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Climate Change
Socioeconomic Effects

Edited by Juan Blanco and Houshang Kheradmand

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Edited by **Juan Blanco** and **Houshang Kheradmand**

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Notice

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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 variations can be both natural or anthropogenic (Simard and Austin 2010). In either case, the change in the current climate will have impacts on Earth's biogeophysical system. 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, creating discussions in economy, science, politics, etc. There is no doubt 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 seasons, with winters expected to warm up significantly more than summers. In addition, changes in precipitation are also expected, which could lead to an 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 global warming effects. These uncertainties highlight the need for more research on how global events have effects at regional and local scales, but they also indicate the need for our societies 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 when, compared to the total number of cars, only a small percentage of drivers suffer car accidents. In addition, the most risky maneuvers (i.e. excessive speed, not stopping on red light) 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 situation of driving without insurance and without respecting road signals.

All policies and practices for economic, industrial and natural resource management need to be founded on sound scientific foundations. The second section of this book offers an interdisciplinary view of the socioeconomic effects issues related to climate change, and provides a glimpse of state-of-the-art researches carried out around the world to inform scientists, policymakers and other stakeholders.

The recent rapid increase in human population, industrial activities and resources consumption especially over the past century has raised concerns that humans are beginning to discover a new Socio-Economic and Ecological world with challenging benefits and issues and a real need for “not damaging more the planet”.

The scientific consensus is that the current population expansion and accompanying increase in usage of resources is linked to threats to the ecosystem. According to projections, the world population will continue to grow until at least 2050, with the population expected to reach more than 10 billion in 2050. The scientific simulations including the climate change based on experiences is one of the best approaches to assess the risk and plan to manage related issues (Preston 2005, AGO 2006).

Examining the potential socio-economic aspect of climate change and developing a sustainable management policy and strategy to manage the future issues is a holistic and multi-disciplinary approach including all critical issues such as food, water, energy, environment, health, revenue, life- quality, traditions at local, national, regional and global levels. The idea of sustainable development grew from numerous environmental movements in earlier decades. Summits such as the Earth Summit in Rio (Brazil, 1992) were major international meetings to bring sustainable development to the mainstream.

However, records proving humanity’s ability to move toward a sustainable society appear to have been quite poor so far. The concept of sustainability means many different things to different people, and a large part of humanity around the world still live without access to basic necessities (UN 1992).

This book shows some of the socio-economic impacts of climate change according to different estimates of the current or estimated global warming. A series of scientific and experimental research projects explore the impacts of climate change and browse the techniques to evaluate the related impacts:

- Inmaculada Martínez-Zarzoso, Nicolas Korves and Anca Monika Voicu, have tried to evaluate Free Trade “Socio-Economic and environment impacts” and helped to imagine the power of Trade and its consequences.
- Cees van Woerkum and Anne Marike Lokhorst describe the broad range of human behaviors and their impacts on the natural environment.
- Paul E. Parham, Céline Christiansen-Jucht, Diane Pople and Edwin Michael review current knowledge on the impacts of global change and provide valuable models for a better understanding of future disease challenges.

- Arthur Saniotis, Alana Hansen and Peng Bi discuss how climate change could affect not only the environment, but, as a major issue, could also affect environmental health on a worldwide scale.
- Ying Zhang, Peng Bi and Baofa Jiang present a systematic review and research results about climate variability and impacts on the Chinese population's health.
- Alexendra Lutz demonstrates the needs for impact assessments at local scales with the accurate tools and techniques to assess impacts on water resources.
- Zhang Biao, Li Wenhua, Xie Gaodi and Xiao Yu have calculated and estimated the water conservation function and its economic value of the forest ecosystem in Beijing thanks to mathematical simulations.
- Adalberto Tejeda-Martinez, J. Abraham Torres-Alavez, Alfredo Ruiz-Barradas, Saúl Miranda-Alonso, Sonia Salazar-Lizán have studied climate variations (in the State of Veracruz - Mexico) as well as evidences of climate change based on precipitation and temperature tendencies.
- Zofia Wysokinska analyzed the EU new members competitiveness and environmental products market combined with the policy and strategy to combat climate change such as Sustainable construction, recycling, bio-based products and renewable energies (European Commission 2007).
- László Babinszky, Veronika Halas & Martin W.A. Verstegen have presented the impact of changing meteorological factors on crop production and metabolism of farm animals, including effects on volume and quality of animal products based on human nutrition aspects.
- Venkataramana Sridhar and Xin Jin have identified five climate models that are relevant to capturing the future trends in precipitation and temperature representing a wide range of conditions and also change by time. The models include CCSM3, HADCM3, IPSL CM4, MIROC 3.2 and PCM.
- Karim-Aly Kassam, Michelle Baumflek, Morgan Ruelle and Nicole Wilson have examined through two case studies the concepts of vulnerability and adaptation in the contexts of Arctic and sub-Arctic communities
- García-Mozo H., Mestre A. & Galán C. have analyzed vegetative and overall reproductive phenology of different species in southern Spain which have special economical interests.
- M. Trnka, P. Hlavinka, M. Dubrovsky, E. Svobodova, D. Semerádova, L. Bartosova, J. Balek,
- J. Eitzinger, M. Mozny, Z. Zalud have evaluated the major impacts of changing climatic conditions in the Czech agriculture, determined by comparing its current and expected state.
- Robert Kalbarczyk, Beata Raszka & Eliza Kalbarczyk have evaluated the increase of average air temperature impact on tomato production in Poland.
- Bruce McCarl, Sung Ju Cho, Jinxiu Ding and Chin-Hsien Yu have reviewed the knowledge on agricultural vulnerability to climate change.
- Alejandro Ismael Monterroso Rivas, Cecilia Conde Álvarez, Carlos Gay García and Jesús David Gómez Díaz have contributed to the sensitivity analysis

development which helped to characterize the current and future sensitivity of the municipalities of Mexico.
- Hichem Ben Salem, Mourad Rekik, Narjess Lassoued & Mohamed-Aziz Darghouth have analyzed the livestock relationship with global warming and consumption trends.
- H. Huebener and H. Wolf presented the analysis and assessment about regional climate change in the federal state of Hesse (central Germany). Models used: Global Climate Model (GCM), Regional Climate Models (RCM) and Empirical Statistical Downscaling (ESD).
- Buchholz Wolfgang, studied the ethical issues, particularly in the context of climate policy by using normative (prescriptive) approach.
- Valny Giacomelli Sobrinho, descripts the BESF model (Bio-Economic model for carbon Sequestration by Forests) use benefits for addressing the trade-off between forestry-CDM and REDD. That model could also be applied to other countries or regions.
- Jari Lyytimäki analyzed the climate change media coverage and noted the need to take both ecological and socio-economic factors in consideration.

These 23 chapters provide a good overview of the different changes impacts that already have been detected in several regions of the world. They are part of an introduction to the research being done around the globe in connection with this topic. However, climate change is not just an academic issue important only to scientists and environmentalists; it also has direct implications on various ecosystems and technologies. The other two books of this series "Climate change – Geophysical foundations and ecological effects" and "Climate Change – Research and technology for climate change adaptation and mitigation" explore these topics in detail. We can thus only 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. Special 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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1

Is Free Trade Good or Bad for the Environment? New Empirical Evidence

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1. Introduction

One of the most important debates in trade policy concerns the impact of trade liberalization on the environment and, hence, on climate change. "Increased trade liberalization, increased trade, increased production, increased energy use and climate change," while treated as separate issues until the early nineties, have become the focus of scholars researching trade and the environment (Stoessel, 2001). In particular, the debate originated in the early 1990s, following negotiations over the North American Free Trade Agreement (NAFTA) and the Uruguay round of the General Agreement on Tariffs and Trade (GATT), both of which emerged during a time of rising environmental awareness. Environmentalists argued that the creation of NAFTA would result in an environmental disaster for Mexico and pointed to the Maquiladora zone, where trade with the United States caused a concentration of industry that had detrimental effects on the local environment.
Moreover, trade is related to numerous environmental problems. The Handbook on Trade and Environment emphasizes that trade acts as facilitator of the "international movement of goods that, from an environmental perspective, would best never be traded. With hazardous wastes and toxic materials, the environmental risks increase the further the goods are transported, since spillage is always possible. Equally, such 'goods' may end up being dumped in countries without the technical or administrative capacity to properly dispose of them, or even assess whether they should be accepted. Trade also makes possible the over-exploitation of species to the point of extinction—there is rarely enough domestic demand to create such pressure." Examples include the threats to species such as elephants, due to trade in ivory, the deterioration of air quality in parts of China attributed to export-led growth, and unsustainable harvest rates in tropical rainforests due to trade in timber (Copeland and Taylor, 2003).
A major concern is that the increasing competition between companies induced by further trade liberalizations causes a "race to the bottom" in environmental standards, because countries might weaken their environmental policy in order to shelter their industry from

international competition or to attract foreign firms due to low costs of environmental protection as a similar incentive as low labor costs.

In contrast, advocates of free trade point out the potential "gains from trade," in particular, the increases in income generated by trade. These have likely contributed to major improvements in air and water quality in developed countries over the last decades because the citizens' demand for environmental quality is likely to increase with income. Another possible benefit of trade is the increased transfer of modern (and thus cleaner) technologies to developing countries, as multinational corporations might find it simpler and more effective to apply the same technology in all of their locations. Similarly, the Porter hypothesis (Porter and van der Linde, 1995) states that a tightening of environmental regulations stimulates technological innovation and thus has a positive effect on both the economy and the environment.

Furthermore, supporters of free trade emphasize that trade restrictions are an ineffective way to protect the environment and that environmental problems are better dealt with by adopting effective environmental controls. Recently, the debate has been further intensified by the creation of the World Trade Organization (WTO) and by new rounds of trade negotiations that include several trade and environment issues, such as the Doha Declaration.

At the heart of the debate over how trade affects the environment are the questions as to whether environmental goals are being threatened by free trade and the WTO, and whether trade liberalization will cause pollution-intensive industries to locate in countries with relatively weak environmental regulations. Furthermore, since different countries undertake different levels of climate-change mitigations, significant concern has arisen that carbon-intensive goods or production processes from high income and stringent environmental regulation countries could potentially migrate to low income and lax environmental regulation countries (e.g., countries that do not regulate greenhouse gas {GHG} emissions). This is known as the pollution haven hypothesis (PHH). Although two distinct hypotheses concerning pollution havens have sometimes been blurred together by the subject literature, it is crucial to distinguish between them (we follow the definition of Taylor, 2004).

First, a "pollution haven effect" (PHE) occurs when tightening of environmental regulation leads to a decline in net exports (or increase in net imports) of pollution-intensive goods. In terms of capital mobility, a PHE exists if tightened environmental stringency causes a capital outflow in the affected industries. The existence of a pollution haven effect simply indicates that environmental regulations have an influence on trade volumes, capital flows and plant location decisions. Second, according to the PHH, the pollution haven effect is the main determinant of trade and investment flows. It predicts that trade liberalization will cause pollution-intensive industries to migrate from countries with stringent environmental regulations to countries with lax environmental regulations. The latter countries will have a comparative advantage in "dirty" goods and will attract foreign investment in their polluting sectors.[1] Simply put, a PHE takes trade policy as given and asks what happens if a country tightens environmental regulations. The PHH, however, takes differences in environmental policy as given and asks what happens if a country liberalizes trade. Although these two concepts are different, there is a clear link between them. The predictions of the PHH can only be true if there is a strong PHE. While the existence of a pollution haven effect is necessary, it is not sufficient, however, for the PHH to hold.[2]

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[1] The production shift might occur as a consequence of either trade or foreign direct investments.

[2] Additionally, this implies an alternative test for the pollution haven hypothesis: The finding of a small pollution haven effect is evidence against the pollution haven hypothesis.

This chapter aims to answer the following questions: Placed in the context of the PHH, is free trade good or bad for the environment? Do developed countries export their pollution-intensive production to developing countries? Is trade liberalization responsible for increased greenhouse gas (GHG) emissions (e.g., CO_2) and/or sources of GHG emissions (e.g., SO_2) contributing to climate change? Our investigation uses panel data for 95 countries during the period 1980-2004 and regresses three measures of pollution, nnamely per capita emissions of sulfur dioxide (SO_2), emissions of carbon dioxide (CO_2), and energy consumption on trade intensity (the sum of exports and imports divided by GDP), thereby controlling for income per capita, year and country-specific effects. We carry out the analysis as follows. First, we perform the estimation for the full sample of countries. Second, we divide the countries into three categories according to their income levels: low, middle and high income. Based on our analysis, we argue that it is not possible to find any implications for the PHH in regressions over the full sample, but, rather, over distinct income groups. Our results show moderate support for the PHH for CO_2 emissions and energy consumption, but no significant effect could be obtained for SO_2 emissions. Concerning the impact of trade liberalization on climate change, its indirect effect on anthropogenic climate change has been present through an increase in transport activities and an increase in the use of fossil fuel energy. However, trade alone is certainly not the root cause for anthropogenic climate change.

This chapter is organized as follows. Section 2 provides a summary of the theoretical and empirical background for purposes of our empirical application. The section also summarizes briefly the literature pertaining to the impact of trade liberalization on climate change. Section 3 discusses methodological issues related to this research. Section 4 describes the data and the empirical analysis and presents the results. Section 5 summarizes the main findings and concludes.

2. The effects of trade and trade liberalization on the environment and climate change: theory and empirics

2.1 Theory

2.1.1 How does trade in general affect the environment?

There is a close and complex relationship between the effects of trade on the environment. This typically led scholars to decompose the environmental impact of trade liberalization into scale, technique and composition effects[3]. Furthermore, when trade is liberalized all these effects interact with each other.

Scale effect

Trade liberalization expands economic activity and fuels economic growth. As the scale of global economic activity increases due, in part, to international trade, Environmental change/damage will occur. In addition, the literature suggests that, when the composition of trade and the production techniques are held constant, the total amount of pollution must increase. Thus, the scale effect has a negative impact on the environment. Simply put, "if the scale effect dominates technology and composition effects and if externalities are not internalized, economic growth will always be harmful to the environment" (Stoessel, 2001).

[3] Antweiller et All (2001), Grossman & Krueger (1991), Lopez & Islam (2008), Cole (2003), Stoessel (2001),

Trade is also credited with raising national incomes. The literature reports a great deal of evidence that higher incomes affect environmental quality in positive ways (Grossman & Krueger, 1993; Copeland and Taylor, 2004). This suggests that, when assessing the effects of growth and trade on the environment, we cannot automatically hold trade responsible for environmental damage (Copeland and Taylor, 2004). Since beneficial changes in environmental policy are likely to follow, the net impact on the environment remains unclear. Within the scale effect the income effect is subject to controversy. The less controversial part regards the fact that extreme poverty tends to lead to people exploiting the environment in order to survive. The more controversial part concerns the "hump-shaped" or the inverted U-shaped relationship between per capita income and pollution, also known as the Environmental Kuznets Curve (EKC). The essence of the EKC is that raising incomes per capita are not linearly correlated with environmental deterioration. Rather, pollution increases in its early development stages until it reaches a turning point, and then declines since concern with environmental quality increases and long-term issues start to prevail (Stoessel, 2001; Copeland, 2005; Copland and Gulati, 2006).[4]

Technique effect

Researchers widely agree that trade is responsible for more than 75% of technology transfers. New technology is thought to benefit the environment if pollution per output is reduced. Furthermore, if the scale of the economy and the mix of goods produced are held constant, a reduction in the emission intensity results in a decline in pollution. Hence, the technique effect is thought to have a positive impact on the environment (Stoessel, 2001; Mathys, 2002).

Composition effect

Trade based on comparative advantage results in countries specializing in the production and trade of those goods that the country is relatively efficient at producing. If comparative advantage lies in lax environmental regulations, developing countries will benefit and environmental damage might result. If, instead, factor endowments (e.g., labor or capital) are the source of comparative advantage, the effects on the environment are not straightforward. Therefore, the impact of the composition effect of trade on the environment is ambiguous (Mathys, 2002; Stoessel, 2001).

2.1.2 How does trade liberalization affect the environment?

The impact of trade liberalization on the environment has been studied by many scholars over time and is the main focus of environmentalists.

