases of cocksfoot plants increased by 35% on average during drought. Fructans are the most abundant WSC in some perennial grasses such as cocksfoot and tall fescue, which differ in the degree of polymerisation (DP). High DP fructans are likely to constitute a pool of reserves that is used as substrate as soon as rewatering occurs after moisture stress (Volaire, 1994, 1995). Plants that are adapted to moisture stress (e.g. some of the cocksfoot lines) tend to orientate their metabolism and enzymatic activity towards the constitution of a reserve pool of high DP fructans as soon as drought is imposed (Volaire & Lelièvre, 1997). High DP fructan concentrations are also known to increase in the pseudostem of the perennial ryegrass during drought (Thomas, 1991). The high WSC perennial ryegrass cultivar Aurora had high growth and yield stability during drought and good regrowth after drought (Amin & Thomas, 1996).

Perennial grass plants exhibit different leaf morphological traits which, although more qualitative than quantitative, may well contribute to dehydration avoidance under moisture stress. Bolger et al. (2005) studied a range of native and introduced perennial grasses of south-eastern Australia and observed that the grasses showed different leaf morphological traits at 3 distinct stages of soil drying and plant dehydration. The 3 stages are: Stage I – water is freely available and transpiration from plants leaves remains unaffected as soil water declines; Stage II – soil water availability begins to limit plant uptake, and plant transpiration declines progressively with declining available soil water; Stage III – plant transpiration and stomatal conductance have reached minimal levels, water loss from the plant is constrained and leaves die. In their observation (Bolger et al., 2005), cocksfoot and Kangaroo grass (*Themeda* spp.) folded their leaves whereas wallaby grass (*Austrodanthonia caespitosa*) and *Eragrostis* tightly rolled their leaves at the beginning of Stage III. In contrast, red grass (*Bothriochloa* spp.) and phalaris rapidly shed most of their leaves at the beginning of Stage III, a 'plastic' response reducing leaf area and water loss and thereby contributing to dehydration avoidance. Species such as *A. racemosa* did not fold, roll, or shed leaves rapidly at the beginning of Stage III, but accumulated a large amount of cuticular wax on leaves to reduce water loss. A. *caespitose* rolled its leaves and had a large amount of cuticular wax as well.

An important mechanism that is believed to contribute to the stress tolerance and persistence of perennial ryegrass and tall fescue is the mutualistic association between the perennial grasses and the asymptomatic fungal endophytes, *Neotyphodium lolii* (Latch, Christensen and Samuels) Glenn, Bacon and Hanlin (formerly *Acremonium lolii* Latch, Christensen and Samuels) in perennial ryegrass and *N. coenophialum* (Morgan, Jones and Gams) Glenn, Bacon and Hanlin in tall fescue (Heeswijck & McDonald, 1992; Quigley, 2000). Endophytes can produce alkaloids, of which ergovaline, lolitrem B, and peramine are the most important and therefore have commonly been studied (Rowan et al., 1986). Ergovaline and lolitrem B are toxic to grazing livestock, whereas peramine deters insect attack but has no known effect on domestic animals (Gallagher et al., 1984). The role of endophytes in protecting their grass hosts from insect attack was first reported by Prestidge et al. (1982) in New Zealand, and later in Australia (Heeswijck and McDonald, 1992). Improved resistance of endophyte-infected perennial ryegrass to insects has provided a graphic demonstration of the benefits that endophytes can confer on their host plant. Studies (Heeswijck & McDonald, 1992; Hill et al., 1990; Reed et al., 1985) of the effects on other plant attributes such as seedling establishment and tolerance to water stress showed that the performance of the perennial grasses was enhanced by increased levels of endophyte infection. The greater tolerance of endophyte-infected grasses to drought may result from the effect of the fungus on host-water relations, and it has been suggested that improved osmotic adjustment and turgor maintenance in the basal meristematic and elongating zone of vegetative tillers are involved (West et al., 1990*)*. More information is needed to verify how and to what degree endophytes can contribute to drought tolerance and plant survival in varying environmental conditions. A study by Pecetti et al. (2007) showed that the effect of endophyte presence on persistence was nil in the Mediterranean site and slightly positive in the subcontinental location. They concluded that Mediterranean conditions may be too extreme for any enhancement of persistence to be solely provided by the endophyte, and the physiological adaptation of the grass germplasm was more critical for these environments. The development of novel endophytes in the past decades have aimed to strengthen the ability of endophyte-infected perennial grasses in stress tolerance and resistance to insect attack and reduce toxicity to grazing animals.

5. Development of new perennial grasses

Selection for greater seasonal and yearly productivity, higher nutritive value and lower establishment costs has long been the key breeding objectives for perennial temperate grasses in southern Australia (Oram & Lodge, 2003). This continues to be the major focus in perennial ryegrass improvement for dairy pastures. Over the past decade, however, emphasis has been placed on persistence, adaptation to a wider range of soil conditions, lower toxicity, greater compatibility with legumes, and resistance to pests and diseases, particularly for extensive sheep and cattle grazing pastures due to the changes of climatic conditions experienced in the regions. Waller & Sale (2001) reviewed the persistence problems encountered by perennial ryegrass and concluded that grazing management to encourage seedling recruitment, better genotypes and improved management of soil fertility and pH would be beneficial for high survival of the species. Attempts have also been made to introduce drought resistant traits from natural ryegrass populations persisted in marginal rainfall environments or genes from other persistent plant species such as tall fescue (Humphreys & Pasakinskiene, 1996; Humphreys & Thoma, 1993; Oram & Lodge, 2003).

While perennial ryegrass is highly valuable in establishment, production and feed quality for livestock, it is not generally considered a suitable plant for low rainfall environments in southern Australia. Indeed there are few cultivars of any temperate perennial grasses commercially available for farmers in temperate regions that receive <500 mm annual rainfall (Harris et al., 2008; Reed, 1996). Therefore, attempts have been made to introduce and incorporate genes from plants of low rainfall origin, such as the Mediterranean and North Africa. Australia was one of the first countries to deliberately exploit Mediterranean ecotypes of perennial grasses, due to climatic similarities, the value of pasture plants from the regions and the discovery and domestication of the Mediterranean grass phalaris (Culvenor, 2009; Oram et al., 2009). The adaptation of the perennial temperate grasses into lower rainfall environments has been substantially expanded in Australia by the replacement of early northern European introductions with more drought-hardy and summer-dormant germplasm from Mediterranean regions (Culvenor, 2009). A number of cultivars based on Mediterranean ecotypes were released during the 1950s to the 1970s. For example, Sirocco phalaris was released after selection of a Moroccan accession for seed production (Oram, 1990). Currie cocksfoot selected from an Algerian accession was released in 1958.

Recent emphasis on persistence under low and variable rainfall conditions in southern Australia has seen an increased exploitation of more summer-dormant *hispanic* cocksfoot germplasm. Two new commercial cultivars, Sendace and Uplands, based on *hispanica* accessions collected in Spain were released for drought-prone environments (Hurst and Hall, 2005a,b). More recently (2004 – 2008), work has been conducted in Victoria and northern NSW, to develop improved cultivars of cocksfoot and tall fescue for medium to low rainfall environments of southern Australia. Four elite cocksfoot lines of fine- to very fine-leaved *hispanic* type were developed for further evaluation (Harris et al., 2008). These lines showed excellent persistence and yielded 34 to 40% higher than Currie, the commonly sown cocksfoot cultivar, following a severe summer drought period in 2006 (e.g. 270 mm annual rainfall at a site in Victoria). Experimental varieties of tall fescue based on Sardinian accessions with good summer and winter production and persistence, and a separate variety based on northern African accessions that were highly persistent but retained green leaf over summer on the North-West Slopes of NSW, were also selected in this project (Harris et al., 2008). Further evaluation of these lines has been undertaken to verify their adaptation and persistence across multiple regions in Victoria and NSW.

6. Deferred grazing strategies to improve the resilience of Australian native grasses

Recent recognition of the value of native grass pastures, and their drought resistance and ability to grow in infertile or acidic soils, has led to the selection and release of cultivars in several species (Garden et al., 1996; Lodge, 1996; Oram & Lodge, 2003). In practice, however, native grasses have been largely ignored for sown pastures in Australia, because of the superiority of exotic improved grasses in high-input livestock grazing systems, the biased comparisons of native and introduced pastures (Johnston et al., 1999), and the difficulties in achieving large-scale seed production and successful pasture establishment of native grasses. Native grasses are primarily distributed in areas with low fertility and acidic soils and marginal land classes such as steep hill country where overgrazing, land degradation and climate change impacts have resulted in low groundcover by pasture plant over summer and autumn. These not only have a significant economic (e.g. lack of green feed and low stocking rate) but also environmental impact (e.g. soil/nutrient runoff, recharge and loss of biodiversity) on the grazing industries in southern Australia (Nie et al., 2009).

While it is not currently practical to sow native grasses on a large scale, it is beneficial and critical to develop management strategies to rehabilitate degraded native pastures where native grass population is low (<30%). Over the past decades, a number of studies (e.g. Garden et al., 2000; Nie & Zollinger, 2008) have been undertaken in southern Australia to look into management strategies, grazing management in particular, for the restoration of native grasses. The studies have been focused on three mechanisms that can lead to success: 1) seedling recruitment of native grasses; 2) spread of existing native grass plants; and 3) stronger competition of native grasses with other species (either through seeds or plants). A management option that can promote one or all of the three is deferred grazing that matches the timing of grazing or resting of a pasture to an appropriate growth stage of the pasture grasses (Nie & Mitchell, 2006). For instance, withholding grazing from mid-spring to mid-summer allows desirable perennial plants to set seed and conserve energy, leading to higher recruitment rates of new plants and tillers in autumn and winter. Grazing heavily after annual grass stem elongation but before seed head emergence, followed by resting over spring and summer, will increase the amount of seed produced by perennials while reducing the seed by annuals. A series of experiments have been conducted to develop deferred grazing strategies for native grass restoration on marginal land classes (Nie & Mitchell, 2006; Nie & Zollinger, 2008; Nie et al., 2009). Key results are summarised below.

6.1 Types of deferred grazing

There are several types of deferred grazing which have been designed to achieve different management targets (Nie & Mitchell, 2006). The higher the proportion of desirable native species, the more effective the deferred grazing will be in the restoration process.

6.1.1 Long-term deferred grazing

Long-term deferred grazing involves no defoliation from October to the autumn break (the first significant rainfall event of the autumn/winter growing season) in the following year to build up the soil seed reserves and moisture and restore ground cover by perennial species. This strategy aims to rehabilitate degraded paddocks with low percentage of perennial species (e.g. 5-10%) quickly and effectively.

6.1.2 Short-term deferred grazing

Short-term deferred grazing involves no defoliation between October and January each year, aiming to increase soil seed reserves and plant population density, and to use feed in mid summer when there is generally a feed shortage. In addition, this treatment may reduce fire risk by grazing long grasses down in early summer.

6.1.3 Optimised deferred grazing

With optimised deferred grazing, the withholding time from grazing depends on morphological development of the pasture plants. This deferred grazing starts after annual grass stems elongate but before seed heads emerge so that the growing points of annual grass plants can be effectively removed by grazing. The completion of this grazing strategy depends on pasture conditions (seed set, growth and herbage on offer), generally from late summer to early autumn. This strategy aims to reduce the amount of seed produced by annual grasses and alter pasture composition – lifting the proportion of perennials while suppressing the annual grasses through seed production.

6.1.4 Timed grazing

Timed grazing is an alternative form of the long-term deferred grazing. It is used to build up the soil seed reserve, restore ground cover and recruit new plants. Pasture is grazed using a large mob of sheep greater than 100 sheep/ha over a short grazing period ranging from 10 to 20 days depending on size of paddock, followed by a resting period up to 130 days. This strategy targets the rehabilitation of much degraded paddocks with a very low percentage of desirable species (e.g. ~5%).

In addition, strategic management of pastures can be combined with all types of deferred grazing to deliver the best outcomes. This is often referred to as strategic deferred grazing. For instance, onion grass (*Romulea rosea*) control and fertiliser application can be applied following optimised deferred grazing in an onion grass infested paddock, which may greatly increase the yield and nutritive value of pastures.

6.2 Key impacts of deferred grazing

6.2.1 Soil seed reserve

Soil seed reserve is the number of seeds in topsoil (0 – 3 cm) measured in autumn (Nie & Mitchell, 2006). It is an indication of seed production from a grazing system in the previous seasons. The germinated seed population (an estimation of soil seed reserve) of perennial and annual grasses, two major species categories in a hill pasture, varied greatly under different grazing regimes (Fig. 5). Long-term, short-term and optimised deferred grazing produced 637 – 1850 perennial grass seeds/m^2 whereas set stocking had 570 seeds/m^2. Optimised deferred grazing was the most effective treatment to reduce annual grass seed production, with the germinated seed population being the lowest among the other grazing regimes.

6.2.2 Plant density

The results from a long-term grazing experiment (Nie & Mitchell, 2006) have shown that deferred grazing regimes significantly increased perennial (predominantly native grasses) and reduced annual grass tiller density (Table 2). However, there were no significant differences in the densities of onion grass, legumes and broadleaf weeds.