The PHH states that differences in environmental regulations are the main motivation for trade. The hypothesis predicts that trade liberalization in goods will lead to the relocation of pollution intensive production from countries with high income and tight environmental regulations to countries with low income and lax environmental regulations. Developing countries therefore will be expected to develop a comparative advantage in pollution intensive industries, thus becoming pollution havens. In this scenario developed countries will gain (clean environment) while developing countries will lose (polluted environment). Table 1 below summarizes these ideas.

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[4] The name of the environmental Kuznets curve relates to the work by Kuznets (1955), who found a similar inverted U-shaped relationship between income inequality and GDP per capita (Kuznets, 1955).

The "factor endowment hypothesis" (FEH) claims that pollution policy has no significant effect on trade patterns but, rather, differences in factor endowments determine trade. This implies that countries where capital is relatively abundant will export capital intensive (dirty) goods. This stimulates production while increasing pollution in the capital rich country. Countries where capital is scarce will see a fall in pollution given the contraction of the pollution generating industries. Thus, the effects of liberalized trade on the environment depend on the distribution of comparative advantages across countries. A summary of the FEH is presented in Table 2 below.

Country	Environmental Policy	Comparative Advantage	Environmental Quality
Developed (high income)	Strict environmental regulations	"Clean" industries	"Clean"
Developing (low income)	Lax environmental regulations	"Dirty" industries	"Dirty"

Table 1. Overview of the pollution haven hypothesis.

The race-to-the-bottom hypothesis asserts that developed countries refrain from adopting more stringent environmental regulations due to competition with countries that have lax environmental regulation (Stoessel, 2001; Esty and Geradin, 1998).

Country	Comparative Advantage	Effects on pollution
Developed (capital abundant)	Pollution intensive goods	Pollution increases
Developing (capital scarce)	Non-pollution intensive goods	Pollution decreases

Table 2. Overview of the factor endowment hypothesis.

The "Porter hypothesis" assumes a race-to-the-top, meaning that strict environmental regulations have the potential to induce efficiency while encouraging innovation that helps to improve competitiveness (Porter and van der Linde, 1995; Stoessel, 2001).

In summary, the literature identifies the existence of both positive and negative effects of trade on the environment. The positive effects include increased growth accompanied by the distribution of environmentally safe, high quality goods, services and technology. The negative effects stem from the expansion of scale of production and consumption that could potentially threaten the regenerative capabilities of ecosystems while increasing the danger of depletion of natural resources.

2.1.3 How do trade and trade liberalization affect climate change?

The literature presented in this section focuses on sectors where trade liberalization has consequences on the emission of GHGs, which, in turn, affect climate change.

Trade and trade liberalization increase global production and consumption of goods and services, generate increases in countries' incomes, and fuel economic growth. Higher trade volumes and increased trade in general are directly correlated with increased transport activities and increased demand for energy. How can these affect climate change?

According to the Center for International Climate and Environmental Research in Oslo, Norway, "The transport sector is responsible for a large share of gas and particle emissions that affect the climate. These emissions also threaten human health, crops, and the material infrastructure. Higher standards of living and increased travel are largely to blame." Current means of transportation use fossil fuels whose burning generates around 21.2 billion tons of CO_2 per year, a GHG that enhances radiative forcing, thus contributing to climate change. McConnell (1999) points out that emissions of carbon monoxide (70 percent of which are produced by the transport sector) and carbon dioxide (25 percent of which are also produced by the transport sector) are destabilizing the earth's climate. Landis Gabel (1994) notes that transport is one of the major causes of environmental erosion in industrial countries. This is attributed to the depletion of non-renewable energy resources, noise and the development of infrastructure.

Road traffic is seen as the main contributor to climate change (mainly, warming) given its large emissions of CO_2 as well as significant emissions of ozone and soot. Road transportation is credited with generating more GHG than rail, and significantly more than sea-based freight transport (Stoessel, 2001).

Ships and planes regarded in a climate context are a special category. They are not covered by the Kyoto Protocol[5], and emissions consist of components with short lifetimes and specific local effects. Ship emissions of NOx in unpolluted areas have a big impact on ozone formation. According to Stoessel (2001), ships have the advantage of carrying 90 percent of world's trade while being responsible for around 2 percent of global CO_2 emissions. Air traffic, however, shows the most rapid and quantitatively significant increase in emissions. Its emissions of NOx in areas that are rather clean have a large impact on ozone formation.

Without overlooking the environmental degradation caused by the increase in transport services as a result of trade liberalization, one should note several positive effects of trade liberalization in the transport sector. First, trade liberalization in the transport sector results in productive and allocative efficiency in the use of transportation services. Second, the existence of a larger market for more efficient transportation has the potential to generate technological developments in that area. Third, energy-intensive travel may be avoided by using electronic communication (Horrigan and Cook, 1998). Teleconferencing and telecommuting also reduce and even eliminate travel by offering people the possibility to work from home. All these advances in electronics and communication technologies will eventually contribute to GHG abatement. Policy is also seen as a key factor in reducing GHG emissions. Reducing mobility, improving energy and changing transport fuel's mix are only a few of the policy options that countries can adopt in an effort to reduce GHG emissions.

As with transportation, increased trade liberalization resulting in higher per capita incomes also raises the demand for energy. Consumption of fossil fuels also rises in response to trade liberalization, especially in developing countries (Millsteed et all, 1999). Increased CO_2 emissions due to the burning of fossil fuels and energy use contribute to the greenhouse effect which, in turn, negatively affects climate change. Moreover, coal mining contributed 13 percent of the global methane emissions in the early 1990s. According to Stoessel (2001), where lack of market reform (internal liberalization) already has adversely affected pollution, trade liberalization will further aggravate these market and policy failures. The typical example is the coal market, where the effect of trade liberalization on climate change depends on the internal deregulation of the coal sector. In order to avoid changes in patterns of trade that potentially bring more pollution, internal liberalization should precede external

[5] The Kyoto protocol is an international agreement whose major feature is that it sets binding targets for 37 industrialized countries and the EU for reducing GHG emissions.

liberalization. It has been pointed out that internal liberalization changes the relationship between industry and the government. This will then change the instruments available to governments for mitigation of climate change. Fells and Woolhouse (1996) suggest several solutions to market failure: replacing the market, encouraging the market to operate more efficiently through an incentives and costs system, and extending the application of property rights and creating a new market. The authors note that no policy tool is considered superior to the other. Also worthwhile mentioning are subsidies that have beneficial implications on climate change, such as subsidies that support the use of nuclear energy, renewable energy sources, hydroelectric power, as well as energy efficient investments (OECD, 1997).

In conclusion, both internal (market reform) and external (trade) liberalization in the energy sector are important factors in mitigating climate change, and the implementation of one without the other is thought to be detrimental to the atmosphere. While market reform on its own is trusted to decrease GHG emissions significantly, the net effect of combined internal and external liberalization, however, seems to be ambiguous.

2.2 Empirics

In general there are two main methods to obtain empirical evidence on pollution havens. The first uses investigations contained in case studies or interviews (e.g., interviews of industry representatives on location choices).[6] The second uses econometric analyses. The econometric studies in turn can be classified into three broad categories. The first category includes direct examinations of location choices, which mainly focus on investigating environmental factors that determine new plant births within the US as a consequence of a lack of comparable cross-country data. The other two categories are indirect examinations of output and input flow. The former group of empirical studies explores the influence of differences in environmental stringency on output measures such as emissions or net exports, whereas the latter group of studies tests whether environmental regulations have an effect on the movement of inputs, such as capital and in particular foreign direct investments (Brunnermeier and Levinson, 2004).

This section presents a survey of the empirical literature, focusing on the studies of output flows. There are two reasons that explain our focus on this literature. First, there is a high number of scholarly contributions in this area of research and, second, our own empirical analysis is conducted in this manner.

The typical strategy of early studies is to regress trade flows on a measure of environmental stringency and other relevant control variables (such as income per capita) using cross-sectional country data. An early study is Tobey's (1990) paper. The author uses a cross-sectional Heckscher-Ohlin-Vanek model of international trade to examine trade patterns in five pollution-intensive sectors. For each sector he regresses net exports on country-specific measures of factor endowments and environmental stringency for 23 countries (the index of environmental stringency is an ordinal ranking of countries, based on subjective surveys). The results show that the environmental stringency index is insignificant in all regressions, leaving the author to conclude that environmental stringency has no measurable effect on net exports of polluting industries. Furthermore, in an additional omitted variable test

[6] For a survey on this literature, see, for example, Brunnermeier and Levinson (2004). The authors find the results of this literature group inconclusive, and moreover, because the predicted effects are solely based on survey responses, there is no way to isolate and quantify them.

consisting of a larger country sample, Tobey cannot reject the hypothesis that environmental stringency has no effect on net exports. However, the validity of his conclusions seems questionable because the vast majority of the estimated coefficients are insignificant (especially the measure of environmental stringency).

An often cited paper is the investigation of Grossman and Krueger (1991) on the environmental effects of NAFTA. This study is among the first to find an "environmental Kuznets curve" (EKC) relationship between economic growth and pollution. The first exercise uses a cross-country sample of concentrations of air pollutants in various urban areas to explore the relationship between economic growth and air quality over time (while controlling for country, site and city specific characteristics). Finding that concentrations of sulfur dioxide and dark matter increase at low levels of per capita GDP and decrease at high levels of per capita GDP, the authors argue that this occurs because the technique effect offsets the scale effect (the EKC relationship). In a second exercise, Grossman and Krueger follow the approach of Tobey (1990), using data on US imports from Mexico classified by industrial sector. They investigate whether pollution abatement costs[7] in the US could explain the Mexican specialization and trade patterns, thereby confirming the results of Tobey (1990), according to which environmental policy seems to have no effect on trade flows. The authors find that the composition effect created by an increase in US-Mexico trade is affected by factor endowments rather than by differences in pollution abatement costs (thus giving support to the factor endowment hypothesis). The coefficient of pollution abatement costs is negative in four of their six cross-industry regressions that explain US imports from Mexico (and is statistically significant in only two of these cases). This result contradicts the initial predictions, and the authors note that the perverse sign might be due to omitted variable bias.

Lucas et al. (1992) use a pooled cross-sectional model in order to investigate whether toxic intensity of production changed with economic growth for 80 countries during the period 1960-1988. The authors calculate total toxic emission per dollar of output for different US industrial sectors and make the assumption that these emission intensities remain constant over time and across countries. They find that developing countries as a whole had greater toxic intensity growth during the 1970s and 1980s, but toxic intensity increased in closed fast-growing economies while it declined in open fast-growing economies. This implies that trade liberalization could not have caused the toxic industry flight.

Birdsall and Wheeler (1993) replicate the study of Lucas et al. (1992) for 25 Latin American countries for the period 1960 to 1988 and report similar findings: Pollution intensity growth increased as a whole in Latin America. However, this effect is not associated with more trade openness, as in closed economies toxic intensity growth increased while in open fast-growing countries toxic emission growth declined over time. The authors conclude that pollution havens exist, but not where they are supposed to be in protectionist countries. The cited studies can be criticized on multiple grounds. First they only use income levels and openness as control variables; thus, they do not account for the role of other factors such as resource endowments. Second, because the studies use pooled cross-sections over time, the

[7] In most cases authors use pollution abatement operating costs (PAOC) rather than capital costs (see Ederington and Minier, 2003, for arguments on this matter). We try to keep a differentiation as long as it is explicitly noted by the corresponding authors. However, in general we use the term pollution abatement costs (PAC) for simplicity.

obtained result could be subject to omitted variable bias. Finally, the assumptions used in constructing the toxic emission intensities seem rather questionable (e.g., determinants of sectoral pollution intensities, such as pollution control technologies, regulations and enforcement effort, are assumed to be the same across countries). This is equal to disregarding the technique effect and leaving only the scale and composition effects (Brunnermeier and Levinson, 2004).

Van den Bergh (1997) use a trade flow equation (a gravity model of international trade) to explain the bilateral trade flows between 21 OECD countries and examined how differences in strictness of environmental regulations between countries influenced a country's imports and exports. The authors ran three regressions: for total bilateral trade flows, for an aggregation of pollution-intensive-sectors, and for an aggregation of pollution-intensive-sectors that are non-resource based. As a measure of environmental stringency they constructed an environmental index for both the exporting and importing countries from two OECD environmental indicators in 1994.[8] Other control variables included GDP, population and land area for both countries, the distance between them and three dummy variables (contiguous countries, EFTA member, European Community member). The results are partly consistent with the PHH in that the environmental index has a significantly negative effect on exports (in the first regression on total trade flows). In the second regression (dirty trade flows only) the effect is insignificant, which is consistent with the findings of Tobey (1990) for the 1970s. The authors argue that this might be due to the fact that many trade flows from dirty sectors are from resource based industries and thus from immobile industries. This is undermined by the results of the third regression (non-resource based dirty trade flows) that again show a negative and significant coefficient. On the import side the results are counterintuitive. All three regressions indicate a negative influence of country environmental regulation on imports. This leads Van Beers and van den Bergh to speculate that strict environmental regulations may provide an excuse for many governments to introduce new import barriers.

Mani and Wheeler (1998) search for the existence of pollution havens during the period 1960-1995 by using information on industrial production, trade and environmental regulation. Their study compares the development of the polluting to non-polluting output ratio (the share of pollution-intensive products relative to total manufacturing) over time with the development of the import to export ratio of polluting industries for the OECD and for Asian and Latin American emerging countries. The authors find evidence for the PHH. In the OECD countries the polluting to non-polluting ratio declined, while at the same time the import to export ratio of polluting industries increased. This is accompanied by an increase in the polluting to non-polluting ratio and a fall in the import to export ratio in Asian and Latin American countries during the same period. The authors argue that the existence of pollution haven effects revealed by their research had no major significance for several reasons. First, most of the dirty industry development seems to be explained by domestic factors, e.g., the consumption/production ratios in developing countries remained close to unity during the whole period under study. Second, the increase in the share of dirty products in developing countries is mainly caused by a high income elasticity of

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[8] Van Beers and van den Bergh (1997) actually constructed two indices: one broad index which included indicators of protected areas, unleaded gas market share, recycling rates of paper and glass, population with sewage connection, and energy intensity; and a narrow index, which included only two indicators related to energy intensity. The results of their estimations refer only to the narrow index.

demand for basic industrial products. While income continued to grow, this elasticity declined. Third, tougher environmental regulations seem to have played a role in the shift to cleaner sectors. All these factors led the authors to conclude that the evidence found on pollution havens seemed to have been self-limiting, because economic development induces pressure on polluters to increase regulation, technical expertise and clean-sector production. Thus, the authors only regarded pollution havens as transient. The investigation conducted by Mani and Wheeler can be criticized on the grounds that that their findings are based on speculations, since no comprehensive model is developed that might explain the observed structural changes.

In sum, earlier studies investigating the effects of environmental regulations on output flows provided rather mixed results. In general, the estimated coefficient of the explanatory variable is small in magnitude and therefore insignificant. This can be attributed to the fact that the studies mentioned mainly used cross-sectional models which were unable to control for unobserved heterogeneity and endogeneity of right-hand-side variables.

The recent literature attempts to correct the deficiencies of previous studies by employing panel data. The typical strategy is to regress trade flows or data of pollutants such as sulfur dioxide or carbon dioxide on a measure of environmental stringency or a measure of openness respectively and other relevant control variables (such as income per capita and factor endowments) for a given period.

A number of recent studies are closely linked to our investigation. Antweiler et al. (2001), whose work represents an extension of Grossman and Krueger's (1991) paper, develop a theoretical model based on the decomposition of the effect of trade on the environment into scale, composition and technique effects. Then they estimate and add up these effects to explore the overall effect of increased trade on the environment, thereby allowing for pollution haven and factor endowment motives. Factor endowment motives of trade seem to dominate pollution haven motives, implying that high income countries tend to have a comparative advantage in pollution-intensive goods. When the estimates of scale, technique and composition effects are added up, the results point to the fact that increased trade causes a decline in sulfur dioxide concentrations. Based on their analysis, Antweiler et al. conclude that freer trade seems to be good for the environment.

Heil & Selden (2001) present evidence on the relationship between trade intensity and global patterns of pollution using data on carbon emissions across 132 countries from 1950 to 1992. In contrast to other studies that rule out the pollution shifting across countries by not interacting trade measures with income, Heil and Selden use a more functional form and show that increased trade intensity increases carbon emissions in lower income countries while lowering carbon emissions in higher income countries. Their findings support the PHH.

Dean (2002) uses the literature on trade and growth, as well as on the environmental Kuznet's curve, to show that freer trade does not necessarily harm the environment like some might believe. The author derives a simultaneous equations system that incorporates multiple effects of trade liberalization on the environment. Using pooled Chinese water pollution data pertaining to provinces, the estimation considers the scale, composition and technique effects. The results suggest that freer trade further worsens environmental damage via the terms of trade while alleviating it via income growth. The simulations seem to suggest that the net effect on China is beneficial.

Cole's and Elliott's (2003) approach is similar to Antweiler's et al. (2001). The authors examine the compositional changes in pollution arising from trade liberalization and investigate the cause, i.e., the FEH and/or the PHH. Similar to Antweiler et al., Cole and Elliott find evidence supporting both factor endowment and pollution haven motives for SO_2, and that these effects seem to cancel each other out (leading the authors to conclude that this is a possible reason why many studies tend to find no evidence for the PHH). The estimated net effect of trade depends on the pollutant and on the pollutant's measurement (per capita emissions or pollution intensities). A trade-induced increase in income of 1% will cause a decline in per capita SO_2 emissions of 1.7% (but the net outcome is uncertain because the trade intensity elasticity is positive). Trade reform causes a reduction in per capita BOD emissions, while for NO_x and CO_2 further trade liberalization will increase emissions. However, if pollution intensities are used instead of emissions the results change: For all four pollutants, increased trade would reduce the pollution intensity of output.

Frankel and Rose (2005) contribute to the debate over trade and the environment by asking the question: What is the effect of trade on a country's environment, for a given level of GDP? The authors use exogenous geographic determinants of trade as instrumental variables to take account of the endogeneity of trade. They find that trade tends to reduce three measures of air pollution. Statistical significance is found to be high for concentrations of SO_2 , moderate for NO_2, and absent for particulate matter.

The authors find a positive impact of trade on air quality (the estimated coefficient of trade is always negative) and support for the EKC (the estimated coefficients on the income square term are negative for all air pollutants). No evidence is found for "a-race-to-the-bottom" driven by trade or support for the PHH.

Similar work to that of Antweiler's has been done by Cole (2004, 2006), who examines the relationship between trade liberalization and energy consumption, and by Abdulai and Ramcke (2009), who examine the relationship between growth, trade and the environment both theoretically and empirically.

Cole (2004) tests for pollution havens as well as factor endowment motives by controlling for lagged income per capita (scale and technique effects) and capita-labor ratio (composition effect). The author finds evidence for both factor endowment and pollution haven hypothesis. Trade liberalization increases energy use for a capital-abundant country and decreases it for a capital-scarce country. Additionally, a high income country will find energy use falling in response to liberalized trade, whereas a low income country will experience an increase in energy consumption. The author estimates elasticities to assess the impact of trade liberalization on energy consumption for the mean country. Both the estimated scale-technique and trade-composition effects are positive, which implies that the mean country will experience increasing per capita energy use in response to trade liberalization. For the regressions with energy intensities, the technique effects are negative and the trade-composition elasticities positive; thus, the net outcome is uncertain.

Abdulai and Ramcke's (2009) results indicate the existence of an EKC for most pollutants, with some reservations. The hypotheses concerning the link between trade and environmental degradation cannot be entirely confirmed. However, the results bring modest support to the PHH. The authors further mention that there is some evidence that trade liberalization benefits sustainable development in rich countries, but can be potentially harmful for poor countries.

3. Estimation issues and methodologies

In this section we discuss the different methodologies applied in the studies described in the previous section. In particular, we highlight what the crucial choices are in designing a study whose aim it is to test the PHH. Of course, a comparison of the findings is complicated by the studies' different underlying assumptions and methods. Even when the same methods are employed, the investigations may use different samples or sets of variables.

First, different dependent variables have been used as a measure of economic activity ranging from plant births, production emissions and net imports to inward and outward foreign direct investments. One might argue that the different applied variables are the causes of the mixed results reported in the literature. Xing and Kolstad (2002) argue that capital flows will be more affected by differences in environmental regulations than good flows because a country's production mix will only change in the long run. However, the choice of the dependent variable seems to be less important in regard to the ability to find evidence on pollution haven effects. Other factors appear to be more important, in particular the applied econometric approach (panel versus cross-section).

In the discussion of the dependent variable two further issues arise if pollutants are employed as dependent variables. These will be discussed briefly because the empirical analysis in the following part will also employ data on different pollutants as the dependent variable.

3.1 Concentration versus emission data

The EKC literature illustrated that the estimated relationship between economic variables (e.g., per capita income) and pollution can vary depending on whether pollutants are measured in terms of emissions or concentrations.[9] Overall, it is important to note that data on concentrations is directly observable, while data on emissions is not.. Therefore, emission data has to be constructed, and the method of construction differs by pollutant. Further, both measurement types have advantages and disadvantages. First of all, it has to be clear that concentrations and emissions provide different information. City-level concentrations offer more information related to the human health impact of a specific pollutant due to the direct link between the health of a city's population and pollution concentrations within that city. National emissions provide more information on nationwide environmental issues (climate change or acid deposition); thus, the link to city-level concentrations might be rather weak. Some policies that aim to reduce the detrimental health impact of air pollution could reduce city-level concentrations but not national emissions (e.g., encouraging of firms to locate outside the city). Furthermore, the use of concentration data leads to some issues in estimation and therefore requires the inclusion of several dummy variables in order to capture site-specific effects. Fixed site-specific effects, such as the nature of the observation site (e.g., city, suburban or rural), or the type of measuring equipment, are easy to control for using dummy variables. On the other hand time-varying site-specific effects, such as the average temperature of the site (might affect energy consumption) or the level of rainfall at the site (rainfall typically reduces concentrations), are more complicated (Cole and Elliott, 2003).

An example of a study employing concentration data as the dependent variable is Antweiler et al. (2001). The authors include numerous dummies to allow for site-specific effects (suburban, rural, average temperature and precipitation variation). An advantage of this study through the use of data on concentrations is the separation of technique and scale

[9] See for example Selden and Song (1994).

effects, which is not possible with national emission data.[10] In sum, as these two data types offer different information, the estimated results of a study using concentration data might differ from the results of a study using emission data.

An illustrative example for this is the study by Cole and Elliott (2003), using concentrations to test if the findings of Antweiler et al. (2001) also hold for emissions. In general, they support the results of Antweiler et al., which indicate that the form of pollution measurement has little effect on the estimated results.

In contrast, Naughton (2006) closely follows the approach by Frankel and Rose (2005), but uses emission data instead of concentration data. The author argues that the correlation between concentrations and emissions is low and thus might not be a good test of the environmental impact of trade, because theoretical models find a relationship between emissions, not concentrations, and trade. This data modification has significant effects. Naughton's estimated positive effect of trade on the environment is four times larger than what Frankel and Rose found, which implies that the measurement of pollution matters.

3.2 Results differ by pollutant

We might also expect the results to depend on the particular pollutants. Antweiler et al. (2001) propose that, in order to be useful for a study of this nature, a pollutant must possess as many of the following characteristics as possible: (1) It should be a by-product from goods production; (2) It should be emitted in greater quantities per unit of output in some industries than others; (3) It should have strong local effects; (4) It should be subject to regulations because of its adverse effects on the population; (5) It should have well-known abatement technologies; and (6) It should have data available from a wide mix of countries.

Most studies employ pollutants such as SO_2, NO_x or BOD, which possess all of these characteristics. CO_2 however, does not have a local impact and has not received a great deal of regulation in the past. SO_2, NO_x and BOD have received a greater degree of regulation than CO_2 (Hettige et al., 2000). Most domestic CO_2 regulations were implemented only in the last 5 to 10 years; attempts for multilateral regulations, such as the Kyoto Protocol, have been rather weak, and progress has been slow. Furthermore, all pollutants vary in characteristics such as atmospheric lifetime or health impact.

Indeed, estimated results in the empirical literature often differ by pollutant even in the same study. Cole and Elliott (2003) find in their study on four different pollutants that the impact of trade depends on the pollutant and on whether it is measured in terms of per capita emissions or pollution intensities. For the latter, they find for all four pollutants a negative effect on output. On the contrary, the estimated effects are different in magnitude and sign for all pollutants if measured in per capita emissions. In sum, the results often differ between pollutants, and there is no reason to expect that the finding for one pollutant will be robust for other pollutants (Cole and Elliott, 2003).

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[10] Antweiler et al. (2001) include as a measure of the scale effect the city economic intensity which is measured by GDP per km^2. Cole and Elliott (2003) use national emission data, but are able to estimate technique effects as well as a combined scale-technique effect due to the use of both per capita emissions and pollution intensities as dependent variables.

3.3 Target variable

Numerous studies test for the PHH by using a measure of environmental stringency as the explanatory variable. Some measures have obvious weaknesses. For example environmental stringency indices (used in studies such as Tobey, 1990; van Beers and van den Bergh, 1997; Harris et al., 2001) might lack objectivity. On the other hand, as mentioned by Wagner and Timmins (2008), it is possible that such a measurement captures the correlation even better than objective measures. Nevertheless, it is generally still preferable to apply an objective measure in order to present unambiguous results, so that clear policy implications are applicable.

Empirical papers that aim to explain an environmental variable, such as emissions, employ an indicator of trade liberalization or openness as explanatory variable. To our knowledge, all of those studies use the trade intensity (the sum of imports and exports divided by GDP). It might be interesting to check if the results hold for other measures of trade openness as well.

3.4 Level of industry data aggregation

A common characteristic of most studies relates to the use of aggregated industry data (researchers pool together all industries) in order to examine if countries or regions with differences in environmental regulations differ in pollution-intensive activities. However, there are a number of studies that use disaggregated data (industry specific data) to examine if specific industry sectors in a country are affected differently by environmental regulations.

Some researchers (for example, Grether and de Melo, 2002; Mathys, 2002) note that an aggregate analysis hides specific patterns in each industry and, hence, may mask pollution haven effects in specific industries. They argue that, if there is indeed a PHH story in the data, it is more likely to be found at the disaggregated level. Similarly, Ederington et al. (2005) identify and test three explanations for the lack of evidence on the PHH. These reasons are that (1) most trade takes place between developed countries; (2) some industries are less geographically footloose than others; and (3) for the majority of industries environmental regulation costs represent only a small fraction of total production costs. In all these three cases, aggregated trade flows across multiple countries could conceal the effect of environmental regulation on trade for countries with distinct patterns of regulation, in the more footloose industries, or in those industries where environmental expenditures are significant, respectively. The authors find support for the first two explanations: Estimating the average effect of an increase in environmental costs over all industries understates the effect of regulatory differences on trade in more footloose industries and on trade with low-income countries. On the other hand, a study that uses disaggregated data might be problematic, too. For example, most cross-industry studies only examine dirty industry sectors (e.g., Tobey, 1990). Those industries could share some unobservable characteristics (e.g., natural resource intensiveness) that also make them immobile. Restricting the sample to pollution-intensive industries might lead to the selection of the least geographically footloose industries. Furthermore, it would be reasonable to add clean sectors for a comparison, because we would expect that the effect of pollution regulations on pollution-intensive sectors is different (or even has the opposite sign) from the effect on clean sectors (Brunnermeier and Levinson, 2004).

3.5 The role of factor endowments

Recent studies that control for the role of factor endowments in addition to environmental regulations as the source of comparative advantage find that both effects are at work and tend to cancel each other out (see, for example, Antweiler et al., 2001; Cole and Elliott, 2003; Cole, 2006). In general, these studies state that a country with a low capital-labor ratio will experience pollution to fall with trade liberalization, while it will increase for a country with a high capital-labor ratio. Furthermore, a low-income country (with lax environmental regulations) will find an increase in pollution as a result of increased trade, while pollution will fall for a high-income country.

These findings might be an explanation of the failure of the earlier literature to find support for the PHH. Furthermore, these results are consistent with the earlier indications of theoretical models that comparative advantage is determined jointly by differences in regulation policy and factor endowments.

Empirical testing of the linkages between trade and the environment is complicated by two issues: unobserved heterogeneity and endogeneity.

Unobserved heterogeneity refers to unobserved industry or country characteristics which are likely to be correlated with strict regulations and the production and export of pollution-intensive goods. Assume a country has an unobserved comparative advantage in the production of a pollution-intensive good; consequently it will export a lot of that good and also will generate a lot of pollution. Ceteris paribus, it will impose strict regulations to control pollution output. If these unobserved variables are omitted in a simple cross-section model, this will cause inconsistent results, which cannot be meaningfully interpreted (in this example, a simple cross-section model would find a positive relationship between strict regulations and exports). The easiest solution to this problem would be to use panel data and incorporate country or industry specific fixed effects (Brunnermeier and Levinson, 2004).

The endogeneity problem is that pollution regulations and trade may be endogenous, i.e. the causality might run in both directions (problem of simultaneous causality). Assuming trade liberalization leads to higher income, which in turn causes an increase in the demand for environmental quality, it follows that environmental regulations could be a function of trade. A possible solution to this problem is to use instrumental variables techniques. However, the instruments should possess the following characteristics: vary over time and correlate with the measure of environmental stringency (but not with the error term) (Brunnermeier and Levinson, 2004).

3.6 Cross-section versus panel data and endogeneity correction

The early literature based on cross-sectional data tends to reject the PHH, or even finds, counterintuitively, that economic activity is concentrated in regions with stricter environmental regulation. However, for the majority of these studies the estimated coefficients are statistically and economically insignificant.

In contrast, recent studies using panel data do find at least moderate pollution haven effects in general. This is notable in that it does not depend on the explained variable. Studies on plant locations (e.g., Becker and Henderson, 2000) output flow such as imports (such as Ederington and Minier, 2003; Ederington et al., 2005; Levinson and Taylor, 2008) or emissions (e.g., Cole and Elliot, 2003), and on FDI (for example, Keller and Levinson, 2002; Cole and Elliott, 2005; Cole et al., 2006; Wagner and Timmins, 2008) all estimate a significant pollution haven effect using panel data. These results indicate that it is important to control for unobserved heterogeneity.

Empirical investigations that control for endogeneity of environmental policy tend to find more robust evidence on moderate pollution haven effects. For example, Ederington and Minier (2003) and Levinson and Taylor (2008) find no significant effect of pollution abatement costs if they are treated as exogenous. If they model these costs, however, as endogenous, the authors do find a statistically significant effect. Yet any instrument variable analysis is always an easy target for criticism, since it will be sensitive to the choice of instruments. Frankel and Rose (2005) use instruments to control for the endogeneity of income and trade and find no support for the PHH. As they use a cross-sectional approach, however, the authors cannot control for unobserved heterogeneity.

What are the crucial factors for an empirical investigation testing the PHH? We found that the essential choices are which empirical methods are applied. It does not seem to matter whether these studies examine plant location decisions, investment or trade patterns.

Early studies based on cross-sectional analyses typically tend to find an insignificant effect of environmental regulations, while recent studies using panel data to control for unobserved heterogeneity or instruments to control for endogeneity do find statistically and economically significant pollution haven effects.

Furthermore, recent studies try to incorporate the traditional sources of comparative advantage into the analysis and find that both factor endowments and environmental regulations jointly determine the trade-induced composition effect. These effects however tend to cancel each other out leading the researchers to conclude that this might be a possible explanation of the failure to find evidence on the PHH in earlier studies.

4. Empirical analysis

In this section we conduct an empirical analysis in order to test for the pollution haven hypothesis. We choose to employ a panel study with aggregated data across countries and time. Despite the potential problems of such a study that were mentioned in Section 3 and the motivation to find more robust evidence at the disaggregated level, we follow this approach for several reasons. The first reason is its simplicity. The study design is relatively simple, while still providing a comprehensive and transparent test on this hypothesis. Moreover, this approach asks an interesting question: Whether a specific country or a specific group of countries tends to become a pollution haven for other countries (and this is the question which dominates the public debate). Additionally, the high number of contributions to this type of study reflects the relevance of this approach (examples include Heil and Selden, 2001; Antweiler et al., 2001; Cole and Elliott, 2003; Cole, 2004; Cole, 2006; Abdulai and Ramcke, 2009).