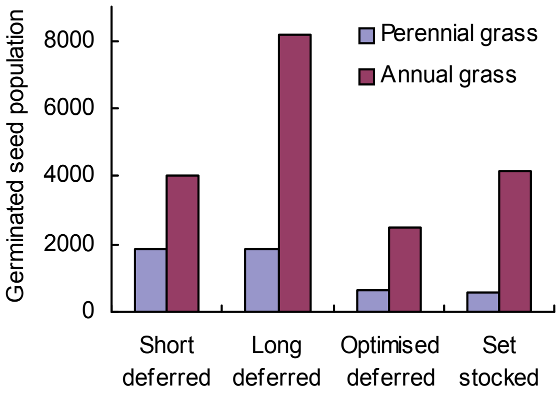

Fig. 5. Germinated seed population (seeds/m^2) under short-term, long-term and optimised deferred grazing and set stocking (adapted from Nie & Mitchell, 2006).

Treatment	PG	AG	ONG	Legume	Weed
Short deferred	8338	5396	3159	630	466
Long deferred	9003	4713	3552	460	239
Optimised deferred	9998	2558	3800	411	245
Set stocked	6245	8890	4786	681	248

Table 2. Mean plant density (tillers or plants/m^2) of perennial grass (PG), annual grass (AG), onion grass (ONG), legume and broadleaf weed (Weed), under different grazing regimes from a 4-year grazing experiment (adapted from Nie & Mitchell, 2006).

6.2.3 Ground cover

Ground cover remained greater than 70% up to mid January regardless of how the pasture was grazed (Fig. 6). However, when a large amount of dead annual grass under set stocking was removed by grazing from January to March, ground cover declined dramatically, before increasing in autumn (April/May) after some rainfall. Ground cover was consistently higher with all deferred grazing regimes due to limitation of grazing over summer/autumn and increased perennial native grass population (Nie et al., 2005).

6.2.4 Herbage and animal production

Herbage production under deferred grazing regimes increased by 31 – 66% compared with set stocking, two years after deferred grazing regimes were implemented (Table 3). Overall, deferred grazing treatments increased dry matter digestibility (DMD), crude protein content (CP) and metablisable energy (ME), but reduced neutral detergent fibre (NDF), in comparison with set stocking. The increases range from 2 – 13% for DMD, 10 – 30% for CP and 4 – 18% for ME. Short-term and long-term deferred grazing reduced NDF by 7% and 3%, respectively, but optimised deferred grazing did not, compared with set stocking. The results largely came from increased density and ground cover by perennial native grasses under deferred grazing (Nie & Mitchell, 2006). An economic analysis on deferred grazing and other grazing regimes revealed that this management strategy can conservatively increase stocking rates by between 25 to 50% within 3 years on hill country currently carrying less than 8 DSE/ha (J Moll Pers. Comm.).

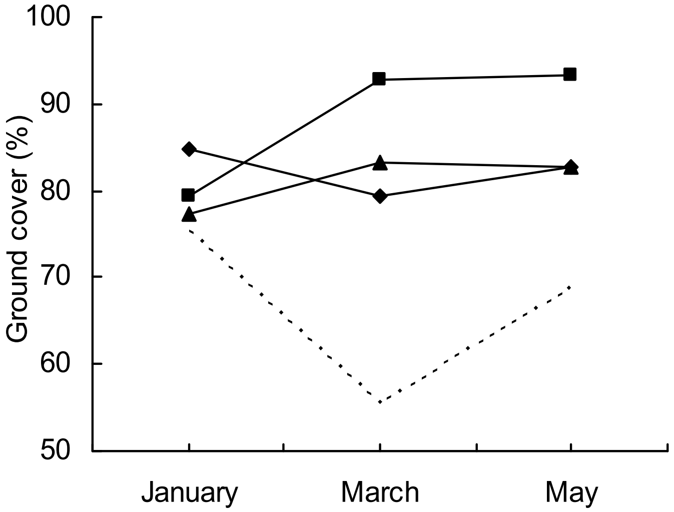

Fig. 6. Ground cover over summer/autumn under short-term deferred grazing (■), long-term deferred grazing (♦), optimised deferred grazing (▲) and set stocking (--) (adapted from Nie et al. 2005).

Treatment	HA	DMD	CP	ME	NDF
Short-term deferred	3500	59.1	12.7	8.6	62.0
Long-term deferred	4141	56.0	11.1	8.0	64.5
Optimised deferred	4433	53.4	10.8	7.6	66.8
Set stocking	2662	52.2	9.8	7.3	66.5

Table 3. Herbage accumulation (HA, kg DM/ha) from July 2005 – July 2006 and mean nutritive value: DMD – dry matter digestibility (%); CP – crude protein (%); ME - metabolisable energy (MJ/kg DM); and NDF - neutral detergent fibre (%) under various grazing regimes (adapted from Nie & Zollinger, 2008).

6.2.5 Plant roots and soil properties

Deferred grazing has a profound effect on below ground plant growth. Root biomass under deferred grazing was increased deeper in the 0-60 cm soil profile compared with set stocking (Nie et al., 1997). With deferred grazing, about 85% of the roots were in the 0-20 cm soil and 15% in the 20-60 cm soil whereas under set stocking over 95% of the total root biomass was in the 0-20 cm soil profile, and only <5% was within 20-60 cm profile. The effect of grazing wet soils has been recognised as a potential problem for soil health. Stock treading has been shown to increase soil compaction and decrease soil porosity and water infiltration. Management options to reverse compaction without cultivation are desirable. Deferred grazing can reduce soil bulk density by over 10%, increase soil pore size and water movement rate through the removal of stock treading, the growth and subsequent decay of plant roots and the activity of soil fauna, such as earthworms. It also increased the soil moisture content of the 0-10 cm of topsoil (Nie et al., 1997).

7. Conclusion

The significantly lower annual rainfall experienced in southern Australia over the past decade together with long term climate change projections have placed great emphasis on the use of pastures for the grazing industries that are more tolerant to drought and heat stress and persistent under varying climatic and soil conditions. Perennial temperate grasses, both improved exotic and native species, are the key components of pastures for livestock grazing in southern Australia. The four commonly sown improved perennial grasses, perennial ryegrass, phalaris, tall fescue and cocksfoot possess intrinsic traits, have different growth patterns and require suitable environmental conditions to be productive and persistent. Adaptive traits such as rooting depth and summer dormancy have been exploited to develop new cultivars; however, the research has been focused on limited traits and species (e.g. summer dormancy for cocksfoot) and there is a need to expand the breadth of research in term of species, their adaptive traits and technologies to define the traits. Unlike improved exotic perennial grasses, there has been little research on the adaptive traits and plant development for Australian native grasses, although they have evolved in Australia for millions of years and are well adapted to the soil and climate. Nevertheless, recent studies in southern Australia have developed grazing management strategies to restore degraded native pastures. The results have demonstrated the economical and environmental benefits of using deferred grazing to rejuvenate native grasses to adapt to edaphically and climatically stressed landscapes.

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Global and Local Effect of Increasing Land Surface Albedo as a Geo-Engineering Adaptation/Mitigation Option: A Study Case of Mediterranean Greenhouse Farming

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1. Introduction

Current warming trends have been generated by a recent imbalance in the Earth's energy budget, characterized by the reduction in 2.6 Wm^{-2} of the global mean annual outgoing terrestrial longwave (LW) radiation from pre-industrial times (Forster et al., 2007). As a result, there is an excess of incoming solar shortwave (SW) radiation that is driving surface and atmospheric temperatures to higher values of equilibrium. This alteration is called radiative forcing (RF) of the climate, and is very probably originated on the unprecedented growth of greenhouse gases (GHGs) in the atmosphere due to human activities.

The reduction to zero emissions might be the only long term effective action to stabilize temperatures at reasonable levels (Mathews & Caldeira, 2008), before impacts are too catastrophic to manage. But on the other hand, in recent years there is a growing interest in the design of geo-engineering strategies to offset this warming exerted by GHGs through radiative rebalancing of the Earth´s energy budget. These proposals can be divided in two groups, according to which parte of the energy budget is addressed for rebalancing. The first group, named as Solar Radiation Management tecniques (SRM), joins up all strategies that attempt to reduce the net amount of SW radiation absorbed by the Earth, by limiting the solar energy reaching the planet. SRM can be achieved by increasing the reflectivity or "albedo" of the Earth to SW radiation at different levels of the atmosphere, at the surface, or even from the outer space. The second group, called Carbon Dioxide Removal (CDR), groups all strategies that aim to increase the amount of LW radiation emitted by the Earth, directly counteracting the greenhouse effect by actively removing the excess CO_2 from the atmosphere, and storing it in long term reservoirs.

One practical way to make comparisons among the potential impacts on climate of different agents is using estimated RF values, thought it must be borne in mind that this metric does not fully represent their overall impact on climate (Pielke et al., 2002), and that further modelling studies are required. Lenton & Vaughan (2009) have recently quantified in terms of RF the climate cooling potential of a wide range of geo-engineering proposals discussed in the recent literature (Boyd, 2008), taking into account their current feasibility of implementation. In the case of proposals aimed to increase the Earth's albedo at low levels, their estimation of RF potentials (SWRF) is summarized in the Table 1:

Option	Fraction of Earth for implementation	Albedo change within area	Planetary albedo change	Global Radiative Forcing (Wm^{-2})
		Increase marine cloud albedo		
Mechanical	0.175	0.074	0.011	−3.71
Biological	0.1	0.008	0.000056	−0.019
		Increase land surface albedo		
Desert	0.02	0.44	0.0064	−2.12
Grassland	0.075	0.0425	0.0015	−0.51
Cropland	0.028	0.08	0.0011	−0.35
Settlements	0.0064	0.15	0.00046	−0.15
Urban	0.0029	0.1	0.00014	-0.047

Table 1. Estimated radiative forcing potential of different SRM geo-engineering proposals (Adapted from Lenton & Vaughan, 2009).

As it can be concluded from these values, most SRM geo-engineering proposals seem to have a limited effectiveness in offsetting present and projected forcing due to GHGs increase. Only “whitening” marine clouds through aerosol seeding, or enhancing albedo on a huge fraction of the Earth’s surface through land cover changes, i.e. on big desserts, could achieve levels of forcing high enough as to counteract present unbalance, as well as the estimated forcing due to a doubling of atmospheric CO_2 (+3.71 Wm^{-2}) (Forster et al., 2007). However, these two approaches are still in an early stage of development, and their global scale implementation seems not to be feasible nowadays due to technical and financial barriers related to its big required scale of application.

Nonetheless, though this can be true at a global scale, a different perspective of geo-engineering is usually missed: its value as an effective and cost feasible strategy for local and regional adaptation to projected warming. The increase of land cover albedo at small scales appears nowadays as one of the few available geo-engineering options, particularly to offset or minimize global warming impact over human settlements. The physical basis of this strategy is an SRM approach, reflecting back to the outer space a higher amount of reflected shortwave solar energy than pre-existing land cover over a given area. This way, less energy is available to heat the surface air above when emitted back as sensible heat flux from the surface, thus resulting in a net cooling effect that can totally or partially compensate warming due to GHGs in the area of implementation. At the moment, the most promising strategy of SRM geo-engineering, increasingly being considered by policymakers, is increasing urban albedo through cool roofs and pavements promotion.

2. Cool roofs strategy

In May 2009, the US Secretary of State Steve Chu launched a global call to promote albedo increase in major urban areas in the world. This is one of the first calls from a high level policymaker to promote ge-enginering strategies to counteract global warming. His call was supported by a simulation study carried out by scientists at the Lawrence Berkeley National Laboratory (USA) (Akbari et al., 2008). In this work it was estimated that global implementation of cool roofs in the big metropolitan areas could offset as much as 44 Gt of emitted CO_2, an amount that would counteract the radiative effect of the growth in CO_2-equivalent emission rates for 11 years.

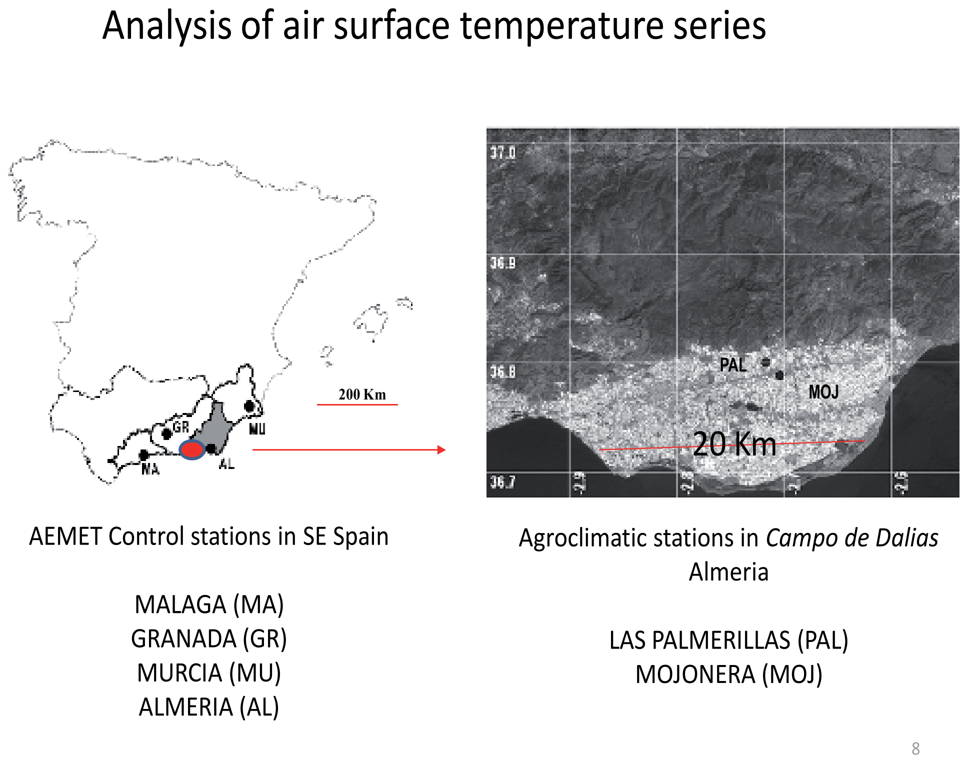
However, an essential parameter to project micro-climate impacts of this geo-engineering strategy not addressed in this study was to determine the local climatic sensitivity associated to a given density and total surface of albedo enhancement. This question needs further radiative transfer modelling validated with empirical study cases. This means that projections of changes in mean temperature and other variables must be linked to independent variables such as extension and distribution of modified surface, time for local climate to adjust to new reflectivity, and changes in RF due to projected increases GHGs emissions. Some global simulations have been published with estimations of temperature changes associated to surface albedo changes (Betts, 2000; Myhre & Myhre, 2003). A further progress in this field is a recent work (Menon et al., 2010) that includes an estimation of the climatic sensitivity of the development of this strategy on global urban areas through a GEOS-5 GCM simulation. In this work they showed the potential effectiveness in reducing high summer temperatures in urban areas, thus mitigating the effects of urban heat islands on energy consumption, pollution, and human health. The potential of cool roofs and pavements for regional adaptation was also reported, with an increase in the total outgoing radiation by 2.3 Wm^{-2} for an average 0.01 increase in surface albedo in the continental US, and land surface temperature decreased by 0.03 K.