The analysis uses panel data on 95 countries during the period 1980-2004 and regresses three measures of pollution on trade intensity, hence controlling for income per capita, year and country specific effects (and indirectly also for population growth by employing the dependent variables in per capita terms).

4.1 Estimation method

The empirical specification applied in this analysis follows recent studies such as Heil and Selden (2001), Cole (2004), Frankel and Rose (2005), and Abdulai and Ramcke (2009) in employing the standard EKC framework with trade as an additional explanatory variable to test for the PHH. The model specification is given as follows:

$$\ln(ED)_{it} = \beta_0 + \beta_1 \ln(GDP)_{it} + \beta_2 [\ln(GDP)]^2{}_{it} + \beta_3 \ln(TRADE)_{it} + \delta_t + \mu_i + \varepsilon_{it,} \quad (1)$$

where *ED* denotes environmental degradation for country *i* and year *t* (this term includes the pollutants that are analyzed: per capita emissions of SO_2, per capita emissions of CO_2, and per capita energy consumption). *GDP* is gross domestic product per capita, *TRADE* is the trade intensity (the sum of exports and imports divided by GDP) and ε_{it} is the stochastic error term. δ_t are the time specific fixed effects that control for time varying omitted variables and stochastic shocks which are common to all countries but which change over time (e.g. technological progress). μ_i are the country specific fixed effects that account for effects specific to each country which do not change over time (e.g. climate and resource endowments). The notation "ln" denotes the natural logarithm.

Unobserved heterogeneity is a potential problem. It refers to omitted variables that are fixed for an individual (at least over a long period of time). If the unobserved heterogeneity is correlated with the explanatory variables, OLS is biased and inconsistent. Fixed Effects (FE) could be employed to obtain consistent results. If the unobserved heterogeneity is uncorrelated with the explanatory variables, OLS is unbiased and consistent. In this case, we might still employ Random Effects (RE) in order to overcome the serial correlation of panel data and thus improve efficiency. Both employ a different approach as the FE model treats the δ_t and μ_i as regression parameters, while the RE model treats them as components of the random disturbance. We use a Hausman test to test the null hypothesis that RE is consistent. In some cases we cannot reject this hypothesis. However, throughout our analysis we report estimation results for both fixed and random effects.

Two methodological issues arise. Some authors such as Stern et al. (1996) argue that many studies fail to test for heteroskedasticity and autocorrelation. First, heteroskedasticity might be present due to the large variations in the income and environmental variables. Therefore we apply a modified Wald statistic for groupwise heteroskedasticity (following Greene, 2000, p. 598). In all regressions we can reject the null hypothesis of homoskedasticity.

The second issue concerns serial correlation. In order to control for this, we employ a Wooldridge test for serial correlation in panel-data models (Wooldridge, 2002, p. 282) and an Arellano-Bond test (Roodman, 2006, p. 34).

In sum, we test for heteroskedasticity and autocorrelation and can confirm the presence of both conditions in all of the specifications. Therefore, we use robust standard errors in both fixed and random effects estimation. The employed FE model calculates Driscoll-Kraay (DK) standard errors (Driscoll and Kraay, 1998).[11] DK standard errors assume the error structure to be heteroskedastic, autocorrelated up to some lag and possibly correlated between the groups. The RE specification uses robust standard errors (see, for example, Cameron and Trivedi, 2009, p. 233).

Estimations over the full sample could mask different effects between countries, since the estimated trade coefficient only shows the average change in the pollution level over all countries, and it is not possible to derive implications for the PHH or FEH.[12] To overcome this drawback, we divided the sample into different income groups (See Table 3 below).

The results should differ for the separate income groups, if the PHH or the FEH is true and dominant. The PHH would predict that trade increases pollution for low income countries

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[11] A two-way FE model is applied (both time and country specific effects are included, one-way FE only includes country fixed effects).

[12] A positive trade coefficient for all countries could thereby give support to the "race-to-the-bottom" hypothesis and a negative coefficient to the Porter hypothesis. However, clear implications would only be possible if one analyzes the environmental policy in the respective countries.

and decreases it for high income countries. Hence, the trade coefficient should be positive for low income countries and negative for rich countries. In contrast, the opposite should be true for the FEH under the assumption that poor countries are capital scarce and rich countries are capital abundant, and that pollution-intensive goods are also capital intensive in their production.

Low Income		**Middle Income**		**High Income**	
Angola	Madagascar[13]	Algeria	Mauritius[13]	Australia	Korea, Rep. of
Bangladesh	Mali[13]	Argentina	Mexico	Austria	Malta
Benin	Mozambique	Botswana	Panama	Belgium	Netherlands
Bolivia	Malawi[13]	Brazil	Paraguay	Canada	New Zealand
Burkina Faso[13]	Nigeria	Bulgaria	Peru	Denmark	Norway
Cameroon	Nicaragua	Chile	South Africa	Finland	Oman
China	Nepal	Colombia	Swaziland[13]	France	Portugal
Côte d'Ivoire	Pakistan	Costa Rica	Syrian Arab Rep.	Gabon	Saudi Arabia
Ethiopia	Philippines	Dominican Rep.	Thailand	Germany	Spain
Ghana	Rwanda[13]	Ecuador	Trinidad and Tobago	Greece	Sweden
Haiti	Sudan	Egypt	Tunisia	Hong Kong	Switzerland
Honduras	Senegal	El Salvador	Turkey	Hungary	United Kingdom
India	Togo	Guatemala	Uruguay	Iceland	USA
Indonesia	Uganda[13]	Iran, Islamic Rep. of	Venezuela	Ireland	
Kenya	Vietnam	Jamaica		Israel	
Sri Lanka	Zambia	Jordan		Italy	
Morocco	Zimbabwe	Malaysia		Japan	

Table 3. Income groups.

The World Bank country classification uses GNI per capita to classify every economy into four income groups (low income, lower middle income, upper middle income and high income) (World Bank, 2009). We follow this approach, but we divide the sample into three different income groups (low, middle and high income), merging the two middle income groups into one middle income group. Studies as Abdulai and Ramcke (2009) only use two income groups, low and high income groups. In our opinion such a separation is questionable. Recall that in terms of the PHH we expect to find differences between poor and rich countries. Rich countries tend to have strict environmental regulations, and therefore export their dirty good production to low income countries with lax environmental policy. It should be expected that especially middle income countries should be an attractive relocation site in this context, because they inherit laxer environmental stringency than their richer counterparts and should also provide a sufficient infrastructure for the firms' production sites. Extremely poor countries might lack this needed infrastructure and are less interesting "pollution havens,"as the costs for building up the production may be too high. The division into low and high income countries means that

[13] No data on energy consumption, thus not included in respective regressions

middle income countries such as Mexico, Turkey, Brazil or Venezuela, which are often indicated as potential pollution havens in public debates, are incorporated into the high income group. If these countries are in fact pollution havens, separate regressions over low and high income samples are likely to show no support for the PHH, as the potential effects for the pollution havens are probably offset by the rich developed countries in the high income group. For the PHH to be true we expect the trade coefficient to be negative for the high income group and positive for low and middle income groups (particularly for the latter countries as they are often indicated to be pollution havens).

4.2 The data

The sample includes 95 developed and developing countries and covers the period 1980-2004.[14] A complete list of countries can be found in Table 3. Data availability is the criterion used to select the countries; those with no data on specific variables or too many missing values are not considered.[15] Descriptive statistics and definitions of the variables are shown in Table 4 for the whole sample and in Table 5 for each income group.

Variable	Definition	Obs.	Mean	Std.Dev.	Min.	Max.	Source
SO2PC	SO_2 emissions (kg per capita)	1995	1.856	1.302	-4.679	4.947	World Bank (2008)
CO2PC	CO_2 emissions (metric tons per capita)	2375	0.454	1.631	1.631	3.205	Stern (2005)
ENERGYPC	Energy use (kg of oil equivalent per capita)	2174	7.069	1.012	4.551	9.391	World Bank (2008)
GDP	GDP per capita, PPP (constant 2005 international $)	2362	8.554	1.241	5.762	10.749	World Bank (2008)
TRADE	Trade Intensity (the sum of exports and imports divided by GDP)	2361	4.053	0.559	1.844	5.917	World Bank (2008)

Table 4. Variable definitions and descriptive statistics.

Our study uses the following variables: one dependent variable, environmental degradation; two direct measures of air pollution, CO_2 and SO_2 emissions; and one indirect measure of pollution, the energy consumption. All of them are measured in per capita terms to control for pollution generated by population growth.[16] Sulfur dioxide, or SO_2, is produced in various industrial processes, e.g., during the combustion of coal and oil, which

[14] For SO_2 emissions, the data is only available for the period 1980-2000.

[15] E.g., no Eastern European countries were included, as there is no data for a large part of the sample period 1980-2004.

[16] An initial approach employed total emissions as the dependent variable and total population as a control variable. The estimated coefficient of total population was very close to 1 for all pollutants in all regressions, and thus we chose to calculate and use the pollutants in per capita terms (according to the rules of logarithmic calculation).

often contain sulfur compounds. SO_2 dissolves in water vapor to form acid, and interacts with other gases and particles in the air to form sulfates and other components that can be harmful to people and their environment. SO_2 contributes to the formation of acid rain and is linked with increased respiratory symptoms and disease, difficulty in breathing and premature death (EPA, 2009). Sulfur dioxide data was obtained from Stern (2005) and are measured in kg per capita.

Variable	Income Group	Obs.	Mean	Std.Dev.	Min.	Max.
SO2PC	Low Income	714	0.769	0.979	-1.976	4.849
	Middle Income	651	2.141	1.021	-0.996	4.947
	High Income	630	2.793	0.956	-4.679	4.717
CO2PC	Low Income	850	-1.282	1.077	-3.575	1.351
	Middle Income	775	0.785	0.839	-1.858	3.205
	High Income	750	2.083	0.454	-0.058	3.110
ENERGYPC	Low Income	700	6.027	0.415	4.552	7.107
	Middle Income	724	6.935	0.573	5.857	9.149
	High Income	750	8.172	0.494	6.732	9.391
GDP	Low Income	837	7.164	0.574	5.762	8.229
	Middle Income	775	8.665	0.360	7.721	9.568
	High Income	750	9.992	0.332	8.552	10.749
$(GDP)^2$	Low Income	837	51.652	8.225	33.206	67.717
	Middle Income	775	75.207	6.240	59.611	91.551
	High Income	775	99.956	6.553	73.134	115.553
TRADE	Low Income	837	3.861	0.485	1.844	5.187
	Middle Income	775	4.109	0.592	2.446	5.433
	High Income	749	4.212	0.538	2.779	5.917

Table 5. Descriptive statistics for income groups. All variables are in natural logarithms.

Carbon dioxide, or CO_2, emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They incorporate carbon dioxide produced during consumption of solid, liquid as well gas fuels, and gas flaring. Carbon dioxide is one of the major greenhouse gases and CO_2 emissions play a central role in the global climate change debate. The employed CO_2 emissions are measured in metric tons per capita and were obtained from the World Development Indicators 2008 (WDI 2008) (World Bank, 2008). Note that CO_2 is purely a global externality, whereas SO_2 is a local air pollutant.

Data on energy consumption was also taken from WDI 2008 and is measured in kg of oil equivalent per capita. It is an indirect source of pollution, in particular air pollution. The consumption of energy and especially the burning of fossil fuels are the major causes of most air pollutants. Therefore it is a useful approach to examine the effect of trade on energy consumption (Cole, 2006). WDI 2008 additionally provided data on income, trade and population. The income measure is given by gross domestic product (GDP) per capita in purchasing power parity (PPP) terms in constant 2005 international dollars. Trade intensity as a percentage of GDP is calculated as the sum of exports (X) and imports (M) of goods and services measured as a share of GDP (X +M/GDP). Total population was used to calculate emissions per capita. All the variables are in natural logarithms in order to make the variables less sensitive to outliers.

5. Results

5.1.1 Sulfur dioxide

The results for the full sample are presented in Table 6. We estimate equation 1 for SO_2 emissions by applying a FE regression with Driscoll-Kraay standard errors and a RE regression with robust standard errors due to the presence of heteroskedasticity and autocorrelation. Following the result of the Hausman test, we cannot reject the null hypothesis that the RE estimates are consistent. The coefficients are only slightly different in magnitude in both specifications. The income terms show the expected EKC relationship.[17] The coefficient of GDP is positive and statistically significant, while its square term is negative but insignificant (in the FE model). However, an F-Test showed that GDP and its square term are jointly significant (p-value: 0.000). In the RE model, both terms are highly significant. In both models, the TRADE coefficient is positive and statistically significant. This would imply that further liberalized trade would cause an increase in per capita SO_2 emissions on average. However, this increase is small in magnitude: A 1% increase in TRADE would cause on average a less than 0.1% increase in emissions ceteris paribus (in the RE model). As mentioned, no implications for the PHH are possible. A regression over the full sample requires the effect of TRADE to be uniform across all countries, but the signs and magnitudes of the overall effects may mask important differences between countries. If one wants to test the pollution haven hypothesis, one approach to do so is to divide the sample into income groups.

The estimates change in the income group regressions (see Table 7). The Hausman test indicates that RE is consistent. Middle and high income groups again show the EKC relationship (GDP is positive, its square term negative). This is not the case for low income countries. There the signs are reversed. All these estimates are statistically significant at the 1% level. Surprisingly, the coefficients on trade are not as expected. Only for high income countries do we find a positive relationship between trade and SO_2 emissions per capita, which is contrary to our expectations. This indicates that further trade liberalization increases SO_2 emissions for rich countries. This finding is contrary to the PHH, but could provide support for the FEH. However, no clear implications are possible as the results for middle and low income countries are insignificant.

5.1.2 Carbon dioxide

The results for CO_2, which are presented in Table 8, are similar to those of SO_2 for the whole sample. Again, we estimate equation 1 for CO_2 emissions by applying a FE regression with Driscoll-Kraay standard errors and a RE regression with robust standard errors. The FE estimates are preferred due to the result of the Hausman test. The estimates of FE and RE specifications are nevertheless similar. The expected EKC relationship is present: GDP and its square term are positive and negative, respectively. All are statistically significant

[17] It is not my focus, however, to find evidence on the EKC or to discuss it extensively. The focus is to find evidence for the pollution haven hypothesis.

at 1%. TRADE is again positive and highly statistically significant, although small in magnitude, indicating that increased TRADE causes rising emissions on average ceteris paribus.

Dependent Variable	**(1) SO_2 per capita**		**(2) CO_2 per capita**		**(3) Energy use per capita**	
Independent Variables	**FE** (DK[a])	**RE**[b]	**FE** (DK[a])	**RE**[b]	**FE** (DK[a])	**RE**[b]
GDP	2.334**	2.315***	1.480***	1.611***	-0.268**	-0.311**
	(1.010)	(0.691)	(0.188)	(0.271)	(0.117)	(0.148)
$(GDP)^2$	-0.092	-0.093**	-0.043***	-0.042***	0.050***	0.055***
	(0.069)	(0.043)	(0.011)	(0.015)	(0.007)	(0.009)
TRADE	0.092*	0.089**	0.080***	0.090***	-0.011	-0.011
	(0.047)	(0.040)	(0.024)	(0.023)	(0.012)	(0.013)
Constant	-11.321***	-11.063***	-9.243***	-10.522***	5.545***	5.571***
	(3.403)	(2.592)	(0.749)	(1.209)	(0.430)	(0.607)
Observations	1979	1979	2358	2358	2159	2159
Groups	95	95	95	95	87	87
Hausman Test (p-value)	0.91 (1.000)		81.48*** (0.000)		37.09* (0.093)	
Autocorrelation coefficient	0.880	0.839	0.810	0.873	0.905	0.925
R^2 (within)	0.146	0.146	0.858	0.342	0.839	0.564
F-Test: all country effects = 0[c]	101.69***	13635.46***	169.04***	20477.97***	290.47***	21481.41***
F-Test: all year effects = 0[d]	130000***	321.47***	20408.55***	(19.52)	91563.29***	41.55**

Table 6. Estimation results for the full sample. Standard errors in parentheses. ***, **, *, indicate significance at 1%, 5% and 10%, respectively. All the variables are in natural logarithms. a) Fixed Effects estimation with Driscoll-Kraay standard errors. b) Random Effects estimation uses robust standard errors. c) RE estimation employs a Breusch-Pagan LM Test for individual effects. d) if year effect test- statistic is in parentheses, year effects were not significant and thus not included in estimation.