Menon et al. (2010) increase substantially the potential forcing that can be achieved by urban albedo enhancement, in comparison to Lenton & Vaughan (2009) estimations. The difference is due to divergences in the estimations of global urban area (1% of global land surface in the first work). Nevertheless, and though the global average increase in the total outgoing radiation was 0.5 W m^{-2} for a simulated 0.1 increase in urban albedo in all global land areas, the global summer temperature reduction obtained by these authors still seems to be negligible (0.008 K), if we take into account that the projections for future warming at the end of this century range from 2-6 °C, depending on emission trends. However, the reductions obtained in regional and seasonal temperatures are big enough as to consider albedo enhancement as a key adaptation strategy for the next decades, and these global simulations studies highlight the need to study the potential of albedo forcing at smaller scales, i.e. in regional or local domains. A growing number of simulation research with meso-scale models such as Weather Research and Forecasting (WRF, National Center for Atmospheric Research, Boulder, CO, USA) is getting added to literature, but there are still a very few observational studies that show the impact of recent land albedo changes in long term air surface temperature trends. One of these studies (Campra et al., 2008) is summarized in the next section.

3. Albedo enhancement experience by greenhouse farming development in South-eastern Spain

In order to increase the total area of modification of land cover reflectivity, other categories of land use have been proposed to develop this geo-engineering approach, such as pasture and agricultural land, oceans and big desert areas. In the case of farmland, there are several low cost effective strategies that have been proposed to increase reflectivity. The increase in cropland albedo by replacing currently grown crops with high reflective varieties has been recently suggested as a new "bio-geo-engineering" approach (Ridgwell et al., 2009). According to climate simulations made by these authors, the potential for mitigation of

regional warming could reach a summertime cooling of >1ºC in mid-latitude arable regions of the northern hemisphere through an albedo increase of 0.04. Same as with urban albedo enhancement, limited impact on global warming was obtained in these simulations.
On the other hand, a particular type of agricultural land cover, greenhouse farming, has shown its efficacy offsetting local warming, showing a net cooling effect in the long term climatic data, as it has been shown in our empiric study in SE Spain (Campra et al., 2008). This recent experience of greenhouses development has resulted in a unique pilot-scale trial, based on field observations of air surface temperatures trends in three decades of a non deliberate geo-engineering experiment based on of the impact of changes in albedo at the biggest concentration of greenhouses in the world (27,000 ha), located at the province of Almeria (Fernandez et al., 2007).



Analysis of air surface temperature series

AEMET Control stations in SE Spain

MALAGA (MA)
GRANADA (GR)
MURCIA (MU)
ALMERIA (AL)

Agroclimatic stations in *Campo de Dalias*
Almeria

LAS PALMERILLAS (PAL)
MOJONERA (MOJ)

Fig. 1. Location of control (MA, GR, MU, AL) and experimental (PAL, MOJ) stations where air surface temperature series where analyzed in SE Spain (Campra et al., 2008).

Air surface temperature series of agro-climatic stations inside the greenhouses area (MOJ and PAL, Fig 1) showed an anomalous long term cooling trend of -0.3 ºC/decade from 1983 to 2005, during the years of greenhouses expansion, while the control stations located around the area, where no influence from greenhouses land cover is assumed to occur, showed a regional warming trend of +0.4 ºC/decade, that matches with generalized warming in the western Mediterranean area in the same period (Fig. 2).

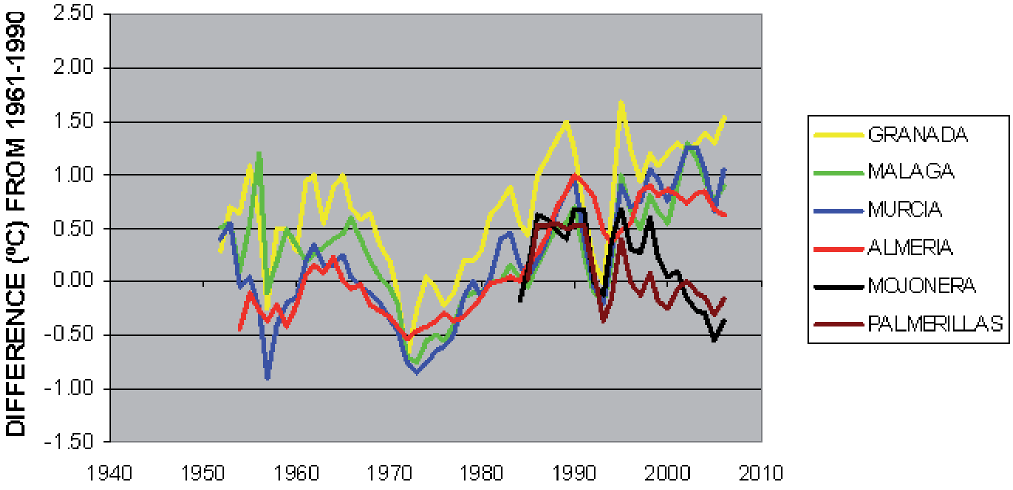


Fig. 2. Anomalies in air surface temperature series in SE Spain (Campra et al., 2008).

The working hypothesis of this study was that this differential climatic trend was caused by the gradual expansion of a highly reflective land cover of plastic greenhouses over a broad area. The increase of surface albedo reduces the net solar SW energy absorbed in the area, and this change in the energy budget might have been the most probable cause of the cooling trend detected in the agro-climatic stations in the area. In order to test this hypothesis, remote sensing albedo data from MODIS were analyzed to compare outgoing SW fluxes (OSW) from greenhouses area, and previous land cover type of semi-arid pastures. The difference series between the two outgoing fluxes is a measure of the SWRF due to land cover change (Fig. 3).

Our ongoing research using meso-scale simulations with WRF (unpublished results) shows changes in the energy budget according with the working hypothesis. The reduction in the sensible heat flux (HFX), and the net SW radiation (netSWrad) are solid evidences of the existence of a causal relationship between albedo change and the decrease in surface air temperatures (Fig 4).

The greenhouses development experience is a solid empiric proof that through designed SRM geo-engineering strategies such as the albedo effect, “cool islands” can be generated to protect human settlements by a low-cost and low-impact effective approach, helping to protect human health, lives and food production from global warming and increased frequency of heat waves projected for the next decades.

Our study shows that the main direct benefit of high albedo surfaces is the potential for adaptation to climate change at local scales, offsetting global warming through the generation of local microclimates in high vulnerability human settlements. This local effect is the key finding of our study in the province of Almeria, but is generally forgotten or just assumed to be a “secondary indirect benefit” of a global CO_2 offsetting. Geo-engineering aimed at increasing albedo at local or meso-scale is not even considered as a mitigation or adaptation measure in international protocols, or IPCC-UN reports. In fact, this strategy can help closing the loop between adaptation and mitigation, an unresolved issue in climate mitigation policies (Parry, 2009).

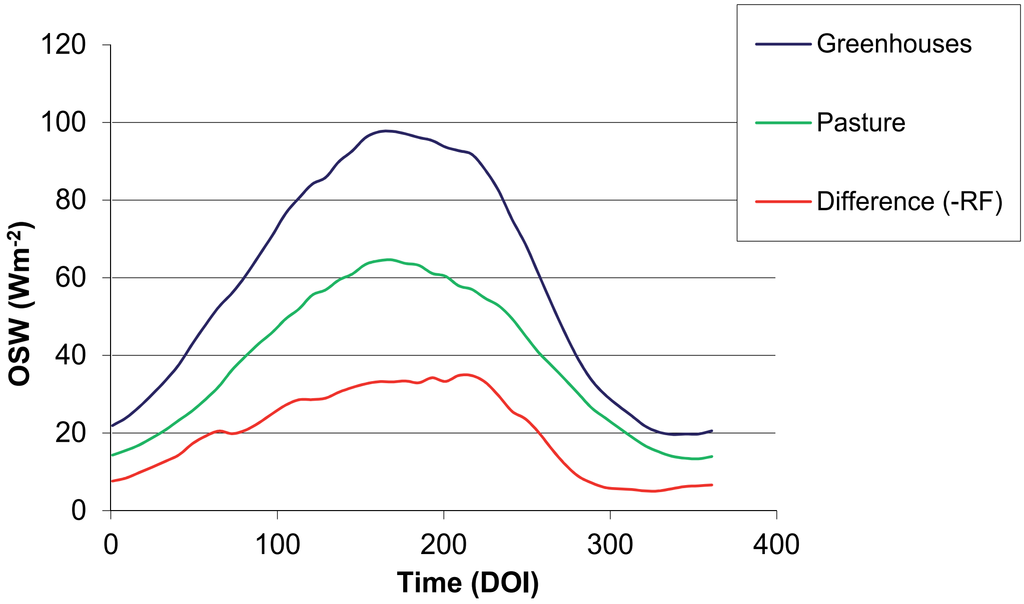


Fig. 3. Annual time series of outgoing solar radiation (OSW) from greenhouses and pasture surface and radiative forcing (-RF) as difference series (Campra et al., 2008).

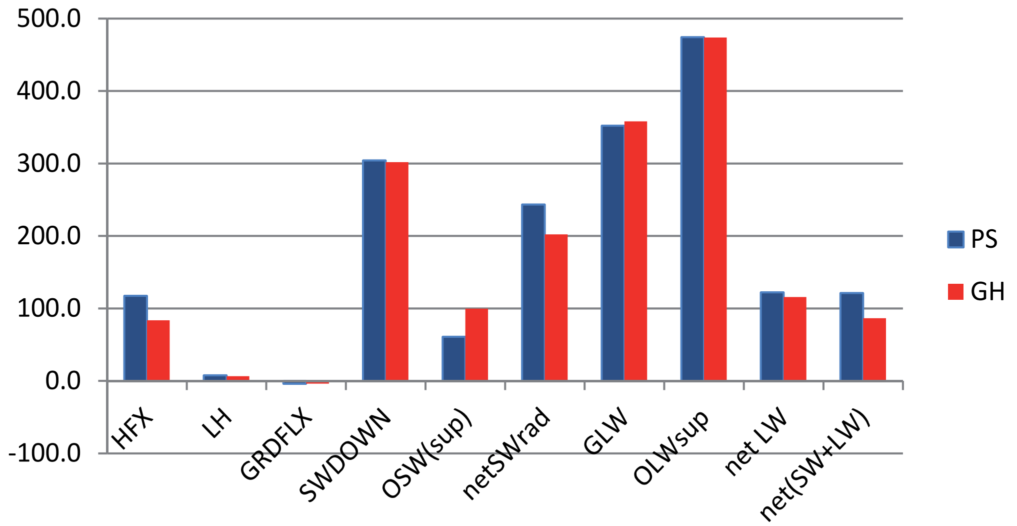


Fig. 4. Change in the surface energy budget components from pasture land use (PS) towards greenhouses land use (GH) (in Wm^{-2}). WRF simulation output: monthly averages for August 2005 (data not published). Radiation components: HFX=sensible heat, LH=latent heat, GRDFLX=ground flux, SWDOWN=incoming solar rad., OSW=outgoing solar rad., netWSrad=net incoming solar rad., GLW=incoming long wave rad., OLW$_{sup}$=outgoing long wave rad., netLW=net long wave rad., net (SW+LW)=total net rad.

Nonetheless, modelling of the greenhouses land cover change case has not yet been completed as to try to extrapolate the particular outcomes to other areas in the world with a scientifically sound basis. The case of Mediterranean greenhouses development is a very singular experience of climatic geo-engineering whose conclusions by now only apply to a particular set of modified variables affecting a particular local climate. In this sense our ongoing research aims at developing an operative methodology through building a meso-scale WRF model of this particular case, constrained by field climatic observations and remote sensing data of land cover changes that might be adaptable to make projections in different locations in the world.

4. Integration of albedo forcing and carbon footprint of greenhouses production

In our previous research (Campra et al., 2008), we only addressed the impact on the local climate of a change in land cover. However, the net impact on global climate of any geo-engineering option must also be assessed, and three steps are required in the case of surface albedo enhancement strategies:

1. Estimate carbon footprint of the development and maintenance of high albedo surfaces, and compare it to the footprint associated to the economic activities over pre-existing land cover
2. Integrate the global forcing of SW budget change and the forcing exerted by the change in the net GHGs emissions associated to the land use change.
3. Develop meso-scale climate models of the area of implementation of albedo change, in order to simulate the projected change in temperatures in the area of study and in boundary domains around it, up to global scale.

Process	GWP-20	GWP-100	GWP-500
Change in biomass carbon stock	2	2	2
Carbon fixation by crop	-190	-190	-190
Greenhouse infrastructure	283	226	204
Soil preparation	6	6	6
Greenhouse maintenance	<1	<1	<1
Fertilizers	94	93	65
N_2O emissions	55	57	29
Greenhouse disposal	6	3	2
Water pumping	24	22	21
Green waste treatment	83	84	83
Overall emissions (a)	365	303	223
Change in surface albedo (b)	-93	-134	-202
Net with albedo change (c=a+b)	272	168	21
Ratio (c) to (a) (%)	75	56	9

Table 2. Global warming potentials (GWP, in kilograms of CO_2-eq.) at 20, 100 and 500 years associated to the production of 1,000 kg of tomatoes under Mediterranean greenhouses in SE Spain (From Muñoz et al., 2010).

For the case of greenhouse farming, we have estimated the carbon footprint of a representative production by the rigorous methodology of Life Cycle Assessment (LCA) (Muñoz et al., 2010). A cradle-to-gate LCA of an intensive production in the province of

Almeria was first time carried out in this study. First, an inventory of all inputs to the farm was collected. As background emissions data, the Ecoinvent 2.0 database was used (Swiss Centre for Life Cycle Inventories, 2008). This analysis concluded that a gross Global Warming Potential (GWP-100) of 303 kg CO_2-eq. per ton tomato was generated this greenhouse product system (Table 2).

The second step was to develop a novel methodology to integrate SW local radiative forcing and LW global forcing exerted by the indirect GHGs emissions associated to the farming activities, measured as GWPs. Our approach was to consider albedo increase equivalent to "negative emissions" or "emission offset", as this physical change exerts a negative radiative forcing on the climate system opposed to the positive forcing generated by the increase in GHGs. The calculation of CO_2-eq. emissions related to surface albedo change was done with the next three main equations:

1. SW radiative forcing (RF_{TOA}) of a surface albedo change at the top-of-atmosphere (TOA)

$$RF_{TOA} = -R_{TOA}\,\Delta\alpha_{p}, \tag{1}$$

$$\text{where} \quad RF_{TOA} = -R_S\,T_a\,\Delta\alpha_s$$

(R_S= solar radiation at surface ; R_{TOA} = solar radiation at the top of atmosphere; α_p = planetary albedo; α_s = surface albedo; T_a = atmospheric transmittance)

2. CO_2-eq emissions of SW radiative forcing

$$CO_2 - eq. = \frac{A\,RF_{TOA}\,\ln 2\; 2pCo_{2,ref}\,M_{CO_2}\;m_{air}}{A_{Earth}\,\Delta F_{2X}\,M_{air}\,AF} \tag{2}$$

where A is the area affected by the change in surface albedo (m^2), RF_{TOA} is the SW radiative forcing of a surface albedo change (W m^2) , $pCO_{2,ref}$ is a reference partial CO_2 pressure in the atmosphere (383 ppmv), M_{CO2} is the molecular weight of CO_2 (44.01 g mol^{-1}), m_{air} is 5.148×1015 Mg, A_{Earth} is the area of the Earth (5.1×1014 m^2), ΔF_{2X} is the radiative forcing resulting from a doubling of current CO_2 concentration in the atmosphere (+3.7 W m^{-2}), M_{air} is the molecular weight of dry air (28.95 g mol^{-1}), and AF is the average CO_2 airborne fraction.

3. CO_2-eq emissions avoided through land use change, per functional unit (one kg of fresh product)

$$CO_2 - eq. = \frac{LT_{FU}\,R_s\,T_a\,\Delta\alpha_s}{RF_{CO_2}\;AF} \tag{3}$$

Where (LT_{FU}) = land transformation per functional unit (m^2)

As it will be explained in detail in the next section, one of the main sources of uncertainty in these calculations is the calculated value of AF, i.e. the fraction of CO_2 that remains in the atmosphere after carbon cycle has partially removed it in a given time frame. In this study we used a value of 0.48, calculated from the integration of Bern carbon cycle model in a time horizon of 100 years, considering a GWP-100.

Including in the LCA the CO_2-eq emissions equivalence of land cover changes is not a simple task, as many methodological and conceptual problems arise. For instance, the choice of time horizon in the GWP affects the impact of the albedo effect, increasing with time horizon selected. Another source of variability in this methodology is the choice of service lifetime for the activity (here we assumed and expected 50 years lifetime for greenhouse production) (Muñoz et al., 2010). The emission offset increases for shorter lifetimes, for example in this case it increased from 134 to 269 kg CO_2-eq. per ton product when a 25-year lifetime was considered but decreased to 67 kg CO_2-eq. per ton tomato when it was expanded to 100 years.

Through the application of this methodology, the gross GWP-100 estimated (303 kg CO_2-eq. per ton) was reduced to a net 168 kg CO_2-eq. per ton tomato if the change in surface albedo was taken into account. We concluded that the local radiative forcing caused by albedo increase has a remarkable offset effect on the overall GHGs emissions balance of this particular product system, equivalent to 44% of its gross indirect emissions when GWP-100 was considered. However it must be taken into account that albedo effect is always reversible: if in the same system albedo is changed but returned to its previous state at the end of the service lifetime, the net albedo change, and thus, the CO_2-eq. emissions offset, will be zero.

Another particular case where albedo could have an important influence in the CO_2-eq. emission balance is in the context of forestry or any other system involving sharp changes in land cover reflectivity. In this sense, it must be taken into account that forestry plans aimed to mitigate global warming by carbon fixation in biomass should have a complementary assessment of the equivalent forcing exerted by the change in land cover reflectivity. In some regions, particularly in high latitudes where snow cover remains in winter months, this forcing could offset the climatic benefits of carbon fixation (Betts, 2000). This might also happen in semi-arid environments, where the previous disperse shrubland albedo is generally much higher than the forested land albedo.

In any case, other climatic effects apart from temperature changes might be worth to consider, as well as other "conventional" environmental benefits of forestry plans should be regarded as a whole. For example, deforestation in the tropics decreases evapotranspiration rates and increases sensible heat fluxes, resulting in regionally decreased precipitation and increased surface temperature (Bala et al. 2007). In conclusion, new metrics different from radiative forcing and carbon offset might be advisable to take into account these kind of effects of land use change on climate (Pielke et al., 2002). In the words of Dr. R.A. Pielke, "*a more complete indication of human contributions to climate change will require the climatic influences of land-surface conditions and other processes to be factored into climate-change-mitigation strategies. Many of these processes will have strong regional effects that are not represented in a globally averaged metric.*" In conclusion, our study is just a first operative approach to highlight the methodological problems that arise when an integration of land albedo changes with associated GHGs emissions is required prior to the development of climate policy regulations related to land use changes.

5. Estimation of carbon offset equivalences of global albedo enhancement

A key conflicting issue introduced by Akbari et al, 2008 is the conversion of SW radiative forcing (SWRF) generated by land cover changes to equivalent CO_2 emissions offset. In this paper, it was estimated that a carbon emissions offset of 44 Gt CO_2 could be achieved by albedo enhancement of main global urban areas. Menon et al. (2010) used the same conversion factors and raised this figure to 57 Gt CO_2 using a summer General Circulation Model (GCM) simulation. These two works are a landmark approach for the estimation of global GHGs offset by albedo increase at urban areas, and offer a remarkable scientific basis for the development of more inclusive climate protocols in the post-Kyoto agreements that do not just rely on GHGs emissions reductions as the only mitigation currency. However, these global estimates should be carefully revised when local or regional effects are to be considered. Furthermore, as we have shown before, there are still complex methodological issues when we pretend to express SWRF due to albedo changes in terms of equivalent reduction in carbon emissions. There are at least 3 main sources of uncertainty that must carefully be taken into account:

1. The calculation of SWRF exerted per unit albedo change, and the use of global or regional averages of this parameter in the estimation of carbon offsets at particular cases
2. The equivalence parameter between SWRF per unit albedo change and the amount of atmospheric carbon that would exert the same but opposite forcing
3. The conversion from that atmospheric carbon to equivalent carbon emissions reduction

5.1 SWRF per unit albedo change

There are still significant uncertainties in the SWRF generated per unit of albedo increase, both at global and local scales. Radiative forcing associated with land use changes has been derived largely from GCM simulations (Hansen et al. 1997; Betts, 2001), using climate simulations, and there are very few observational estimates of this “missing” radiative forcing (Myhre et al. 2005). Some of these studies have shown that the GCM computations significantly underestimate the local SWRF due to land use changes, with observational estimates even more than twice the model-derived values over some regions (Nair et al., 2007). Finally, an additional factor not to be forgotten is that Earth radiation budget changes with time, making more confusing to determine the best value from literature.

In the case of observational studies, such as our work in Almeria greenhouses (Campra et al. 2008), we used and empirical approach and calculated this forcing in our area of study from the outgoing SW radiation (OSR), by the formula from Betts (2001):

$$\mathrm{SWRF} = \mathrm{OSR}_{\text{final land cover}} - \mathrm{OSR}_{\text{fprior land cover}} \tag{4}$$

OSR values were calculated from averaged satellite MODIS data, and SW incoming radiation using an insolation model that accounted for local geographic factors and transmissivity in clear sky conditions (Van Dam, 2000). By this method we calculated an annual averaged SWRF of -19.8 W m^{-2} associated to an average increase albedo of 0.09 in the study area. From these data we can obtain an observational estimate of -2.2 W m^{-2} of SWRF for every 0.01 albedo increase. This forcing is almost double than the forcing of -1.27 W m-2 estimated by Akbari et al. (2008) at global scale. Hansen et al. (1997) did not provide any direct estimate of SWRF associated to a global albedo increase. Instead they used a global climate model with an idealized global geography, and determined the effectiveness of surface albedo forcing applied on fictitious land masses. As they state, this approach was intended to analyze climatic mechanisms, rather than to simulate impacts on specific real world regions. On the contrary, Hatzianastassiou et al (2004), used a radiative transfer model coupled with climatological data to estimate Earth SW radiation budget at top of atmosphere (TOA), and performed sensitivity tests of their model to changes in relevant parameters such as albedo, reporting a 3.3 W m^{-2} change in OSR at TOA with a simulated 10% increase in surface planetary albedo. If we combine this sensitivity of SW radiation budget at TOA with the estimation of surface albedo of 0.129 given by these authors with the same model (Hatzianastassiou et al, 2005), a 0.01 increase of surface albedo equals to a global SWRF of -2.57 W m^{-2} at TOA, again far from Akbari et al. (2008) lower estimate.

It is important to notice that surface albedo changes do not produce equivalent changes in planetary albedo, and must be adjusted by atmospheric absorption and reflection. Thus, when comparing forcings of GHGs TOA, and SWRF due to land use change, both estimates must refer to the net radiative flux change at the same level in the atmosphere, and for the same state of adjustment of the stratospheric temperature profile (Hansen et al., 1997). In this sense, as radiative forcing estimates of GHGs generally refer to values at TOA (Hansen et al., 1997, Myhre et al., 1998), so radiative forcing due to albedo increase must be estimated at TOA as well for comparison. However, adjustment of stratospheric temperatures is not so relevant when dealing with SWRF.

Therefore, the value of estimated global SWRF per 0.01 albedo increase of -1.27 W m^{-2} used in Akbari et al. (2008) needs further discussion, as all CO_2 offset potential calculations are drastically affected by this estimation. For the calculation of this key parameter, they use an averaged value (1984-2000) of total incoming SW Radiation (SWDOWN) at surface of 172 Wm^{-2}, obtained from Hatzianastassiou et al. (2005). This value is at the lower end of previous estimates reviewed by these authors (169-219 Wm^{-2}). Similarly, the value of net SWDOWN at surface (total minus reflected) given by these authors (149 Wm^{-2}), is at the lower range of earth energy budget estimates reviewed (142-191 Wm^{-2}). These values are significantly smaller than most previous estimates, by up to 30 Wm^{-2}, and disagreement is associated with differences in atmospheric absorption. However, Earth radiation budgets at surface and TOA from Hatzianastassiou et al. (2005, 2004) seems very reliable, as they have been validated against surface measurements with good agreement with the model.

Another source of uncertainty of Akbari et al. (2008) estimate is that it is based on the combination of simulated data from two different modelling studies, (Kiehl and Trenberth, 1997, and Hatzianastassiou et al. 2005), thus resulting in a lack of methodological coherence. There is a remarkable difference in net SWDOWN radiation between both estimates, that arises from an overestimation of absorbed SW radiation by atmosphere in the last study (26.7%), compared to earlier studies (20%). However, when calculating f (fraction of radiation absorbed by the atmosphere), Akbari et al. (2008) use a SWDOWN value of 172 Wm^{-2} from Hatzianastassiou et al. 2005, and then simply scale down data from (Kiehl and Trenberth, 1997), considering the value of 30 Wm^{-2} as the OSW radiation AT SURFACE. However, this value is referred in the modelling as the OSW radiation AT THE TOA (although the "30" label in Figure 7 can mislead). It makes no sense to reduce its magnitude by atmospheric correction (*f*) as Kiehl and Trenberth have already accounted for any further absorption in their 67 Wm^{-2} value of total SW absorbed radiation in atmosphere.