Concerning income groups, for low and high income countries the Hausman test indicates that RE are consistent. For middle income countries the null hypothesis that RE are consistent could be rejected only at the 10% level. This means that it could be kept at the 5% level, and thus a RE model is also estimated (see Table 8). Again, we find a statistically significant EKC relationship for middle and high income countries, but not for low income countries. For poor countries the GDP term is negative and insignificant, and its square term is positive (and significant). On the other hand, we do find statistically significant evidence for pollution haven consistent behavior. For low and middle income countries further trade liberalization will increase CO_2 emissions per capita, while it will decrease for high income countries. The TRADE coefficients are positive for both poorer income groups and negative for rich countries. Following the predictions of the PHH this is exactly as expected.

Dependent variable is SO_2 per capita	**Specification**					
	FE (DK[a])			**RE**[b]		
	Low Income	**Middle Income**	**High Income**	**Low Income**	**Middle Income**	**High Income**
GDP	-4.065***	7.948***	22.554***	-4.079***	7.859***	23.830***
	(1.002)	(1.677)	(1.727)	(0.834)	(2.381)	(6.456)
$(GDP)^2$	0.328***	-0.410***	-1.084***	0.329***	-0.404***	-1.165***
	(0.068)	(0.103)	(0.084)	(0.057)	(0.141)	(0.326)
TRADE	-0.015	0.091	0.444	-0.013	0.092	0.285**
	(0.034)	(0.059)	(0.347)	(0.033)	(0.058)	(0.145)
Constant	13.291***	-35.936***	-115.676***	13.334***	-35.602***	-119.71***
	(3.594)	(6.790)	(10.099)	(3.013)	(10.098)	(31.867)
Observations	699	651	629	699	651	629
Groups	34	31	30	34	31	30
Hausman Test (p-value)	0.17 (1.000)	0.83 (1.000)	21.69 (0.539)			
Autocorrelation coefficient	0.831	0.771	0.892	0.954	0.927	0.628
R^2 (within)	0.329	0.227	0.288	0.329	0.227	0.284
F-Test: all country effects = 0[c]	350.64***	242.02***	35.22***	6254.18***	5440.84***	1981.73***
F-Test: all year effects = 0[d]	26793.74***	1314.87***	738.61***	82.18***	63.66***	180.57**

Table 7. Estimation results for SO2 income groups. Standard errors in parentheses. ***, **, *, indicate significance at 1%, 5% and 10%, respectively. All the variables are in natural logarithms. a) Fixed Effects estimation with Driscoll-Kraay standard errors. b) Random Effects estimation uses robust standard errors. c) RE estimation employs a Breusch-Pagan LM Test for individual effects. d) if year effect test- statistic is in parentheses, year effects were not significant and thus not included in estimation.

5.1.3 Energy consumption

For the whole sample (Table 6), we follow the same approach as before (FE with Driscoll-Kraay standard errors and RE with robust standard errors). According to the Hausman test, the null hypothesis that RE is consistent could be rejected at the 10% level (i.e., it could be kept at the 5% level). Both FE and RE are estimated and the estimated coefficients only differ slightly in size. Surprisingly, the results for the indirect measure of pollution are not at all consistent with the results for SO_2 and CO_2. All coefficients have the reversed sign. No EKC relationship is present. GDP is negative; the square term of GDP is positive. The TRADE coefficient is again small in size, but this time negative, implying that an increase in trade on average decreases energy consumption. However, the coefficients on trade are not statistically significant even at the 10% confidence level.

Next, we estimate both FE and RE for each income group. The Hausman test results suggest that for low and high income countries RE is consistent, but not for middle income countries (p-value=0.000) (see Table 9). GDP and its square term are statistically significant in all specifications. Middle and high income countries experience first increasing emissions per capita with rising income and decreasing emissions with higher income increases. The opposite is found for low income countries; the GDP term is negative and its square term positive. For energy consumption per capita we can find evidence for the PHH. The TRADE coefficients are all statistically significant and show the expected signs. Trade will cause poorer countries (low and middle income groups) to increase their energy consumption per capita. On the other hand, rich countries (high income group) will reduce their energy use following further trade liberalization.

Dependent variable is CO_2 per capita	Specification					
	FE (DK[a])			RE[b]		
	Low Income	Middle Income	High Income	Low Income	Middle Income	High Income
GDP	-1.241	3.498***	4.271***	-0.975	3.387***	4.391***
	(0.967)	(0.733)	(0.890)	(0.903)	(0.992)	(1.281)
$(GDP)^2$	0.128**	-0.146***	-0.159***	0.113*	-0.139**	-0.167**
	(0.064)	(0.043)	(0.049)	(0.062)	(0.057)	(0.068)
TRADE	0.105**	0.067***	-0.145**	0.098**	0.067**	-0.135***
	(0.044)	(0.014)	(0.071)	(0.042)	(0.030)	(0.051)
Constant	0.614	-18.742***	-24.237***	-0.494	-18.373***	-24.298***
	(3.535)	(3.135)	(4.057)	(3.248)	(4.307)	(6.064)
Observations	834	775	749	834	775	749
Groups	34	31	30	34	31	30
Hausman Test (p-value)	26.64 (0.483)	6.64* (0.084)	4.63 (0.98)			
Autocorrelation coefficient	0.740	0.793	0.886	0.883	0.927	0.779
R^2 (within)	0.553	0.364	0.331	0.325	0.589	0.387
F-Test: all country effects = 0[c]	169.67***	314.93***	81.03***	6747.91***	7240.81***	4959.66***
F-Test: all year effects = 0[d]	1013.59***	127.91***	1844.71***	40.54**	37.13**	34.76*

Table 8. Estimation results for CO_2 income groups. Standard errors in parentheses. ***, **, *, indicate significance at 1%, 5% and 10%, respectively. All the variables are in natural logarithms. a) Fixed Effects estimation with Driscoll-Kraay standard errors. b) Random Effects estimation uses robust standard errors. c) RE estimation employs a Breusch-Pagan LM Test for individual effects. d) If year effect test- statistic is in parentheses, year effects were not significant and thus not included in estimation.

5.2 Discussion

This section summarizes our empirical findings and critically discusses them.

Econometric issues such as heteroskedasticity and autocorrelation complicated the estimations, and while we still employed methods to control for these matters (robust standard errors), these issues might have weakened the quality of our estimation. Despite this drawback, 62 of the 72 estimated coefficients (86%) are statistically significant, and we do find most results in agreement with expectations. Regressions over the whole sample indicated a positive and statistically significant effect of trade on SO_2 and CO_2 emissions per capita (the effect on energy consumption is negative but insignificant). This result seems to provide support to the “race-to-the-bottom” hypothesis (see footnote 33 for limitations).

With respect to the income group estimations, we could not find statistically significant results for SO_2 concerning the trade variable; thus, no implications on the effect of trade on sulfur dioxide emissions are possible. The results for CO_2 emissions per capita and energy consumption per capita are more optimistic. In general, both dependent variables show consistent results, and the findings are as expected. We do find moderate support for the pollution haven hypothesis. Trade liberalization will cause increasing CO_2 emissions and energy consumption in low and middle income countries, while the opposite will occur in high income countries. However, this effect is marginal. The effect of a 1% increase in trade intensity on CO_2 emissions per capita is about 0.09% and 0.06% for low and middle income countries, respectively (and -0.13% for high income countries). For energy consumption per capita the effect is .05% to 0.06% for low and middle income countries (and -0.15% for high income countries).

Dependent variable is energy use per capita	**Specification**					
	FE *(DK[a])*			**RE[b]**		
	Low Income	**Middle Income**	**High Income**	**Low Income**	**Middle Income**	**High Income**
GDP	-1.767***	1.953***	9.431***	-1.828***	2.348***	7.859***
	(0.489)	(0.682)	(0.296)	(0.391)	(0.905)	(0.914)
$(GDP)^2$	0.145***	-0.071*	-0.448***	0.150***	-0.090*	-0.356***
	(0.033)	(0.042)	(0.016)	(0.027)	(0.053)	(0.046)
TRADE	0.030*	0.062***	-0.174***	0.050***	0.095***	-0.151***
	(0.016)	(0.022)	(0.040)	(0.012)	(0.018)	(0.033)
Constant	11.053***	-4.964*	-40.642***	11.146***	-7.035*	-34.121***
	(1.786)	(2.711)	(1.341)	(1.411)	(3.881)	(4.570)
Observations	686	724	749	686	724	749
Groups	28	29	30	28	29	30
Hausman Test (p-value)	0.57 (1.000)	859.32*** (0.000)	0.71 (1.000)			
Autocorrelation coefficient	0.899	0.891	0.884	0.953	0.923	0.905
R^2 (within)	0.159	0.476	0.452	0.459	0.637	0.683
F-Test: all country effects = 0[c]	451.64***	329.05***	241.41***	7315.30***	6068.25***	6875.27***
F-Test: all year effects = 0[d]	901.25***	1091.70***	21.80***	*(17.15)*	*(27.98)*	*(32.07)*

Table 9. Estimation results for energy consumption income groups. Standard errors in parentheses. ***, **, *, indicate significance at 1%, 5% and 10%, respectively. All the variables are in natural logarithms. a) Fixed Effects estimation with Driscoll-Kraay standard errors. b) Random Effects estimation uses robust standard errors. c) RE estimation employs a Breusch-Pagan LM Test for individual effects. d) If year effect test- statistic is in parentheses, year effects were not significant and thus not included in estimation.

In general, our results are consistent with the findings of other empirical studies. Abdulai and Ramcke (2009) find moderate support for the PHH in their income group regressions for energy consumption as well (however, their estimated coefficients are even smaller than our estimates in magnitude). Some support for the PHH is also found in Cole and Elliott (2003). The authors estimate that a 1% increase in trade generates a 0.05 increase in per capita carbon emissions for the mean country. Cole (2006) finds support for the PHH; according to his estimates; low income countries will increase their energy use and high income countries will decrease their energy use as a consequence of further trade liberalizations. Following his estimated trade elasticities, a 1% increase in trade would increase energy consumption per capita by 1.7% to 3.1% (for the mean country). Similarly, Heil and Selden (2001) conclude in their analysis of CO_2 emissions that increased trade intensity causes falling emissions for high income countries and rising emissions for low and middle income countries. They predict that a 1% expansion of trade would cause a 0.11% increase in CO_2 emissions for a low income country and a 0.14% decrease in carbon emissions for a high income country.

To answer the central question of this paper: Does trade liberalization cause poor countries to pollute more, while causing rich countries to become cleaner? Due to the simplicity of the empirical analysis, we do not claim to have found a clear-cut answer to this question. As mentioned earlier, the aggregated data investigation could hide specific effects, and disaggregated data should be used to find clear evidence for the PHH. Furthermore, we did not directly control for the role of factor endowments, which recent papers try to incorporate in their analyses. Additionally, advanced panel data methods might be able to find more robust evidence. Despite these limitations, our analysis gives a fair approximation on this topic and a rough idea of the direction of the effects of trade on the environment.

6. Summary and conclusions

This investigation is an attempt to answer the following questions: 1. Is trade good or bad for the environment in the context of the pollution haven hypothesis?. 2. Do rich developed countries shift their pollution-intensive production to poor developing countries? 3. Is trade liberalization responsible for increased GHG emissions (e.g., CO_2) and/or sources of GHG emissions (e.g., SO_2) contributing to climate change?

No clear-cut and unambiguous answer to the first two questions is possible, due to the complex relationship between trade and the environment. There are many intervening forces at work. In this paper we emphasized the role that income plays in the context of the effects of trade on the environment. It is a complicated task to disentangle these forces and to identify and quantify the pure effect of trade on the environment. Air pollutants such as SO_2 and CO_2 contribute to numerous health and environmental problems, such as diseases, acid rain, or global climate change in general. Our approach to answer these questions was to examine theoretical and empirical research in this area and to conduct our own empirical analysis on this matter.

First, according to the theoretical models, the impact of trade on the environment can be decomposed into scale, technique and composition effects. The effect of interest is the composition effect that can contribute to increasing and also falling pollution. The direction of the composition effect depends on a country's comparative advantage. In this context, we examined two competing hypotheses on the determinants of comparative advantage and thus the pattern of trade: the pollution haven hypothesis and the factor endowment hypothesis. The pollution haven hypothesis states that differences in environmental regulation are the only determinant of comparative advantage, while the factor endowment hypothesis states that relative factor endowments, such as capital and labor, explain the pattern of trade. It is rather likely that both, differences in environmental policy and factor endowments, jointly determine comparative advantage and thus the pattern of trade. Econometric analyses might be able to answer the crucial question of which of these effects dominates.

We tested empirically for the pollution haven hypothesis and illustrated what potential problems are found in the estimation associated with unobserved heterogeneity and endogeneity. While the majority of early studies typically applied a cross-sectional analysis and tended to find a non-significant pollution haven effect, recent studies that used panel data to control for unobserved heterogeneity or instruments to control for endogeneity did find statistically and economically significant pollution haven effects. Recent papers additionally incorporate the role of factor endowments into their empirical models. Most of them reported similar findings in that both pollution haven and factor endowment motives were at work and they tended to cancel each other out. This offers a possible explanation why most early studies failed to find robust evidence on the pollution haven hypothesis.

We argue that estimations over the full sample would not be able to identify possible implications for the PHH (or the FEH). The estimated coefficient for trade would only show the average change in the pollution level over all countries and would not be able to illustrate differences between poor and rich countries (these differences are the central focus in the argumentation of the pollution haven hypothesis.) Hence, we divided the sample in three income groups (low, middle and high income). Regressions over these groups should differ if the PHH (or the FEH) is true and dominant. The trade coefficient is expected to be negative for high income countries and positive for low and middle income countries. We found that for the whole sample further liberalized trade causes per capita emissions of SO_2 and CO_2 to increase on average, and these results were statistically significant. For energy consumption we found negative and insignificant trade coefficients. Concerning the results of the estimations for each income group, for CO_2 emissions and energy consumption we did find the expected signs for the trade coefficients. Indeed, for low and middle income countries the trade coefficient was positive and for high income countries negative (all statistically significant). In general, these results give support to the pollution haven hypothesis. Trade liberalization will increase emissions in poorer countries (low and middle income economies), while it will decrease emissions in rich countries (high income). Additionally, these results are consistent with findings of other empirical investigations. In contrast, these findings could not be obtained for SO_2 emissions. The estimates were mostly not significant. Only for high income countries did we find a positive effect of trade on sulfur emissions, meaning that trade causes increasing sulfur emissions in richer countries (which might implicate support for the factor endowment hypothesis). However, all the estimates are relatively small in magnitude. On average, a 1% increase in trade intensity would cause an effect of about a 0.1% increase or decrease in emissions all else being equal.

In sum, although the theory and the recent empirical work tend to find moderate support for the pollution haven hypothesis, there is still a lot of uncertainty in this field of research, and results tend to be ambiguous. Whether rich countries' dirty goods production tends to migrate to poor developing countries through further trade liberalization remains unclear. The net effect, however, is likely to be determined by a change in the trade patterns (composition effects). Further empirical research that uses data at a disaggregated level and incorporates the role of other factors such as environmental regulations is necessary to find unambiguous results.

Regarding the issue of whether trade liberalization is responsible for increased GHG emissions (e.g., CO_2) and/or sources of GHG emissions (e.g., SO_2) contributing to climate change, the answer, again, is not so straightforward. If indeed there is a relationship between increased trade and increased production of goods and services, then increased trade will impact the changes in climate a great deal. The impact of trade liberalization on climate change, however, need not be negative. Trade can certainly have both positive and negative effects. The positive effects lie in the increased efficiency of the resources used, the dissemination of environmentally friendly technology, and the creation of the much-needed income to increase environmental protection. The less desirable effects involve the increased scale of economic activity (the scale effect), that can be harmful to ecosystems since they could result in irreversible damage. Equally, existing market and policy failures are thought to be aggravated by trade liberalization (Stoessel, 2001). While trade by itself is not the main cause of anthropogenic climate change, there is evidence that trade liberalization has indirectly contributed to anthropogenic climate change through an increase in transportation activities as well as an increase in the use of fossil fuels energy (e.g., CO_2).

In conclusion, we agree that "trade liberalization is -per se- neither necessarily good nor bad for the environment. Its effects on the environment depend on the extent to which environment and trade goals can be made complementary and mutually supportive. A positive outcome requires appropriate supporting economic and environmental policies" (UNEP, 2000).

7. Acknowledgments

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8. References

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2

Changing Climate Related Behaviors: A Review of Social-Scientific Interventions

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1. Introduction

Climate change is seen as one of the biggest threats facing our world today, and most people agree that changes are needed to avoid disaster. While technical solutions and environmental policies are definitely promising, they can only be successful when accompanied by changes in human behavior (Stern & Oskamp, 1987). This chapter addresses such behavioral changes. More specifically, it focuses on social-scientific interventions aimed at changing climate related behaviors. In recent years we have seen an abundance of scientific work dedicated to changing these behaviors and their determinants and contexts. In this chapter we aim to provide the reader with an overview of these endeavors as well as a possible new direction for research.

First, it is important to define what we mean by climate related behaviors. The studies we review in this chapter focus on the broad range of behaviors, but what they have in common is that they *impact the natural environment*. Within this comprehensive definition, we can distinguish between several types of behaviors (Kazdin, 2009), such as curtailment behaviors (e.g., using less water or saving energy), behavioral choices and decision making about (not) doing something, or doing something differently (e.g., compensating airline travel CO2 emissions, choosing public transport over car), and technology choices (e.g., driving hybrid cars, installing solar panels). Different behaviors come with different costs, both in terms effort and finances. Also, different behaviors are performed in different contexts: some behaviors are performed within the household for example, while others are highly individual. Finally, behaviors differ in terms of the impact they exert on the environment. While all these differences are noteworthy and relevant to take into consideration when studying specific behaviors, in this chapter we choose to include interventions targeting any climate related behavior. Our focus thereby is on the interventions and how they are designed to affect behavior.

In general, we can identify two ways in which researchers have tried to change climate related behaviors. One is through the conventional path of persuasion: by giving people information and raising awareness on the problem and its consequences, researchers aim to change people's attitudes towards climate issues. Attitudes are defined as individuals' evaluations of certain concepts: it is a personal evaluation of whether a given concept is positive or negative (Ajzen & Fishbein, 1980). As attitude is in most circumstances a strong predictor of behavior (Ajzen, 1991) this can be considered a successful route to behavior change. Examples of such interventions include educational programs, mass-media campaigns, informing people and administering feedback. Providing people with (monetary) incentives for the desired behavior is a viable strategy as well. What these strategies have in common is that they treat the individual as a rational decision maker who carefully evaluates the advantages and disadvantages of a certain behavior and chooses to do that what is deemed most appropriate or attractive. By making the 'wanted' behavior appear more important or attractive, behavior change is promoted.

A second class of interventions recognizes that individuals are not always capable or motivated to engage in such processes of extensive decision making. Instead, people are often distracted, indifferent, or unaware of their motivations for specific decisions. Also, a lot of environmental behaviors are habitual: they are part of an everyday routine that is carried out without much conscious thinking. This second class of interventions also recognizes that humans are in essence social beings who are – even without being aware of it- heavily influenced by what others in direct surroundings are doing. In the next two paragraphs, we will give a (non-comprehensive) overview of interventions from both these perspectives. While we do not argue that both types are mutually exclusive and there is never any overlap between them, we do believe that contrasting them presents the reader with a nice state of the art review of social scientific work in the climate domain. We follow up with a possible new perspective on changing climate related behaviors: the action perspective. This perspective addresses people's conversations about climate change and their own climate behaviors as a focal issue. Talking to others can operate as a form of self-persuasion and this can be a powerful tool for change. We will explore this new perspective and discuss how it might open up new direction for research in this area. Finally, we discuss the implications of our review and highlight the research agenda.

2. Interventions aimed at changing climate related behaviors: The classic approach

The classic approach to behavior change is aimed at influencing beliefs, knowledge and preferences relevant to the behavior at stake. The general idea is that once people change their minds, as a consequence they change their behavior. Examples of intervention techniques rooted in this approach include the dissemination of information, giving people feedback and providing them with incentives.

2.1 Education and information

A common approach to promote climate friendly behavior is giving people information about climate issues and behavioral responses to mitigate these. Such information can raise awareness of the seriousness of the climate crisis and increase knowledge about possible solutions (Abrahamse, Steg, Vlek, & Rothengatter, 2005). Information can create or alter beliefs about climate related behaviors and with that, change attitude people hold towards those behaviors. Information can be aimed at large groups of people or at individuals. In the former case, we speak of mass media campaigns. A study by Staats, Wit, and Midden (1996) examined the effectiveness of such a campaign concerning the greenhouse gas effect. It was found that while the campaign did lead to a slight increase in knowledge, intention to change behavior was only affected for those who were already concerned with the environment before having been exposed to the campaign. The effects thus appear to be limited at best. Others (Bamberg & Moser, 2007; Nickerson, 2003) have also concluded that knowledge of environmental issues is not very closely related to behavior. While it is important that people have at least some knowledge of climate issues and possible solutions, it is usually best to combine information with other interventions (Gardner and Stern, 2002).

2.2 Feedback

While mass media and other informational campaigns are usually aimed at bringing out general information, feedback programs tend to be more tailored to the individual (Staats, Harland and Wilke, 2004). Administering feedback entails providing people with information about their current climate related behavior and its consequences. A distinction is made between feedback on the individual and on the group level. The latter is also described as a type of comparative feedback as it provides the opportunity to compare one's behavior with that of others. This way feedback can be successful in changing behavior because it possibly makes salient a social norm in favor of the behavior at stake (Abrahamse, Steg, Vlek, & Rothengatter, 2007). A review of intervention studies aimed at household energy conservation found that feedback was a successful intervention, especially when given frequently (Abrahamse et al., 2007). Other studies on energy saving also revealed feedback to be powerful tool for change (Nickerson, 2003); from these studies some general recommendations for effective feedback can be gathered. First, it is important that feedback is presented in a way that the individual can understand it. While this may seem trivial, it really isn't: not everyone knows what a kilowatt or liter is, depending both on general knowledge and place of birth. Also, it is vital that feedback is administered immediately after the behavior occurs (Geller, 2002) and that the feedback is connected to a tangible behavior – e.g., an increase in energy use due to more air conditioning. This way, the feedback makes clear what can or should be changed. Many devices that are currently used for feedback purposes – such as gas meters – unfortunately do not provide such a clear connection between behavior and its outcomes. We believe that herein lies an important technological challenge.

2.3 Incentives

Another fairly common approach for behavior change, especially for policymakers, is the use of incentives: through subsidy plans or tax rebates climate friendly behaviors, such as buying hybrid cars, installing sonar panels or energy-efficient light bulbs are made more attractive for individuals. Another example is the subsidy schemes to promote agricultural conservation practices that most European countries have set up as part of the EU Common Agricultural policy (CAP). Reinforcing wanted behavior by financially rewarding it seems pretty straightforward and prone to success – when a particular behavior yields a reward, it becomes more attractive, and thus positive attitudes toward the behavior should increase. Yet, caution is advised, as such reinforces may backfire. The mechanism through which such backfiring might occur is the so-called 'crowding out' effect (Frey, 1997). To explain this phenomenon it is important to distinguish between intrinsic and extrinsic motivation. When behavior is intrinsically motivated, it is performed not because of an external reward or a wanted outcome, but purely for the sake of the behavior itself. If we see motivation as a continuum, at the other extreme end we find extrinsic motivation which is based solely on rewards that the behavior will yield. Needless to say that in reality, behavior is usually not completely intrinsically or extrinsically motivated, but rather falls somewhere in between. What happens when behavior that is intrinsically motivated gets rewarded? Research has shown that rewarding a behavior can cause a decline in intrinsic motivation for this behavior. People start attributing their motivation to the reward and thus their motivation becomes dependent on that reward. If the reward gets taken away (which happens often during changes in political climate), people are no longer motivated. Therefore, financially rewarding climate related behaviors creates a dependency that is self-sustaining, costly, and thus vulnerable.

2.4 The classic approach: Summary and conclusions

We reviewed three commonly used intervention techniques that are rooted in the classic approach to behavior change: information, feedback and incentives. All three interventions are based on changing attitudes towards climate related behaviors. Attitudes consist of beliefs about outcomes of behaviors (e.g., 'Using public transport decreases my carbon footprint') and the value people attach to these outcomes (e.g., 'I find it important that my carbon footprint does not grow'). Giving people information and feedback may create or alter beliefs about those behaviors, while the provision of incentives might affect the value component of the attitude.

Such interventions are warranted on the attitude-behavior relationship and as such, they assume that conscious, rational ideas about behavioral consequences and their importance underlie human decision making. Recent studies, however, have shown us that decision making is often characterized by bounded rationality and prone to be influenced by many context variables, often times outside awareness. In the next section, we will review interventions based on such less rational considerations. Specifically, we will focus on social influence and commitment making, priming, emotions and the self-concept.

3. Interventions aimed at changing climate related behaviors: The unobtrusive approach

3.1 Social influence: Social norms and commitment making

People are strongly influenced by their social environment, and their feelings, thoughts and behavior are usually very much affected by what others do and say. This phenomenon is referred to as *social influence*, and it comes in many forms. The two that will be discussed here are social norms and commitment making. Both interventions are drawn from social influence and have shown to influence a plethora of climate related behaviors.

3.1.1 Social norms

One of the most successful lines of research in the area of climate and behavioral change has definitely been (an still is) that towards the use of social norms. But what are they? Social norms are behavioral rules of a group, as perceived by the individual. As such they describe what is seen as common or appropriate, and individual group members use this information as a guide for their own behavior. Note that the term 'group' is used loosely and can refer to such compositions as cultures, families, peer groups, and even dyads. Descriptive social norms refer to what an individual thinks others do in a particular situation, while injunctive social norms refer to what an individual thinks others approve or disapprove of (Cialdini, Reno & Kallgren, 1990). For instance, seeing lots of other people recycling provides a strong descriptive norm: it informs us of the behavior of others. Hearing people talk about how recycling is important as it benefits our environment provides an injunctive norm as it informs us of other people's approval of this type of behavior. There is ample evidence for social norms influencing a wide range of climate related behaviors. A recent study by Göckeritz et al. (2010) showed that beliefs about conservation behaviors of others (descriptive normative beliefs) were significantly associated with people's own conservation behavior. This relation was even stronger for those who also held strong beliefs about others approval of conservation (injunctive normative beliefs).

In another study on the effect of norms on climate related behavior, a team of researchers looked into the reuse of towels by hotel guests. Nowadays, as part of programs on conserving resources and saving energies, hotels often ask their guests to consider using their towels for more than one day. One often finds these requests on signs placed in the bathrooms. These researchers (Goldstein, Cialdini, & Griskevicius, 2008) examined whether a social norms approach would lead to an increase in towel recycling. In half of the hotel rooms, the standard 'please help save the environment by recycling your towel' message was replaced by a message stating that the majority of guests at this hotel recycled their towels. Results showed that guests who had been presented with the latter message were 26% more likely to recycle their towel, indicating once again the strong effect that behavior of others has on us.

3.1.2 Commitment making

Another behavioral change strategy rooted in the concept of social influence is commitment making, whereby an individual is asked to make a pledge or commitment to change their behavior. Usually such commitments are made in a group of peers. Several studies have shown a positive effect of commitment making on behavior change. For instance, Burn and Oskamp (1986) carried out a commitment intervention that was aimed at household recycling. Participants in the commitment conditions were approached by a Boy Scout who asked them to sign a pledge card. If they signed the pledge, the scout handed them a sticker to post in their home to remind them to recycle. Results of this study showed a significant difference between the commitment condition and the control group in frequency of recycling.

Cobern, Porter, Leeming and Dwyer (1995) conducted a study in which they examined the effects of two types of commitment on residential grass recycling. Participants were asked to commit to grass recycling and, in a second condition, were also asked to talk to their neighbors about their recycling. The commitment to the target behavior was written, but the commitment to talk to their neighbors was done verbally. Both types of commitment were made with the experimenters present. Results showed that only participants who made both types of commitment significantly changed their behavior.

Another study (Lokhorst, van Dijk, Staats, van Dijk & de Snoo, 2010) looked at the effects of commitment making on farmers' nature conservation efforts. Here, the commitment making was combined with feedback on current conservation and tailored information on how to improve. Results showed that one year after having committed to change, farmers showed an increased intention to conserve, more time spent on conservation and an expansion in area of (semi-)natural habitat on their farms.

Both the social norms and the commitment making approach this seem viable strategies to change climate related behaviors. Still, the nature of their effectiveness remains a topic of debate. Commitment making is often assumed to rely on the presence of peers, creating some sort of social pressure to adhere to one's commitment. Yet other studies show that people adhere to commitments even in the absence of others (Kerr, Garst, Lewandowski, & Harris, 1997), rendering the social pressure explanation less likely. While it may be interesting on a theoretical level to pit these explanations against each other, in real life situations they probably operate in tandem. What may start as a feeling of being pressured into something by the soial environment may eventually become internalized. As for social norms, one of the current questions in research is whether their effects are automatic, outside of conscious processing, or whether they require some level of cognitive elaboration. Recent studies indicate that while normative social influence can occur automatically (Nolan, Schultz, Cialdini, Graskevicius and Goldstein, 2008), certain context variables (such as for instance personal involvement) can enhance elaboration (Göckeritz et al., 2010). Again, this is in line with our notion that in real life settings, multiple factors work together in influencing behavior.

3.2 Use of heuristics and priming

While discussion about the automaticity of normative social influence remains, recently there has been an interest in other automatic influencing: that of the use of heuristics and primes. This work is based on the assumption that because climate change is characterized with uncertainty – the topic is too difficult to fully grasp-, people's beliefs about climate change will be based on heuristics and accessible schemas susceptible to primes. Heuristics are rules of thumb; cognitive shortcuts that people use to guide their decisions when risks or probabilities are difficult and uncertain. Examples of such shortcuts are 'the experts know', or 'if the majority says so, it must be true'. Primes are stimuli that activate schemas: associated networks of related concepts to influence perception and behavior. Research by Joireman, Truelove and Duell (2010) shows that not only are beliefs in global warming correlated with outdoor temperature (the higher the temperature, the stronger the belief in climate change) but also that priming people with heat related cognitions increased beliefs in climate change. That is, participants who performed a word search puzzle containing heat related words (such as boil and fry) showed a stronger belief in global warming than participants whose word puzzle contained neutral words. Two important conclusions can be drawn from this research. One, as the researchers themselves point out: when investigating beliefs about climate change, one should be careful in designing the survey and selecting the time and place of measurement, avoiding any context factors that might prime heat-related cognitions and with that affect climate change beliefs. Second, to the extent that beliefs about climate change underlie climate related behavior, this line of research opens up a new wide array of possible intervention techniques based on automatic influencing. One could for instance investigate what other concept people associate with climate change and how they can be used in real life interventions.

3.3 Self-concept and labeling

When psychologists speak of the self-concept, they refer to an individuals' perception of the self; in other words, how a person sees him- or herself. The self-concept is thus a bundle of self-assessments, such as for instance 'I am attractive', 'I am bad at algebra', and 'I am someone who cares about the environment'. The latter example suggests that these aspects of the self-concepts may underlie climate related behavior and can therefore be targeted in interventions. It has been suggested for instance that the making of commitments makes salient or even alters certain aspects of the self-concept that are relevant to environmental decision making, and that this change mediates the effect of commitment making on behavior (Lokhorst, Werner, Staats, van Dijk, and Gale, in press).

Based on this connection between the self-concept and behavior is a technique named 'labeling', where one assigns a trait, belief, or any other label, to a person and then makes a request that is consistent with this label. Research shows that people are likely to follow up on these requests. Pallak and Cummings (1976) conducted a study aimed at energy conservation. They approached participants with the request to start saving energy. One half of the participants were told that their names would appear in the local newspaper as "public-spirited, fuel-conserving citizens". After a month the homeowners in this sample saved significantly more energy than the control group. Then, the participants were told that it would not be possible to publicize their names in the paper after all. For a period of 12 months the researchers measured the energy usage of these families. It appeared that during these months they had actually conserved more fuel than during the time they believed their names would be printed in the newspaper (Pallak & Cummings, 1976).