In order to make this key issue clearer, we can better use a simple analytical approach recently employed to evaluate the radiative forcing potential of different geo-engineering options (Lenton & Vaughan, 2009). Forcing at TOA caused by planetary albedo change $\Delta\alpha_p$ can be estimated from average incoming solar radiation at TOA (DSR), by the formula:

$$SWRF_{TOA} = DSR_{TOA}\,\Delta\alpha_p \qquad (5)$$

But planetary albedo has two components, atmospheric albedo (α_a), and surface albedo (α_s), and the latter must be corrected at TOA with atmospheric absorption (A_a) and atmospheric albedo (α_a). This way, forcing due to land albedo increase (SWRF) can be calculated as:

$$\text{SWRF} = \text{DSR}_{\text{TOA}} [\Delta\alpha_s (1- \alpha_a) (1- A_a)] \tag{6}$$

Lenton & Vaughan (2009) make a global estimation of forcing using global energy budget values (α_a, A_a, and net DSR_{TOA}) taken from Kiehl and Trenberth (1997) to obtain an $\text{SWRF}_{\text{TOA}} = \text{DSR}_{\text{TOA}}\ 0.579\ \Delta\alpha_s$. Through this formula we can obtain a parameter of SWRF for every 0.01 increase in surface albedo equal to -1.98 W m^{-2}. This is the constant parameter value these authors use to assess the potential for all geo-engineering options based on surface albedo increase.

However, if alternatively we use global energy budget values from Hatzianastassiou et al. (2005), then

$$\text{SWRF}_{\text{TOA}} = \text{DSR}_{\text{TOA}}\ 0.50\ \Delta\alpha_s \tag{7}$$

and SWRF for every 0.01 increase in surface albedo results in -1.71 W m^{-2}, still well above Akbari et al. (2008) estimate (+34%).

These conflicting issues have been exposed above to highlight that forcing per unit to albedo increase is a key parameter that needs a more detailed analysis and validation against local surface measurements, as the final associated carbon offset is directly biased by the value of choice.

As an example, in Table 3 is summarized the big changes in final annual CO_2 offset potential of urban albedo increase at urban areas in the state of California, implemented in a 15 year period, depending on the value used in different works for this parameter.

	Akbari et al., 2008	Hatzianastassiou et al., 2005	Lenton & Vaughan, 2009	Lenton & Vaughan, 2009	Campra et al., 2008
Data source[1]	Ref.	RAD	ERB1	ERB2	AL
SWRF per +0.01 albedo (W m-2)	-1.27	-2.57	-1.98	-1.71	-2.2
California Urban offset ($MTCO_2$-eq/year)	31	63	48	42	54

[1] Data used for estimations: Ref.= from Kiehl and Trenberth, 1997, and Hatzianastassiou et al. 2005; RAD= From radiative transfer model; ERB1= based on radiation budget from Kiehl and Trenberth, 1997; ERB2= based on radiation budget from Hatzianastassiou et al., 2005; AL= empiric value for Almeria study case, from MODIS OSW data (lat N 36° 45′)

Table 3. Forcing per unit albedo change and estimation of associated carbon emissions offset in California urban areas, according to the values of this parameter in different works

Finally, it must be taken into account that energy radiation budget of the Earth changes with time, and this is affecting the value of this key parameter. For instance, Hatzianastassiou et al. (2005) detected a decadal increase in solar absorption of 2.2 Wm^{-2}, over the period 1984-2000, probably due to reduction of low level clouds.

On the other hand, a linear relation between global albedo increase and SWRF cannot be directly applied to local or regional cases, whatever the value of the equivalence parameter used. The uncertainties and the geographic variation of the equivalence between albedo increase and SWRF are too big as to simply assume an averaged value of -1.27 W m^{-2} , for any location in the world. Due to variability of latitude and average cloud cover, there will be significantly different values of this parameter than any global average estimate, resulting in an underestimation or over estimations of CO_2 offset potentials of albedo increase.

Ultimately, given the uncertainties in global estimates, in practice the issue of applicating global studies to particular urban areas could be overcome by the use of updated local surface based observational estimates of radiative fluxes, averaging long term climatic data. The effectiveness of the changes in surface albedo is a function of the geographic location of the changes. Estimation of this key parameter must include the time-space variability in net incoming solar radiation fields. Local observational estimates of average SWDOWN and OSR at surface are needed. This estimates must integrate different factors, mainly latitude and average cloud cover, but also key variables in urban areas such as aerosol pollution. Updated surface radiation data sets can be used to determine the annual average of net radiation. Alternatively, SWRF can be calculated from OSR data at TOA obtained from remote sensing products, but resolution of these products might do more practical the use of surface observations when dealing with urban albedo changes.

5.2 The equivalence parameter between SWRF per unit albedo change and the amount of atmospheric carbon offset that would exert the same forcing

This issue ultimately deals with the choice of a correct parameter that accounts for the longwave radiative forcing (LWRF) exerted by a unit CO_2-eq or the estimate of adjusted (TOA) radiative forcing per ton CO_2. Akbari et al. (2008) use a RF value of 0.91 kW/tonne of CO_2 for a 385 ppmv concentration, based on estimates by Hansen et al. (2005) and Myhre et al. (1998), who use a RF [Wm^{-2}] = 5.35 ln(1 + ΔC/C), where ΔC is the difference from pre-industrial times to current CO_2 concentration. The problem is that this parameter can have different values according to the methodological approach, and must also be actualized with present concentration.

5.3 The conversion from atmospheric carbon equivalence to carbon emissions reduction

Given the ultimate goal of computing albedo changes in climate policy, a key issue has arisen when the forcing on climate of a static alteration of the energy budget has to be compared to time-varying forcing exerted by emissions of GHGs. The standard emission metric used in United Nations Framework Convention on Climate Change (UNFCCC) and carbon markets is the GWP (Forster et al., 2007), that was formulated to compare the contribution of different GHGs to climate change over an arbitrary period of time, set in 100 years in the Kyoto Protocol. The calculation of GWPs of different agents involves the integration of their forcing per unit mass increase in a given time horizon, and includes a time-dependent abundance of both the gas considered and the reference gas (CO_2). One of the problems of GWP metrics is that it does not account for the different residence times of different forcing agents. This problem of time varying impacts becomes even more complex when trying to express albedo forcing in terms of GWP. There are two basic conflicting issues here:

1. Whether the use of a correction factor based on CO_2 decay concentration is appropriate or not when comparing to equivalent instantaneous forcing of albedo changes.

As we showed in our approach to the integration of albedo forcing and carbon footprint (Muñoz et al., 2010), this mixing of a static invariant forcing (SWRF) and a time dependent forcing ($LWRF_{CO2}$) that changes with gas concentration is still controversial and methodologically complex, and might be an inappropriate approach.

2. The choice of a given value for the CO_2 airborne fraction (AF). If this correction is applied, the methodological approach chosen to integrate the carbon decay in a given time frame can yield different values of the AF, and marked differences in final carbon offsets.

In one of the pioneering works dealing with the integration of albedo and carbon forcing, Betts (2000) accounts for an AF of emissions of 0.5, assumed to remain constant over forest growth timescales. This figure is used as well by Akabari et al. (2008), and Menon et al. (2010). This value of AF is obtained by a simple arithmetic average of the fraction of fossil fuel emissions remaining in the atmosphere each year for the period 1958-2005 (Denmann, 2007). However, the range of AF in those years is almost (0.3-0.8), and the inter-annual variability is two broad for this fixed value of 0.5 to be considered as an intrinsic property of the climatic system. Furthermore, simulation studies constrained by observations give a similar range of uncertainty in the value of AF, and future projections yield lower AF as CO_2 concentration increases in the atmosphere (Fig. 5).

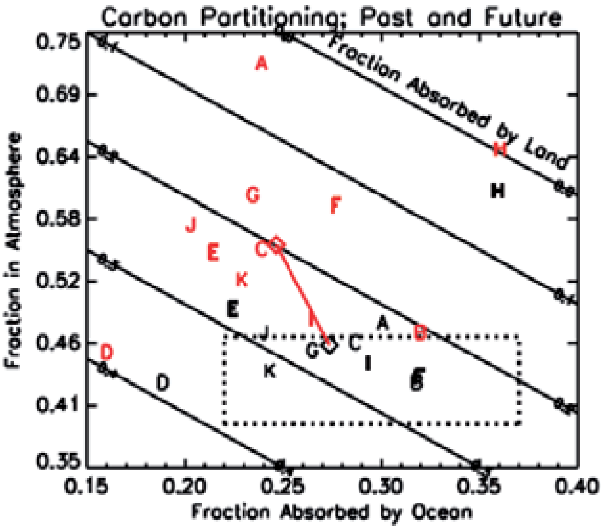


Fig. 5. Predicted increase in the fraction of total emissions that add to atmospheric CO_2. Changes in the mean partitioning of emissions as simulated by the C4MIP models up to 2000 (black symbols) and for the entire simulation period to 2100 (red symbols). The box shown by the dotted line is a constraint on the historical carbon balance based on records of atmospheric CO_2 increase. The black and red diamonds show the model-mean carbon partitioning for the historical period and the entire simulation period, respectively. (From Denmann et al., 2007).

As it can be seen, the choice of an AF of 0.5 seems too simplistic, and other proposals address this issue by introducing correction operations based on atmospheric carbon decay models. For instance, in our work on greenhouses footprint (Muñoz et al, 2010) we used an simple integration of the Bern carbon cycle model (Joos et al, 1996) in a time horizon of 100 years, generally used in the calculation of GWP, to obtain an AF value of 0.48. According to this model, after 10 years 66% of the initial emission remains in the atmosphere, while only 36% remains after 100 years. As a consequence, the choice of a time horizon affects the magnitude of the CO2-eq.emissions. In a more complex formulation, Schwaiger & Bird (2010) use a convolution operation to integrate the instantaneous forcing by albedo change and the inverse of a carbon decay function.

In conclusion, the conversion of albedo forcing into emissions equivalent is still an open and challenging issue that needs further considerations and consensus prior to the development of accounting standards that provide a tool to implement albedo enhancement policies. It must be bear in mind that, if AF no correction is applied, the value of carbon offset estimations will be at least two fold lower than values corrected with AF.

6. Intensive use of land and high yield conservation

By now, in our estimation of the climatic impact of greenhouse farming development we have accounted for on-site impact of changes in the solar energy budget, and for the global impact related to indirect GHGs emissions required for all inputs and processes in the farm. But there is another remarkable indirect trade-off of this land use transformation that must be accounted for, if we wish to have an overall picture of the climatic and environmental effects on the whole territory of the influence of this productive system. When dealing with changes in the use of land and natural resources by a given human population, not only land use changes, but also associated local population migrations, and changes in the intensity of land use in a broader area of their historical settlement should also be included in the analysis. This way, in the southern Mediterranean coast of Spain, the shift from extensive dry crops towards irrigated intensive greenhouse farming has generated the concentration of highly profitable farming activities in a limited portion of the settling territory of the population, while low income extensive farming and grazing activities have been abandoned in an area around ten times larger. This has boosted a spontaneous recovery of natural vegetation, and allowed the development of forestry plans in the abandoned farmland, with the natural or aided generation of huge carbon sinks in soils and biomass. This sinks should be accounted for when estimating the net environmental and climatic impact of greenhouse farming, urbanization processes or any intensification of land use along with similar changes in the human use of the surrounding territory.

As an example, I will summarize the basic figures of this non intentional trade-off, restricted to the province of Almeria for practical statistical reasons. However, it is difficult to determine the geographical limits of the surrounding area of influence affected by greenhouse farming development. The sudden generation of this new source of income has mostly attracted populations from inland mountains of the province of Almeria, but also from neighbouring province of Granada, and furthermore, an intense migration flow of labourers from 200 different countries around the globe seeking for alternatives to the use of their own homeland.

The province of Almeria has a total extension of 877,400 ha. The population has grown from 357,000 in 1957 to 667,600 in 2008. The Gross Value Added (GVA) of the agricultural sector in this province has multiplied 10 times the value in 1957, and 3 times since the beginning of the greenhouses boom in the early 80s, turning from the poorest provinces in Spain to one of the biggest agricultural exports area in the Mediterranean. At the same time, it has turned from a source of emigrants to an attracting pole of migrants from all over the world.

Despite this economic boom and population growth, the extension of natural areas has not decreased in the province in the last decades (Fig. 6). Greenhouse farming has been concentrated in coastal flat lands accounting for 27,000 ha, just a 3% of the total land in the province. On the contrary, hundreds of thousands of hectares of dry crops and semi-arid pastures (40-50% of total surface of the province) have been abandoned inland, and natural Mediterranean plant communities have since then developed a dynamic process of succession that has transformed thousands of hectares to new shrublands with a potential forestry use. Most abandoned crops do not show in the statistic summary in Fig 5, as they are still accounted in official statistics as farmland, and a big portion of pastures that have also been abandoned are included in the natural areas category. In addition, to this spontaneous recovery, Spanish government plans from the 50s, and more recent EU assistance to farm tree planting have increased the forested surface in 90% from 66,000 ha in 1957 to present 130,000. Along with this, historical erosion in this semi-arid territory has been reduced by the abandonment of extensive areas of mountain dry crops that suffered vegetation clearance and tillage in high steep slopes.