Especially noteworthy in this study is that participants in the public commitment condition were told that their names would be listed as "public-spirited, fuel-conserving citizens". Labeling them as such seems to refer directly to their self-concepts as "the kind of people who do such things", and thus made it more likely that they saved energy.

Another way in which the self-concept can be relevant to our topic is illuminated by research on self-affirmation and involvement with climate change and willingness to recycle (Sparks, Jessop, Chapman & Holmes, 2010). In their first study, these researchers were able to show that people who were self-affirmed, that is, who were manipulated into thinking positively about themselves, showed lower levels of denial of climate change, and greater perceptions of personal involvement. How does this work? In general, denial is seen as a defense mechanism: when people are threatened (for instance by climate change), one way to cope with this threat is denying the problem. Self-affirmation theory (Steele, 1988) predicts that self-affirmations boost the self-concept, making defensive reactions less necessary, and leading people to more open to threatening information. This is indeed what these researchers found. Moreover, in their second study, they managed to show that the effect of self-affirmation extended to recycling behavior: participants who were self-affirmed showed greater intentions to recycle than those who were not self-affirmed (Sparks et al., 2010).

3.4 Emotions

An opportunity that as of today has not been given a lot of attention in social scientific research is the idea that emotions might also underlie climate related decision making and behavior. It has been shown for instance that having emotional ties with nature is of significant influence to environmental decision making (Kals, Schumacher and Montada, 1998). More direct evidence for emotions as a successful behavior change technique comes from work by Ferguson and Branscombe in 2010. In two studies they were able to show that experiencing collective guilt concerning greenhouse gas emissions leads people to express greater willingness to conserve energy and to pay 'green' taxes. While guilt of course is a negative emotion, it might very well be that positive emotions (such as for instance pride or happiness) affect climate related behaviors as well. We believe that herein lies an interesting new approach for climate change researchers and communication professionals. Finding out which emotions might affect climate related behaviors and how will provide new input for campaigns aimed at bringing about behavioral change.

3.5 Breaking the habit

Many of the climate related behaviors we perform are habitual; they are not the result of conscious reasoning, weighing in the pros and cons of our options, but simply behaviors we have grown accustomed to and would rather not part with. Such behaviors are usually performed repetitively, in a stable context. Travel mode choice for instance, has shown to be an extremely habitual behavior (Verplanken, Walker, Davis, & Jurasek, 2008). One consequence of behavior being habitual is that people are not very open to acquiring information about alternatives and options for behavior change (Verplanken, Aarts, & Van Knippenberg, 1997). Therefore, classic approaches relying on dispersing information are not likely to be effective. But what can be done to break habits?

Habitual behaviors are cued by recurring stimuli in a stable context (Wood, Tam, & Guerrero Witt, 2005; Wood & Neal, 2007). Therefore, changing this context – and thus the recurring stimuli- should strongly impact these behaviors. This idea is referred to as the discontinuity hypothesis (Verplanken, Walker, Davis, & Jurasek, 2008). Indeed, these authors have shown that a change in context – in their study, people moving house – impacted travel mode choice, but only for those who were already environmentally concerned. The researchers interpreted this as the context change creating a window of opportunity for people to break their habits and let their environmental values influence their behavior. This goes to show that when we try to change behavior we should not only focus on the psychological determinants bust also on possibilities for change in the context in which behavior takes place.

3.6 The unobtrusive approach: Summary and conclusions

We have reviewed several studies that make use of social psychological insights in behavior, its determinants and the contexts in which it is performed. We have seen that concepts such as norms, priming, emotions and the self-concept play a role in climate related behavior and that they can be targeted by interventions. Moving away from the classic approach that is rooted in the attitude-behavior relationship gives us the opportunity to acknowledge that behavior is multi-faceted and context-dependent. It also opens up a new and wired array of different behavior change techniques based on more recent insights from social psychology. Before we move to our general discussion we would like to present the reader with a new perspective on changing climate related behaviors: the action perspective.

4. The action perspective

As we saw earlier in this chapter knowledge about environmental issues is not always closely related to behavior. Many people are aware of the necessity to change their routines because of the climate problem, and are possibly also willing to change, but at the same time utterly incapable of doing so. The reasons are mainly that climate related behavior is not a clear cut separate fraction of human activity, but that it is embedded in social practices and routines, such as daily commuting or living in a spacious and comfortable house with a lot of helpful devices. Changing these practices mostly has social consequences. For instance, travelling by public transport to your office often means spending less time with relatives at home. Opting for the 'better' alternative urges for discursive action to justify the new behavior in the eyes of others. If the choice is a collective one, such as for instance lowering the thermostat in the living room, people might actually have to try and get their family members' permission.

The action perspective is directed at the very process of making change happen in a given social context (Bouwman and Van Woerkum, 2008). It looks at the barriers at the level of everyday life but also at how some people succeed to overcome these barriers. These people can act as role models, not only because others can identify with them, but because they can show how things can get done. These successful changers can be invited to share their experiences on website fora. As another option, their experiences can be played out in soaps, which may be broadcasted on TV for a large audience. The objective is that basically motivated individuals learn to implement their good intentions in their own social context. In their work on so-called guided group discussions, Werner, Sansone, and Brown (2008) also stressed that researchers and policy makers recognize that new behaviors are always embedded in social larger social, environmental, economic, and policy contexts. They propose letting people discuss these new behaviors with others (in guided group discussions) as a means of offering a supportive social setting.

5. Discussion

After having reviewed several strategies aimed at bringing about behavioral change, what can be concluded concerning their effectiveness? Is one type of strategy preferred over the other? Can they be combined? How should professionals select which strategies to employ?

We propose that, in accordance with the action perspective, each behavior change program starts with an extensive study of nature of behavior as well as the context in which it takes place. What can be said about the behavior in question? To what extent is it automatic, habitual, or subject to routines? Are other people involved, or affected by the outcomes? Is the behavior difficult or costly to perform, does it require a high level of specific knowledge? Only when through such careful analysis the specific determinants of the behavior in question can be determined, one can make an informed decision as to what intervention strategy to use to alter the behavior.

For instance, when a behavior is highly habitual, presenting people with information concerning alternative options is not likely to bring about change. Instead, the context in which the behavior takes place should be examined and checked for possibilities: can a window of opportunity be created in which a change in context offers leeway for people to break their habit? Or, when a specific behavior mostly takes places in a strong social environment, what are the dominant normative influences? Can a message be construed that informs people about that behavior of others so that they will change theirs accordingly? Or, when we know that a specific behavior is largely based on heuristic processing, we might look for automatic associations that people use in their decision making. What matter is that interventions should be chosen based on the *nature* and the *context* of the behavior that is targeted.

At the same time, it should be recognized that behavior is always multi-faceted and never determined by one single factor. Likewise, when applying social scientific knowledge to natural settings, one should never assume that one specific strategy will do the trick – instead, a combination of interventions is to be preferred. Numerous studies have shown that usually, combined interventions are most effective in producing durable behavior change (see, for example, DeLeon & Fuqua, 1995; Lokhorst et al., 2010; Staats et al., 2004). So, a few interventions that are likely to yield result should be chosen and combined in a multi-level intervention.

The next stage of any successful intervention program is one that is often overlooked by social scientists: the implementation. Who will be administering the intervention? What are people’s attitudes towards or relations with these institutes, experts or authorities? What media will be used? How will the target group be invited to participate in the program?

Does participation come with a cost, and if so, what cost? Where do people turn to when they have questions? All these more practical aspects of behavior change programs must be taken into consideration when developing an intervention. Just as selecting the right technique, they are key to the success of the program.

Another sometimes forgotten but nevertheless vital aspect of change programs is the follow up. When can behavior change be expected and measured? What is considered long term behavioral change, and how long can you monitor participants? Many intervention programs claim they lead to long term durable change yet fail to check up on participants after the program has ended. Of course, continued monitoring is difficult and costly, but at the same time it is tremendously valuable if we can see how and for how long behavior change can occur.

6. Conclusion

Countering the adverse consequences of climate change relies heavily on changes in human behavior. In order to successfully change behavior, we need to understand its nature as well as the context in which it is performed. This is where the social sciences come into play. We strongly believe that collaboration between the natural and the social sciences is a vital precondition for creating successful behavioral change programs. Hopefully, this chapter has provided an overview of the broad range of possible interventions derived from social scientific research.

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3

Understanding and Modelling the Impact of Climate Change on Infectious Diseases – Progress and Future Challenges

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1. Introduction

The effects of global change on human health have attracted increasing attention in recent years, with anthropogenic influences thought to have significant influences on the Earth's climate (Intergovernmental Panel on Climate Change [IPCC], 2007). Climate change is thought likely to have important effects on human, animal and plant life. In addition to indirect effects on human behaviour such as shifting migration patterns, direct effects of climate change on human health are potentially severe. Together with implications through changing air quality, increased exposure to UV radiation, changes in food production, increasing water shortages and contamination, and economic instability, climate change is widely expected to also significantly affect the global spread, intensity and distribution of infectious diseases (Hunter, 2003; McMichael *et al*., 2006).

In this chapter, we review current knowledge on the impacts of global change on infectious diseases (Section 1), highlighting how combining global and regional climate models with mathematical (and statistical) models of disease transmission (Section 2) provides valuable tools for better understanding future disease scenarios as environmental conditions change. Such models may be used to address important questions on the current and projected impacts of climate change on disease transmission and we illustrate these issues (and the extent to which they have been addressed in modelling work to date) in Section 3. It should be remembered, however, that despite the power of weather, climate and disease models, considerable uncertainties remain. Identifying the origin of these uncertainties, highlighting where improved data may improve model accuracy, realism and confidence, together with translating uncertainties in model inputs into uncertainties in model outputs, are important benefits of modelling. Highlighting where key uncertainties lie is discussed in Section 4, illustrating where future research priorities may be directed to further our understanding of this emerging field.

1.1 Key climatic variables

Although many climatic variables may affect transmission, changes in four main variables are thought to most significantly affect diseases with strong environmental components, namely temperature, precipitation, relative humidity (RH) and wind. Here, we briefly review the impacts of these components on transmission, as well as outlining expected future trends in these variables. It should be noted, however, that climatic variables rarely act in isolation and combinations of variables tend to be associated with climatological niches for optimum transmission of different diseases, e.g. the preferred environmental conditions for optimum proliferation of *Anopheles gambiae s.s.*, *An. arabiensis* and *An. funestus*, the three principal vectors of malaria in Africa.

1.1.1 Temperature

The cold-blooded nature of most vectors (e.g. mosquitoes, fleas, ticks and flies) results in a strong dependence of disease incidence on ambient temperatures through changes in vector and parasite survival and development (Martens, 1998). Other influences of temperature on vectors include those on biting rates, resting and mating behaviours, dispersal and the duration of gonotrophic cycles (Martens *et al.* 1995), while effects on humans include changing migration and movement patterns and increasing susceptibility due to immunocompromisation at temperature extremes. The net effect is a non-linear dependence of pathogen vectorial capacity and basic reproduction number on temperature (e.g. Parham & Michael, 2010).

Global mean surface air temperatures are predicted to increase by several degrees over the next century and while predicted increases over the coming decades are typically consistent between climate models, there is considerable prediction variability from multi-model ensembles over longer timescales for different emissions scenarios and geographic regions. Changes in the occurrence of extreme temperature events are also likely, with predicted increases in more intense, frequent and longer duration episodes (heat waves), along with fewer colder episodes (IPCC, 2007).

Understanding the effect of temperature extremes on disease dynamics has received little attention to date, although strong influences on vectors and parasites at very high and very low temperatures are likely. The survival of malaria-transmitting *An. gambiae* s.l. mosquitoes, for example, has been shown to sharply decrease at prolonged exposure to temperatures above 40°C for immature stages (e.g. Huang *et al.*, 2006) and adults (Kirby & Lindsay, 2004), particularly at extremes in RH. Variation in predicted temperature changes is significant with latitude, but increases in Africa (with median increases around 3-4°C across most of Africa for all seasons) are expected to be greater than the global mean. Predicted increases in regional mean temperatures are likely to cause non-linear changes in disease incidence due to the relationship between temperature and several components of transmission. Process-based models, discussed further in Section 2, however, provide a useful tool for assessing how such complex factors interact and affect prevalence, pathogen reproductive potential and the rate of disease emergence in new regions as climatic conditions change (e.g. Parham & Michael (2010) in the context of malaria).

1.1.2 Precipitation

Precipitation has direct and indirect effects on disease incidence. Direct effects include increased likelihood of water-borne and soil-borne parasitic, bacterial and viral diseases following severe rainfall events, as well as creating new (and modifying existing) breeding sites for transmitters of VBDs. Indirect effects include increasing susceptibility through unsafe drinking water, food contamination or enteric diseases.

Rainfall extremes, including floods and storms, will also play an important role. The impact of high rainfall levels and flooding on increasing disease risk is likely to be strongly dependent on country wealth and overall development state, as well as other social and environmental influences. While the population dynamics of vectors will suffer some negative effects of such events (e.g. breeding site destruction from high intensity and volume rainfall increasing immature mortality (e.g. Paaijmans *et al.* (2007) for malaria)), the net effect is almost always increased vector abundance through breeding site creation. Thus, rainfall has been used as a predictor of VBD incidence for diseases including plague (Parmenter *et al.*, 1999), Rift Valley fever (Linthicum *et al.*, 1999) and malaria (Bi *et al.*, 2003; Thomson *et al.*, 2005). Delays between severe rainfall and vectors identifying new habitats for oviposition, plus other effects such as delays in water temperature reaching suitable levels for immature survival, often result in lags between rainfall events and sharp increases in disease prevalence (Briet *et al.*, 2008; Kristan *et al.*, 2008).

Drought and desiccation are also thought to play important roles. As well as indirect effects such as increasing human susceptibility due to changing immune status from water and food scarcity, the absence of water and soil moisture for prolonged periods decreases vector abundance due to the absence of suitable breeding sites.

Global mean precipitation is predicted to increase under future climatic conditions, together with increases in the intensity (but decreases in the frequency) of extreme rainfall events. Increases in precipitation appear almost independent of the emissions scenario over the coming decades, but display considerable variability thereafter (IPCC, 2007). Indeed, changes in rainfall patterns may have more influence on health risks from climate change than global warming (Allen & Ingram, 2002). However, in contrast to temperature trends, variability in rainfall predictions between models is considerably greater, particularly at lower latitudes. Increases in the intensity of rainfall extremes are projected to be even greater than increases in mean precipitation changes, with associated increased disease risks from flooding and droughts. Despite projected regional changes in seasonal and decadal rainfall patterns differing between climate models, ensemble model predictions highlight significant spatial heterogeneity in expected precipitation pattern changes. Decreasing seasonal rainfall across South African regions, for example, contrasts markedly with projected increases across East Africa (IPCC, 2007).

Despite uncertainty and variability in global rainfall predictions across different models, rainfall increases in East Africa, particularly during the winter months, show greatest robustness in predictions of all African regions. Together with associated temperature increases of around 3°C for all seasons, this has attracted increasing attention in the context of malaria dynamics, with research focussing on questions such as whether recent prevalence changes indicate that climate change effects are already underway in this region (Hay *et al.* 2002a, 2002b, 2005; Pascual *et al.*, 2006, 2008; Zhou *et al.*, 2004).

1.1.3 Relative Humidity (RH)

Changes in RH are most likely to affect the dynamics of VBDs and while effects on parasite development within vectors are unlikely (although uncertain), considerable influences on human health and vector population dynamics (and behaviour) are evident. Extremes in RH have been shown to adversely affect human health (Baughman & Arens, 1996), worsening chronic diseases such as asthma (and other lung and respiratory diseases) and potentially increasing susceptibility to infectious diseases. The effects of changes in RH, however, are likely to most significantly affect vectors, notably on adult survival and activity.

For *An. gambiae* s.l. mosquitoes transmitting malaria, mean adult survival is considerably shortened below 50-60% RH and reduced (albeit by a smaller amount) close to 100% (Pampana, 1969; Warrell & Gilles, 2002), suggesting an optimum RH range for survival. Increased RH has also been shown to affect *An. gambiae* s.l. reproduction, increasing vector abundance (Jawara *et al.*, 2008). However, the favourability of individual species within the *An. gambiae* complex to RH conditions may vary substantially (Colluzi *et al.*, 1979) and changing patterns of land use have been shown to affect RH, e.g. deforestation has been associated with increased vector abundance (Afrane *et al.*, 2007).