This pattern of land use change in the province (Fig. 6) has been boosted in great part by the new source of income generated by off-season greenhouse production, an activity that has grown thanks to the conjunction of a very specific climatic and export marketing condition. Nonetheless, the growth in population, per capita income, along with the reduction in total extension of human use of land, and the increase and recovery of natural areas characterize a pattern of economic development based on the intensification and concentration of land use that can be adapted to different latitudes on the world in order to achieve both local populations needs and natural habitats and cycles maintenance and regeneration.

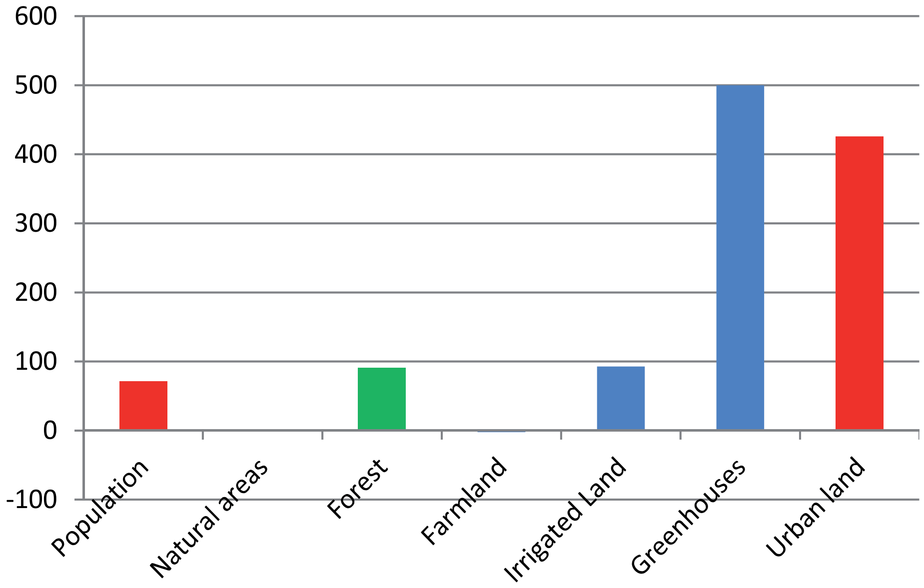


Fig. 6. Rates of change in population and different land use categories in the province of Almeria during the period 1956-2003.

In terms of climate change mitigation, it is important to account for this new carbon sinks generated in this abandoned farmlands. Due to the intense dynamics of this land use changes, the province of Almeria holds one of the most intense carbon sinks in the south of Spain (Agudo, 2007). According to the last regional carbon sink inventory, elaborated according to the IPCC methodology for Land Use and Land Use Change and Forestry (Penmann et al., 2003), the forest areas in the province would be nowadays fixing around 3.8 million tons of CO_2 (Table 4). This figure, only accounting for biomass fixation, should be increased by fixation in soils in regeneration in abandoned farmlands, but this huge sink has not been estimated yet in the area.

	Net carbon fixation in biomass			Province of Almeria
	TCO_2 ha^{-1} stock	surface (ha^{-1})	TCO_2 ha^{-1} a^{-1}	TC ha^{-1} a^{-1}
Forest Land (only trees)	81	154,000	2.5	385,000
Forest Land (shrublands)	120	335,000	10.4	3,490,000
Total				3.87 M TCO_2

Table 4. CO_2 fixation in natural areas in the province of Almeria (from Agudo et al., 2007).

This phenomenon of land use change, associated farmland abandonment, and forests recovery is not unique of greenhouse farming, but is a common trend in many developing areas in the world, such as the northern Mediterranean basin and China (Fig. 8), through natural expansion and afforestation programs.

Global deforestation is mainly due to conversion of forests to agricultural land. However, and though each year about 13 million hectares of the world's forests are lost due to deforestation, the rate of net forest loss is slowing down, thanks to new planting and natural expansion of existing forests due to abandonment of pastures and farmlands. This way, net forest loss dropped from 8.9 million hectares per year in the 90s to 7.3 million hectares per year in the period 2000-2005 (FAO, 2005).

For instance, EU assistance to forestry under the regulation 2080/92, forestry measures on farms, aimed to reduce agricultural surpluses and enhance forest resources, and “combat the greenhouse effect by absorbing carbon dioxide”. In the first period of this plan, one million farmland in EU changed to forestry between 1994 and 1999, a biggest portion in Spain (Evaluation, 2000). Evaluations have shown that this measure has led to the conservation and regeneration of valuable habitats and increases in the use of land for environmental purposes.

It is very important to highlight that this trend goes in the direction of the reversal of historical land use change from pre-industrial reference data of 1750, characterized by a global replacement of forests and natural vegetation by farmland and pastures (Fig. 7). In the last 40 years, 500 million ha have been added to global farmland, 300 out of them are pasture land for extensive livestock grazing. Nowadays, around 40-50% of land surface has an agricultural use, and 80% of deforested land changes towards agricultural or pasture use. Furthermore, present population growth and demands make unsustainable to maintain this trend towards extensive use of land in the present century. Human population is projected to grow from 6,700 million to 9,000 milling around 2050, with skyrocketing demands for meat consumption in developing countries like China and India, due to higher income levels. Is has been estimated that food demands will in crease in 50% in the XXI century. This means increased human use of land, with higher pressure on natural habitats that will additionally suffer intense stress from climatic change. Less adaptation options through migration will be available to natural populations of plants and animals. However, best soils and potential farmland have already been occupied, and further tillage will have to be done in marginal land, with lower quality soils, higher slopes or worst climatic conditions, with lower productivity yields, with growing environmental and sustainability problems.

The only feasible alternative then to make with higher food production compatible with natural habitats conservation and adaptation requirements in a changing climate is the reduction and concentration of human land use through the development of high yield production systems, such as greenhouse horticulture. Additionally, local populations must be offered alternative sources of rent in order to abandon the extensive low income use of land, or they might need to migrate to growing urban areas.

In developed regions such as US and Europe, farmland extension is maintained or decreasing, and forests extension is stabilized or promoted by forestry plans, feasible due to the generation in the last decades of alternative sources of income for rural population, and urbanization processes.

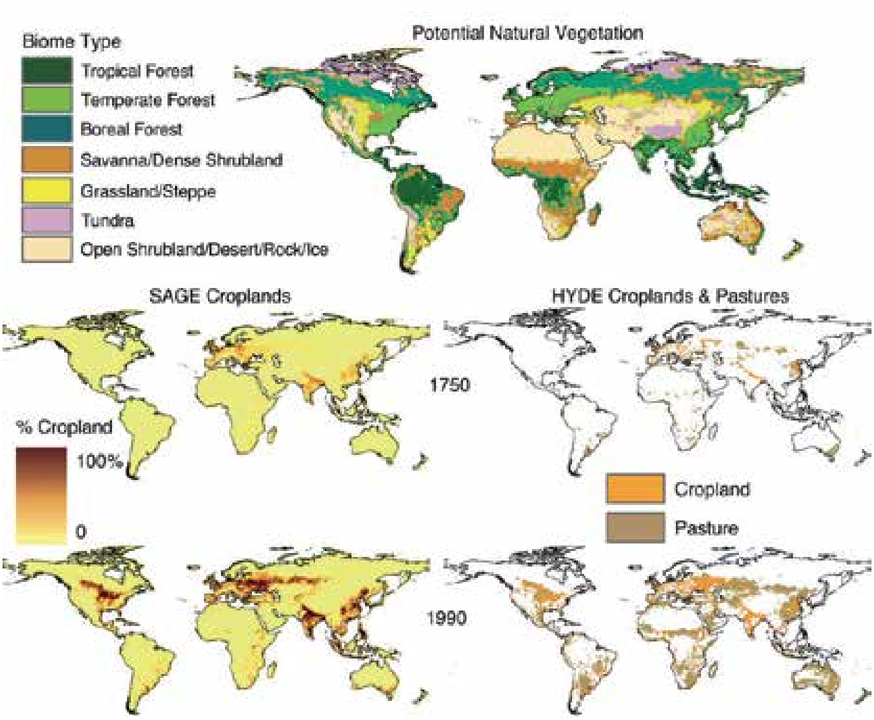


Fig. 7. Potential natural vegetation and land use changes from preindustrial time to present due to agriculture and livestock development (From Forster et al., 2007).

The environmental benefit of this pattern of land use change been named as "high yield conservation", and the essential message states that "growing more crops per acre leaves more land for Nature". On the other hand, intensifying food production systems requires higher energy inputs. This issue of energetic supply must be addressed, but is out of the scope of this chapter. This novel approach, that reconciles human land use of the Earth with natural habitats conservation and regeneration and enhancement of natural cycles, is worth to deserve much more consideration by climate and environmental policies, and might become one key option of the human sustainable use of the available surface of the planet in the present century.

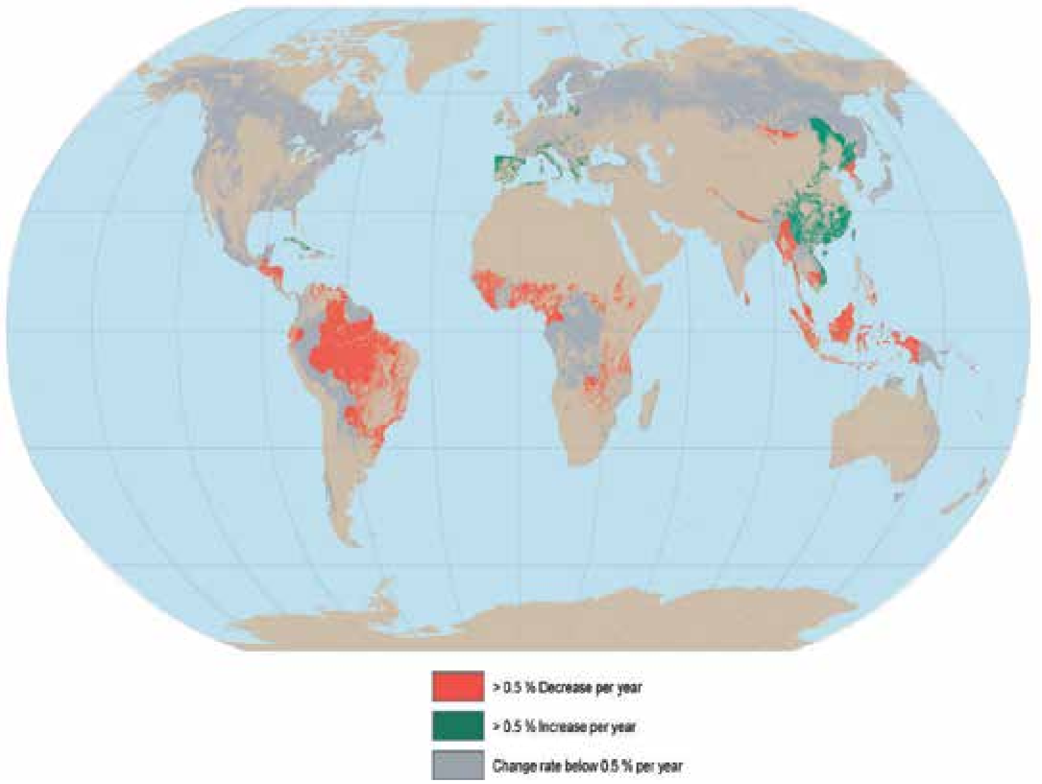


Fig. 8. Recent rates of net forest area change (2000-2005). Red >0.5% decrease per year; Green > 0.5% increase pr year; Grey = change rate below 0.5% per year (FAO, 2005).

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24

Innovations in Agricultural Biotechnology in Response to Climate Change

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1. Introduction

Food security for all will be a prominent issue for the next century. Today one billion people of the world are undernourished and more than a third are malnourished (Godfray et al., 2010). The chronically hungry have compromised immune systems and succumb to easily preventable infections. As the world's population continues to increase, ensuring that the earth has enough food that is nutritious will be a difficult task enough. However, the looming threat of climate change will exasperate the situation even further. The impact of climate change on the world's food supply is predicted to be far-reaching. At high risk is sub-Saharan Africa, a drought-prone continent with a little under 10% of current land designated to have agricultural potential predicted to turn into desert within the next 50-70 years (Global Hunger Index)(Figure 1).

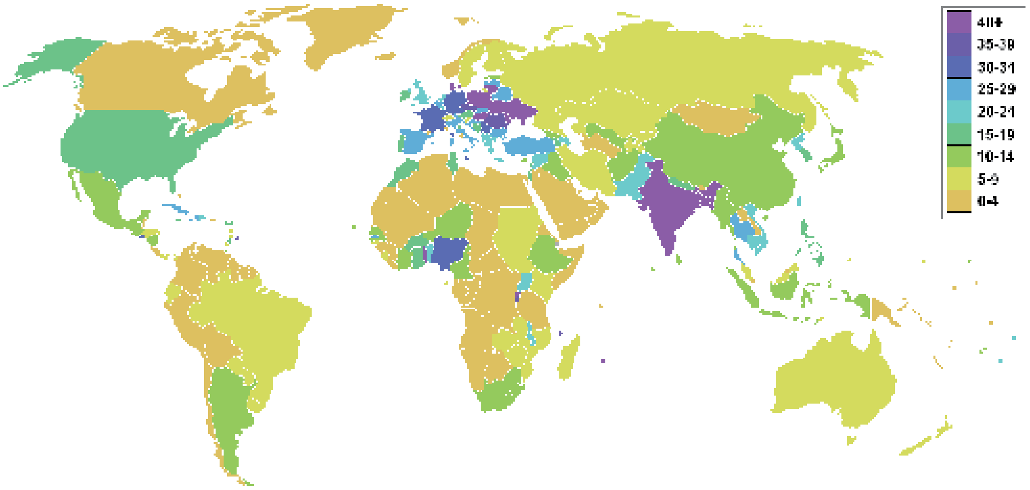


Fig. 1. Arable land percentage by country, as listed on CIA factbook, accessed June 2006.

Drought is also anticipated for Asia, as an accumulative result of climate change. Rice crops tend to be vulnerable to lengthy hot, dry seasons. Himalayan glaciers, which feed the rivers and streams of both China and India, are predicted to lose as much as 80 per cent of their volume within the next quarter century (Global Hunger Index). Meanwhile, temperate zones in other parts of the world such as North America and Europe will encounter extreme weather conditions, such as hurricanes and floods. Different patterns of rainfall in a particular habitat will impact the ecosystem of that region, altering biodiversity and changing the growing seasons of particular crop types.

Even without taking the advance of climate change into account, the burgeoning world population will continue to grow to an estimated 9 billion people by 2050 (Ejeta, 2010). Food prices are predicted to continue to fluctuate wildly as the demand for food increases. The situation is confounded even further by a competition for land and water between crops grown for food and crops grown for energy, in the form of first generation biofuels.

In summation, agricultural productivity must clearly improve by significant amounts in order to meet the world's needs and address environmental stresses brought about by climate change. For example, we must change the way we think about the use of fossil fuels as fertilizers for agricultural production. Climate change will also impact water availability, and crops must be designed with this in mind. Even concerns such as pest management will be affected by climate change in ways that are too unpredictable to determine.

2. Climate change and food security

The world's most food insecure often are rural farmers, subsisting on small farms in developing countries (Figure 2). Also falling under the category of the world's poorest, these farmers cannot afford modern irrigation systems or fertilizers and pesticides. As a result, the soil quality of these farms tends to be nutrient exhausted and susceptible to insects and other pests. These facts set the stage for even greater hardships. The world's food requirements are expected to double by 2050 (Barrett, C.B. 2010). At the same time, the total acreage of arable land that could support agricultural use is already near its limits, and may even decrease over the next few years due to salination and desertification patterns resulting from climate change (CIA Factbook). Fresh water available for agricultural use will increasingly become scarce, and changing weather patterns will impact growing conditions. Without radical changes in agricultural practices, the future could not look any more bleak for the world's poor.

There is a silver lining, however, to all of this gloom and doom. Clearly, changing the way we think about crop production must take place on multiple levels. New varieties of crops must be developed which can produce higher crop yields with less water and fewer agricultural inputs. Besides this, the crops themselves must have improved nutritional qualities or become biofortified in order to reduce the chances of 'hidden hunger' resulting from malnourishment. The use of plants to produce therapeutic proteins, for example, will result in affordable medicines which can better address a burgeoning global population. Furthermore, more arable land can be recovered from polluted regions through phytoremediation and related technologies involving the plant sciences. Agricultural technologies currently under development will renovate our world to one that can comfortably address the new directions our planet will take as a result of climate change.

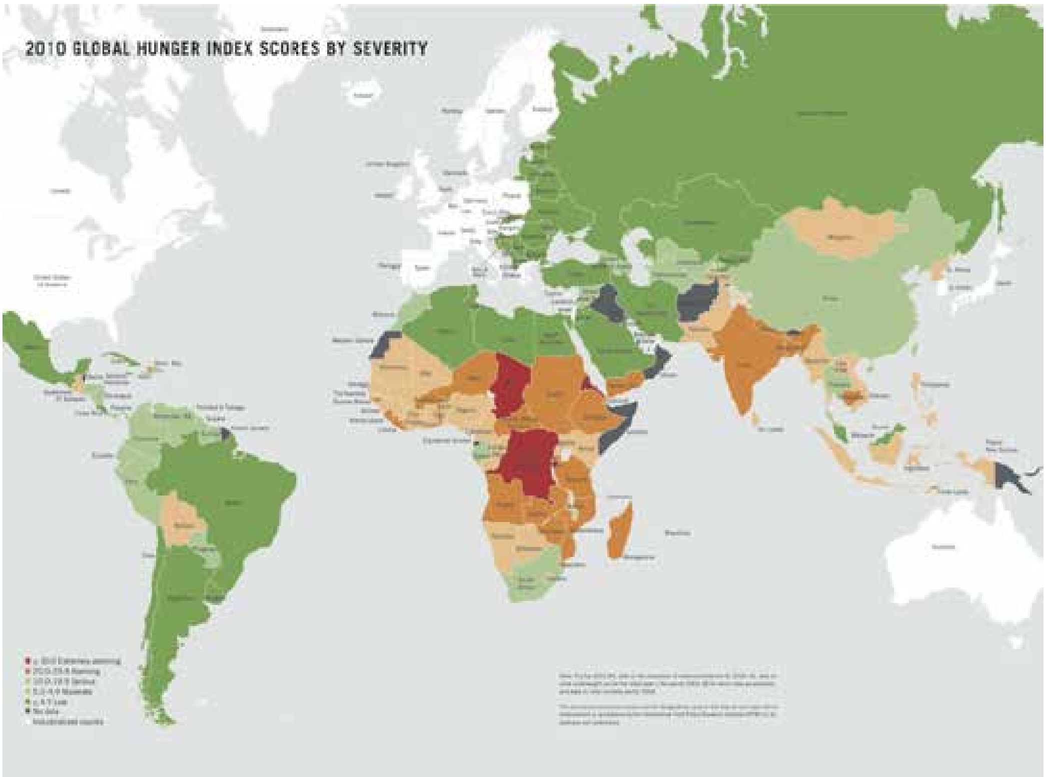


Fig. 2. Global hunger index scores by severity.

3. Sustainable intensification of agriculture and climate change

It is difficult to envision the optimum way to increase crop production using a single uniform strategy. Instead, a variety of approaches must be employed and tailored for any particular agricultural setting. New technologies must be developed to improve crop yield, reduce damage due to pests and minimize food waste, yet also use less land, fertilizer and water. This 'sustainable intensification' includes the marriage of conventional plant breeding with plant biotechnology, including genetic modification (GM) to achieve these goals (Timmmer, 2003, Christou & Twyman 2004).

The world's rural poor have much to benefit by the use of agricultural biotechnology. Genetically modified crops are under construction which are nutrient rich and disease resistant. Transgenic crops are being generated which can thrive in poor soils, tolerate extreme conditions such as drought and heat, and accumulate much needed minerals and vitamins in edible plant parts. Other plants can be generated which will extract heavy metals and pollutants from contaminated soils, providing more arable land. New crops that are designed to be more adaptable to the upcoming ordeals of climate change will make food security far more achievable. The following section describes some of these up-and-coming technologies.

Much attention has been placed on generating crops which are tolerant to heat, drought and other environmental stresses. Plant varieties are required which are capable of surviving and even thriving in a variety of rapidly changing and extreme environmental conditions. Sub-Saharan Africa, for example, a continent already hungry, will face even more heat and desertification. Some regions of Asia, on the other hand, may find high salinity a challenge for crop growth. The methods by which scientists are addressing this challenge are creative to say the least. Plant architecture, for example, can be modified to enable plants to resist adverse environmental conditions. The shape, distribution and consistency of plant roots and leaves can be designed to better catch and retain water in times of extreme drought. Roots can be altered for shallow growth so that they remain close to the surface, the better to collect dew and runoff from precipitation. Similarly, leaves can be modified to trap moisture from escaping by strictly controlling their stomata (pores) (Somvanshi, 2009, Bhatnagar-Mathur *et al.,* 2008, Tester, & Langridge, 2010). Plants with modified photosynthetic machinery can be tailored to be more receptive to changing weather patterns.

As a result of climate change, plants which exhibit tolerance to high salt content in soils will be essential. High salinity currently affects one fifth of irrigated land, resulting at the least in inhibition of crop growth, and at the most, death. Other plant types have developed tactics to respond to high salt conditions; these techniques can be exploited to help today’s crops cope with this unique stress. For example, some plants have developed the ability to sequester sodium ions into cell vacuoles or even block sodium ions from entering plant cells. The genes involved in these diverse mechanisms have been identified and have been transferred to crop plants such as rice, which lack these characteristics. Crops modified in this fashion can then thrive in regions which were previously unsuitable for growth (Tuteja, 2007, Uddin et al.,2008).

The requirement of crop plants for nitrogen through the use of fertilizers may also be impacted as a consequence of climate change. In sub-Saharan Africa, for example, access to artificial fertilizers is poor to non-existent. Yet nitrogen continues to be a necessary staple in agriculture for the industrialized world, and causes problems with respect to runoff into waterways or release to the atmosphere in the form of greenhouse gases. A principal concern is the fact that artificial fertilizers are actually produced from fossil fuels, further entwining industrialized countries to petroleum production, and the dependence which lies therein. Crops which are efficient in nitrogen usage and/or have lower nitrogen requirements are much needed. For example, rice crops have been developed which have the ability to uptake nitrogen from the soil with improved efficiency, thus relieving the intense requirement for nitrogen from fertilizers. Since these plants exhibit an improvement in nitrogen uptake, they can achieve a desired biomass and seed yield with a reduced need for high levels of nitrogen application through fertilizers. Other means by which to reduce the requirement for nitrogen is the generation of corn and other crops which can fix their own nitrogen, through the modification of current nitrogen-fixing bacteria (www.eurekalert.org). These novel technologies will facilitate crop growth in the absence of fertilizers, and could help those in Africa who have limited access to nitrogen-based fertilizers yet will soon face the greatest environmental impact due to climate change.

Global warming will bring about a change in biodiversity in many of the world's microclimates. Insects and other plant pathogens will eventually bridge gaps in their geographical locations and host ranges as never before. As a result, the introduction of both old and new plant pests will bring about a change in management strategies. Just as the prospect of global warming is predicted to bring about increases in mosquito production, and most likely increases in vigorously fought deadly diseases such as malaria and Dengue fever, plant pathogens will also most likely make an appearance in plant hosts where they were unable to gain an advantage before. Plant pathologists will be required to be ever more vigilant in their surveillance of newly emerging epidemics caused by plant pathogens as a result of global warming. The spruce budworm for example, in the boreal forests of North America, has been able to take advantage of the warmer summers and longer growing seasons to reproduce more rapidly each year, resulting in deadly forest infestations. These infestations affect both the natural ecosystems of the forests themselves, as well as the lumber industry, a prime economic engine of the area (canadaforests.nrcan.gc.ca). New disease resistant plants will be required by incorporating molecular breeding strategies with genetic modification. Many crop plants have now been engineered which utilize a number of novel techniques to exhibit resistance against a variety of pathogens, including viruses, bacteria, fungi and nematodes. Some of these techniques involve using gene products from pathogens themselves, as in the case of virus resistant cassava or insect resistant corn. Others will take advantage of evoking systemic defence pathways already inherent in the plant (Gonsalves, 2002, Lay *et al.*, 2003, Gill *et al.,* 1992). Pathogen detection and disease resistance will also be managed by nanotechnology. For example, nanosensors can be utilized to detect plant pathogens, and nanoparticles can encapsulate pesticides and release them on crops or in insects upon consumption in a controlled fashion (google.com/site/isinanoicarnaip/).

4. Biofortified and other nutritionally enhanced foods

One way to address the ever growing need for more food crops is to nutritionally enhance those crops which are currently considered to be staples for the world's poor. By producing biofortified rice, wheat and corn, the principal grains which feed much of the human race today, with increased mineral and vitamin content, the nutritional status for those who have little variety available in their diet can be improved. The generation of plants with enhanced micronutrient content can thus be a means to support those whose food supply may dwindle with respect to diversity in the face of climate change. For example, vitamin A deficiency causes approximately 500,000 cases of blindness in children. By increasing the vitamin A content of rice and other staple crops, this number can be greatly reduced (Mayer, 2007). Other examples of biofortification strategies include zinc and iron enriched corn, cassava and rice, or calcium-enriched carrots and tomatoes (Cockell, 2007, Morris, et al., 2008, Naqvi et al., 2009).

Biofortified foods can be produced either through the generation of transgenic plants which possess additional biosynthetic pathways, such as vitamin A-enriched 'Golden Rice' or by altering the general physiology of the plant in such a way that it is able to extract more micro-nutrients from the soil, such as iron-enriched wheat (Figure 3). The design and generation of plants which accumulate more vitamins and minerals can also be beneficial for the health of the plant itself. Plants which are nutrient-rich are better able to weather more extreme environmental conditions imposed by climate change. Plants which are nutrient rich exhibit vigorous growth, better yield and more resistance to diseases as well (Welch, & Graham, 2004, Bouis, 2003). Biofortified foods can be easily incorporated into the dietary habits and farming programs of the rural poor of developing countries. People who would have access to biofortified foods may very well be better prepared to withstand deleterious effects on their livelihoods due to climate change (Hotz & McClafferty, 2007, King 2002, Gilani & Nasim,. 2007, Nestel, et al., 2006, Zhu, et al., 2007, Jeong, & Guerinot, 2008).

http://www.flickr.com/photos/ricephotos/5516789000/in/set-72157626241604366

Fig. 3. Golden Rice grain compared to white rice grain in screenhouse of Golden Rice plants.

5. Biopharmaceuticals produced in plants

Climate change is predicted to bring more drought, greater salinity, and higher temperatures to countries where people are most vulnerable. A significant proportion of people in these countries are malnourished today, and more problems in this regard can be expected as food prices fluctuate and food security becomes more and more difficult to achieve. People who are undernourished or malnourished are less likely to fend off infectious diseases, and the challenge of providing sufficient vaccines and other medicines is already difficult to meet. Plants can help to rise to this challenge through their ability to act as production platforms for biopharmaceuticals. Indeed, both food and non-food crops are currently being used to produce vaccine proteins against these infectious diseases which are the greatest causes of infant mortality in the Third World today (Hefferon, 2009). Plant made vaccines which target common diarrheal diseases such as Norwalk Virus, enterotoxigenic *E.*

coli, cholera, and rotavirus have all been constructed and have shown promising results in preliminary human clinical trials. These vaccines can be produced rapidly, are inexpensive, can be taken by oral consumption and require no syringes or medical personnel to administer them (Tacket, 2007). These attributes make plant-derived vaccines very attractive for distribution to developing countries. Monoclonal antibodies can also be produced using plant-based systems. Diseases such as rabies, a problem in developing countries but not so much in the West, may be better addressed (Modelska et al., 1998). Other diseases such as hookworm are often not given priority for funding by the West; the inexpensiveness of plant-based production platforms offers an alternative approach for research and development. Hepatitis B Virus and human papillomavirus also represent significant problems in developing countries; plant-made vaccines offer one feasible means by which to combat them (Thanavala, 2005, Venuti, 2009].

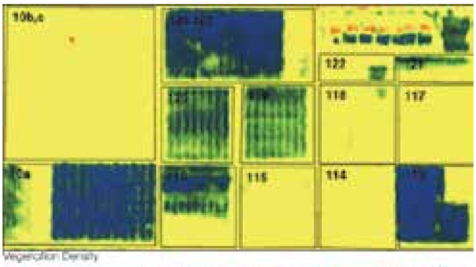
6. Alternative approaches to farming to address climate change

Newer varieties of plants which are more disease resistant, more nutritious, and better able to withstand droughts, high temperature, and high salinity environments are required immediately to prevent humanitarian disaster in the face of climate change. Modern plant breeding strategies have enabled agricultural researchers to develop new strategies to search for and identify traits which could help crop plants withstand extreme environmental conditions. For example, examination of the genetic material from wild relatives of crops has resulted in the recovery of a number of useful genes which have been lost over the course of crop evolution. Retrieval of these old 'wild' genes and their re-incorporation into current crops may facilitate the ability of these crops to adapt and flourish in a rapidly changing environment (Pennisi, 2010). The selection of novel plant traits has been further hastened by the use of autonomated breeding systems (www.lemnatec.com). Through robotics, young plants can be exposed to a specific set of environmental conditions and then be selected for their ability to tolerate stress, maintain high yield, etc., without the requirement of lengthy field tests. Furthermore, new genomics approaches such as marker assisted selection enables desired traits that would help future crops overcome environmental stresses to be identified and followed through breeding strategies (Pennisi, 2010, Baulcombe, 2010).

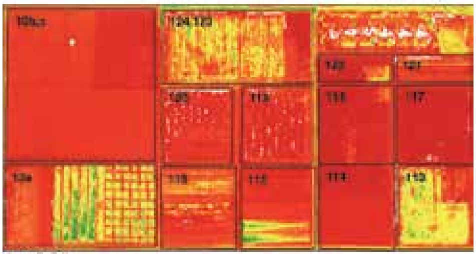
There are other means by which to increase crop production besides changing the traits of the crops themselves. Precision agriculture, for example, refers to new farming methods based on optimizing resources and minimizing inputs, including water and fertilizer. Precision agriculture can include sophisticated devices such as GPS to identify factors ranging from moisture and nutrient content of soils to pest infestation of a given crop (Figure 4). Using this approach, optimal inputs can be applied to a specific region of a given crop when required, rather than uniformally and at predetermined times across the entire field, whether the crop requires inputs or not. The great advantage of this technique is the avoidance of overuse of pesticides, herbicides, fertilizer and water (earthobservatory.nasa.gov, www.ghcc.msfc.nasa.gov).

The same principles of precision farming can also be applied to developing countries, without the requirement of advanced technologies. For example, the concept of drip irrigation, a practice by which small amounts of water are applied to plant root systems by a network of irrigation pipes, has been demonstrated to work successfully for drought-prone areas (Figure 5). Similarly, some resource-poor countries utilize a farming technique whereby tiny amounts of fertilizer are applied to the roots of crops at specific times in the growing season. These low-tech farming practices have enabled farmers who have poor access to water or artificial fertilizers to make the most of their crop yield (Mara Hvistendahl, 2010, Nature Editorial 2010).

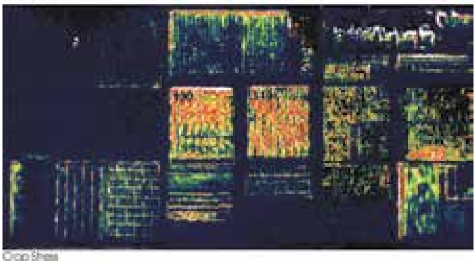
Better management of the high percentage of food that currently goes to waste could also have a beneficial impact on achieving food security. While excess food waste in the supermarket is clearly a problem in industrialized countries, in the Third World, food crops are often spoiled in the field before they are harvested, infected with insects or mold while stored in primitive facilities, or over-ripen during inefficient transport to the marketplace. All of these bottlenecks need to be addressed to prevent excess food waste and improve food availability (Parfitt et al., 2010).



Vegetation Density



Water Deficit



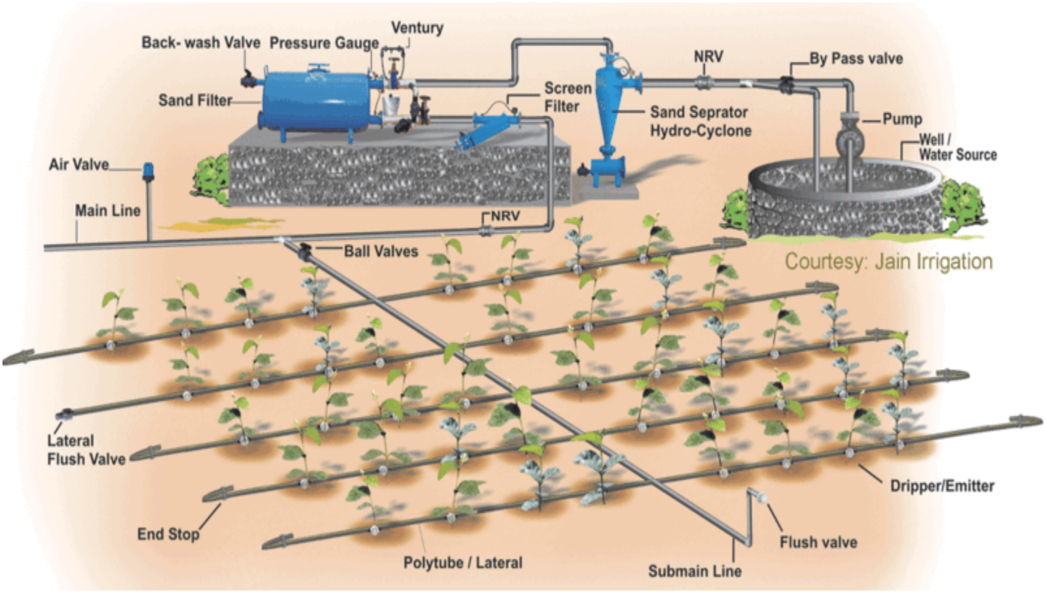
Crop Stress

These three false-color images demonstrate some of the applications of remote sensing in precision farming. The goal of precision farming is to improve farmers' profits and harvest yields while reducing the negative impacts of farming on the environment that come from over-application of chemicals. The images were acquired by the Daedalus sensor aboard a NASA aircraft flying over the Maricopa Agricultural Center in Arizona. The top image (vegetation density) shows the color variations determined by crop density (also referred to as "Normalized Difference Vegetation Index", or NDVI), where dark blues and greens indicate lush vegetation and reds show areas of bare soil.

The middle image (water deficit) is a map of water deficit, derived from the Daedalus' reflectance and temperature measurements. Greens and blues indicate wet soil and reds are dry soil.

The bottom image (crop stress) shows where crops are under serious stress, as is particularly the case in Fields 120 and 119 (indicated by red and yellow pixels). These fields were due to be irrigated the following day. This file is in the public domain because it was created by NASA. NASA copyright policy states that "NASA material is not protected by copyright unless noted".

Fig. 4. Precision Farming.



Courtesy: Jain Irrigation

Fig. 5. Drip Irrigation.

7. Climate change and non-food crops

Non-food crops are also being examined as a means to address climate change. The use of biofuel as an alternative energy source is at the height of controversy. While ethanol production from crops such as corn may indeed provide a substitute for fossil fuels, they unfortunately also compete with corn grown as a food crop and in fact drive up food prices, thus adding to the misery of the world's poor. One option is to use other non-food plants for biofuel production. Switchgrass, for example, can be grown on suboptimal land that cannot be used by corn or other food crops, and produces fuel less expensively than either petroleum or corn (Figure 6) (Bouton, 2007). Algae is another plant source for biofuel which would not negatively impact the world's food supply. These examples represent up-and-coming technologies which will soon move up to the forefront of alternative energy development (Beer *et al.*, 2009).

Other non-food crops address the reduction in arable land acreage available as a result of climate change; these plants are under development for phytoremediation purposes. Man-made pollutants such as heavy metals which have been added to soil and water have reduced the availability of much needed fertile land. Some plant species have the capacity to uptake heavy metals through their root systems and accumulate them in foliage or other tissues. These plants can then be harvested to rid the land of contaminants, thus providing an increase in valuable, arable farmland (Figure 7) (Wu *et al.*, 2007, Memon & Schröder, 2009].

This work has been released into the public domain by its author, Chhe at the wikipedia project. This applies worldwide.

Fig. 6. Switchgrass.

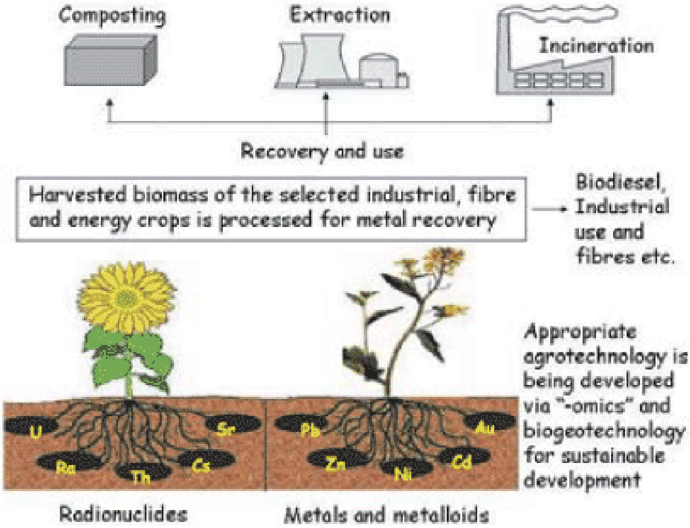


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Fig. 7. Phytoremediation: green technology for the clean up of toxic metals in the environment.

8. Conclusions

Climate change brings with it some daunting challenges. More food must be produced on less arable land than is available today. New agricultural technologies and farming practices must be developed and implemented. This chapter has attempted to address some of the strategies currently under development in the agricultural sciences. One way to achieve global food security requires the utilization of novel plant breeding strategies which will quickly find helpful traits that enable plants to thrive under adverse environmental conditions. Biotechnology will play a paramount role in these approaches. Revolutionary farming techniques, led by precision agriculture, will keep crop yields high while maintaining water, pesticide and nitrogen inputs to a minimum. Key food crops have already been biofortified with micronutrients such as iron and vitamin A. Plants are also being actively pursued as production platforms for biopharmaceuticals, and may very well turn out to be a viable solution for providing medicines to those in remote communities. Innovative uses for non-crop plants in biofuel and phytoremediation will also offer alternatives. With these and other strategies in place, the world will be better prepared to address the future challenges that will result from climate change.

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This book provides an interdisciplinary view of how to prepare the ecological and socio-economic systems to the reality of climate change. Scientifically sound tools are needed to predict its effects on regional, rather than global, scales, as it is the level at which socio-economic plans are designed and natural ecosystem reacts. The first section of this book describes a series of methods and models to downscale the global predictions of climate change, estimate its effects on biophysical systems and monitor the changes as they occur. To reduce the magnitude of these changes, new ways of economic activity must be implemented. The second section of this book explores different options to reduce greenhouse emissions from activities such as forestry, industry and urban development. However, it is becoming increasingly clear that climate change can be minimized, but not avoided, and therefore the socio-economic systems around the world will have to adapt to the new conditions to reduce the adverse impacts to the minimum. The last section of this book explores some options for adaptation.

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