Globally averaged RH is thought to remain approximately constant under climate change and this appears to be a feature of current general circulation models (GCMs) (Allen & Ingram, 2002). Recent work on creating and analysing the first global humidity dataset has shown that RH is almost constant on large spatiotemporal scales, but considerable regional structure and temporal variability remains (e.g. diurnal RH variability may be around 25%) (Willett *et al.*, 2008). Global trends over land are typically negative, but not significant (Willett *et al.*, 2008), and conditions of constant RH serve as further evidence of global warming (Willett *et al.*, 2007). Comparisons between recent RH land means and global maps of malaria prevalence (e.g. Hay *et al.*, 2009) are consistent with the notion of optimum RH for high prevalence, although given the lower density of weather stations contributing to the humidity dataset in the tropics (Willett *et al.*, 2008), further research is required to better understand RH trends and anomalies in areas most severely affected by malaria.

1.1.4 Wind

Global and local changes in wind patterns have three principle effects on infectious diseases, namely (a) affecting the dispersal ability and behaviour of disease vectors (or direct wind-borne pathogen spread), (b) changing hydrological processes such as evaporation that affect vector abundance and (c) affecting human susceptibility due to extreme weather events such as storms and tropical cyclones. Little research has examined the potential impact of changes in wind patterns on diseases, although some work has examined the effect on animal diseases (e.g. Kedmi *et al.* (2010) on epizootic hemorrhagic disease virus in dairy cattle and Sellers *et al.* (1985) on bluetongue in sheep). Peak wind and near-storm precipitation intensities are predicted to increase in future tropical cyclones (IPCC, 2007).

1.2 Current knowledge on the potential impact of climate change

We focus here on providing an overview of the main infectious diseases thought to be strongly affected by climate change, primarily focusing on VBDs, although we also consider the potential impacts on water-borne and other diseases. We focus solely on human diseases, but note that the effects of climate change have also been considered on non-human diseases such as bluetongue, Eastern and Western equine encephalitis, Western Venezuelan equine encephalitis and African horse sickness (Githeko *et al.*, 2000; Summers, 2009). In the case of bluetongue, for example, incidence has been shown to increase most where temperature increases have been greatest and where minimum climatic conditions are met for transmission (Purse *et al.*, 2005).

1.2.1 VBDs

The sensitive nature of arthropod species to changes in climatic variables suggests that of all the infectious diseases potentially susceptible to climate change, VBDs are the most sensitive and we may see shifts in VBD distribution over the coming decades and centuries (WHO, 1999). While there is much speculation on future incidence trends with climate change, few empirical studies have emerged to determine whether impacts are already underway and considerable debate has arisen from those that have (McMichael *et al.*, 2006). This is nowhere better illustrated than the recent (and ongoing) debate about the relationship between malaria and meteorological trends in the East African highlands (Hay *et al.* 2002a, 2002b, 2005; Pascual *et al.*, 2006, 2008; Zhou *et al.*, 2004).

The link between vector survival and lifecycle processes and climatic variables indicates only that VBDs can be affected by climate change; the magnitude and extent of the change given the many factors affecting incidence is perhaps the most important question for the field. The global distribution of malaria, for example, is thought to almost certainly change with climate (e.g. Cook, 1992; Sutherst, 2004), although the magnitude of this change may be relatively small (Rogers & Randolph, 2000), yet VBD transmission is dependent on a multitude of epidemiological, environmental, social, economic and demographic factors (Martens *et al.*, 1995; McMichael *et al.*, 2006). Indeed, mitigating climate change may result in only a very small reduction in the population at risk of malaria by 2080 (Goklany, 2004). Local infrastructure and wealth may also influence the risk of disease emergence in new regions (and the treatment of individuals should outbreaks arise), although the risk of imported infections should not be dismissed (Hunter, 2003; Isaacson, 1989).

Temperature, rainfall and RH thresholds critically affect the geographic regions conducive to malaria transmission, with the majority of cases contained within latitudes of 30°N to 30°S (Hales & Woodward, 2005; Hay *et al.*, 2009), although the possibility of European outbreaks has also been considered (WHO, 1999). However, within regions where climatic sufficiency conditions exist for transmission (and where rainfall sufficiency is usually thought to be more crucial than temperature (e.g. Mabaso *et al.*, 2006)), considerable research is required into the role of climatic influences compared to other factors driving disease dynamics. These include land use changes (including deforestation), changes in transportation infrastructure, changes in immunity, drug and insecticide resistance, urbanisation and the impact of control measures (Afrane *et al.*, 2007; Hay *et al.*, 2002; Lindblade *et al.*, 2000). Local landscape also plays an important role (Ernst *et al.*, 2006) and altitudinal effects on incidence have been considered (Lindsay & Martens, 1998; Reiter, 2008), along with changes in human behaviour (Martens & Hall, 2000; Tatem *et al.*, 2006). In addition, rainfall has been shown to significantly affect vector population dynamics, increasing the number of suitable larval breeding sites, adult abundance, biting rates and the duration of gonotrophic cycles, as well as the seasonal dynamics of different *Plasmodium* strains (Koenraadt *et al.*, 2004; Molineaux *et al.*, 1980; Ndiaye *et al.*, 2006).

Severe climatic events such as ENSO may have disproportionately large effects on disease trends (Kovats *et al.*, 2003), with sudden increases in temperature, rainfall and RH shown to have caused sharp increases in malaria incidence in Punjab and Sri Lanka (Githeko *et al.*, 2000) and Columbia (Bouma *et al.*, 1997; Mantilla *et al.*, 2009). Such climatic anomalies have been used to drive seasonal malaria forecasts (Thomson *et al.*, 2005, 2006). Changes on shorter timescales (e.g. diurnal cycles) have been shown to have important implications for transmission (Paaijmans *et al.*, 2010), since non-linear relationships between temperature and components of transmission mean that small changes in the former may have large effects on the latter, particularly in the most vulnerable regions (Sutherst, 2004).

Alongside malaria, dengue and schistosomiasis are also thought to be significantly affected by climatic changes (Martens, 1998), yet these diseases combined represent less than 7% of the global mortality due to malaria (WHO, 2008), which has therefore attracted most attention to date. However, despite the low mortality rate, the global burden of dengue remains high and it is thought to annually infect around 50-100 million people worldwide, remaining endemic in more than 100 countries (Whitehorn & Farrar, 2010). Dengue transmission demonstrates a similar global distribution to malaria, being primarily concentrated in the tropics and subtropics (Hopp & Foley, 2003; López-Vélez & Moreno, 2005), although this is likely to be affected by climate change (Cook, 1992) and shifts in altitudinal range are also possible (Chan *et al.*, 1999). Transmission occurs via *Aedes* mosquitoes, primarily *Aedes aegypti*, although the introduction of A*edes albopictus* into Europe over the last 15 years has raised the threat of dengue re-introduction into Europe (Semenza & Menne, 2009), as well as the possibility of the re-emergence of other VBDs such as chikungunya (Hochedez *et al.*, 2006).

Aedes abundance has been shown to positively correlate with rainfall and humidity (Gubler *et al.*, 2001; Watts *et al.*, 1987), increasing mean temperatures and the occurrence of ENSO events (Gagnon *et al.*, 2001; Hales *et al.*, 1999; Herrera-Martinez & Rodríguez-Morales, 2010), with changes in humidity potentially playing a significant role (Hales *et al.*, 2002). The development rate of the dengue virus within *Aedes* is strongly influenced by ambient temperature (Martens, 1998; WHO, 1999), e.g. reducing from an incubation period of 12 days at 30°C to 7 days around 32-35°C (López-Vélez & Moreno, 2005).

Climatic changes are also likely to affect the global distribution of schistosomiasis (Cook, 1992; Martens, 1998; Mas-Coma *et al.*, 2009), with transmission potential thought to be particularly sensitive to climate change around the edges of current endemic areas (Sutherst, 2004). Indeed, decreases in snail abundance due to increased mortality with global warming may reduce the epidemic potential of schistosomiasis in these regions (Epstein, 2001), although other areas (e.g. China) may experience an increase in areas suitable for transmission (Yang *et al.*, 2005). Importation of cases into areas previously endemic is also a concern in several areas (e.g. Casimiro *et al.*, 2006).

Other VBDs have also attracted recent attention in the context of climate change. The effects of global warming may cause shifts in the geographic distribution of vectors (through changing migration patterns) and changes to the duration of transmission seasons, with implications for diseases such as tick-borne encephalitis (TBE) and Lyme disease (Epstein, 2001; WHO, 1999). Increasing incidence of the latter has been found in several European countries (Semenza & Menne, 2009), with re-emergence under climate change also considered (Casimiro *et al.*, 2006).

For TBE, milder winters and drier summers are thought to decrease and increase tick activity respectively (Githeko *et al.*, 2000), with implications for tick abundance at higher altitudes and latitudes (Gray *et al.*, 2009). Indeed, given that several parameters appearing in an expression for the basic reproduction number R_0 (see Section 3.1) of tick-borne diseases depend on climatic variables (Randolph, 1998), such diseases are likely to be sensitive to future environmental changes, particularly changes in temperature and RH (Randolph, 2004; Suss *et al.*, 2008), e.g. Rocky Mountain spotted fever (Gubler *et al.*, 2001).

Mosquito-borne diseases, more generally, are likely to experience important changes in transmission potential given the sensitivity of vector and pathogen survival, development and replication to changes in mean climatic drivers and temporal fluctuations about the means (Khasnis & Nettleman, 2005; Reiter, 2001), although factors such as changes in population growth or density may also play a strong role (Tol & Dowlatabadi, 2001). Through changes in vector abundance, distribution and seasonal activity, climatic changes may affect the incidence of other diseases such as leishmaniasis, Yellow Fever, Japanese encephalitis, arboviral diseases, African trypanosomiasis, lymphatic filariasis, onchocerciasis and dracunculiasis (Cook, 1992; Githeko *et al.*, 2000; Gubler *et al.*, 2001; Michael, 2009; Reiter, 2001; Sutherst, 2004). Changes in the patterns of Ross River virus, West Nile virus, Rift Valley fever, American trypanosomiasis and St. Louis encephalitis with climatic variables have also been reported (Epstein, 2001; Casimiro *et al.*, 2006; Gubler *et al.*, 2001; Michael, 2009; Semenza & Menne, 2009).

1.2.2 Other infectious diseases

Around 23% of global deaths due to infectious and parasitic diseases are due to diarrhoeal diseases, with almost half of these occurring in Africa (WHO, 2008). Higher temperatures are shown to frequently accompany increased incidence (McMichael *et al.*, 2006); developing countries, for example, are predicted to show a 5% increase in incidence per 1^{o}C temperature increase (Campbell-Lendrum *et al.*, 2003). Changing environmental conditions may therefore strongly affect the intensity and distribution of water-borne diseases through changes in water quality and availability (Hunter, 2003), e.g. sharp increases in leptospirosis after strong rainfall events and flooding (Githeko *et al.*, 2000; Gubler *et al.*, 2001).

Temperature changes are known to affect the population dynamics of phytoplankton and zooplankton, which in turn affect the abundance of bacteria causing cholera (Lipp *et al.*, 2002), the geographic range and dynamics of which may alter with climate change (Koelle *et al.*, 2005; Pascual *et al.*, 2002). The correlation between ENSO events and cholera has also been considered (e.g. Pascual *et al.*, 2000).

Other impacts include those on food-borne diseases due to higher temperatures increasing bacterial survival and proliferation (Hall *et al.*, 2002). Indeed, correlations have been observed between short-term increases in temperature and both food poisoning (McMichael *et al.*, 2006) and increases in diseases such as salmonellosis and botulism (Semenza & Menne, 2009; WHO, 1999). The link between climatic variables and the incidence of rodent-borne diseases has been reported for diseases such as plague (Githeko *et al.*, 2000; Gubler *et al.*, 2001), as well as influences on soil-borne diseases such as melioidosis (Inglis & Sousa, 2009).

2. The use of models to understand disease transmission

The first application of mathematical modelling to infectious diseases is often attributed to work on smallpox eradication by Daniel Bernoulli in the 18th century (Bernoulli 1760), yet many of the methods currently applied to address public health questions have been developed over the last few decades (e.g. Anderson & May, 1991; Daley & Gani, 1999; Keeling and Rohani, 2007), and application of these methods to model specific pathogens or outbreaks have increased considerably since the mid-1980s.

2.1 Types of disease modelling framework

A range of mathematical frameworks are applicable for the development of environmentally-driven disease models and these may be categorised as taking one characteristic from each of the following classifications.

2.1.1 Population and Individual-Based Models (IBMs)

The primary population models for describing infectious disease transmission are typically compartmental in nature, aggregating individuals according to their disease status and tracking how the number of individuals in each class changes over time. In IBMs, each member of the population is modelled, taking into account individual characteristics or risk factors, and tracking the influence of demographic, social, climatic, environmental or epidemiological processes over time. Population models may take any of the mathematical forms below, while IBMs are typically stochastic as individuals undergo epidemiological processes with a certain probability. The introduction of *p*-state and *i*-state variables by Metz and Diekmann (1986) provides a formal means of distinguishing between population models and IBMs.

2.1.2 Continuous and discrete-state models

Models of the former type are described by continuous *i*-state or *p*-state variables, so that state variables may take infinitely many values within an interval. In the latter case, state variables may take only a finite number of values (e.g. matrix population models or models where only an integer number of individuals is permitted).

2.1.3 Deterministic and stochastic models

In deterministic models, specifying parameter values, the initial values of state variables and a set of equations describing how initial states evolve over time results in model outputs that do not change from one simulation to the next. Mathematical descriptions of deterministic models are generally ordinary differential equations (ODEs), delay-differential equations (DDEs), partial differential equations (PDEs) or integro-PDEs (in continuous-time) or difference equations (in discrete-time). Stochastic models are formulated in terms of random variables, so that even for a fixed set of initial conditions, parameters and rules for evolving state variables, repeated runs of the same model produce different outputs. Stochastic effects are important when population sizes become small and may be used to capture uncertainty, variability and/or noise in disease or climate processes.

2.1.4 Continuous and discrete-time models

In the former, time evolves smoothly over an interval, so that model parameters reflect the rate at which events occur, and such models are often described by a set of differential equations. In the latter, the values of state variables are tracked only at certain time points, typically of fixed separation, and such models are usually described by difference, delay-difference or integro-difference equations.

2.1.5 Non-spatial and spatial models

Non-spatial models assume spatially homogeneous and isotropic transmission, so that each individual is assumed to be infected by all other members of the population with equal likelihood, irrespective of the distance between them. Most pathogens, however, have a spatially local component to transmission, where this spatial element may be in geographic space (i.e. Euclidean distance) or social space (e.g. in terms of human contact networks). Spatial models may be further classified as continuous or discrete-space models and reviews of spatial modelling (and model types) have appeared elsewhere (e.g. Keeling, 1999).

2.1.6 Homogeneous and heterogeneous mixing models

Models assuming homogeneous mixing assume no preferential contact between any two individuals in the population, so that if all individuals have the same contact rate and infection is passed on with a fixed probability per contact, then the model assumes a fixed force of infection across all contact pairs. For pathogen transmission where transmission risk is heterogeneous and varies across pairs of susceptible and infectious individuals according to *i*-state characteristics of the individuals involved, mixing patterns may be described by WAIFW (Who Acquires Infection From Whom) matrices, where homogeneous mixing occurs as a special case when all elements of the matrix are equal.

2.1.7 Models embedded within static or dynamically-varying environments

Here, the environment refers to all processes or influences on disease dynamics external to an individual and these include mixing patterns, contact structure, population demographics, drug resistance, intervention measures and climatic conditions. Disease dynamics of models assuming static environments arise solely from the interaction between intrinsic model processes, while in models whose environments change over time, both intrinsic and external processes may drive dynamics. Mathematically, the latter class of models are frequently implemented through temporal changes in model parameters and this occurs in climate-driven models through, for example, daily temperature variability affecting processes such as vector survival or parasite development.

Given this variation in available approaches, the choice of disease modelling framework to better understand the effects of climate change depends on a range of factors, primarily data availability and the questions of interest. Certain model types will prove advantageous over others when investigating the effect of environmental variables depending on the issues under consideration, the timescale available for the investigation, knowledge on disease natural history, the degree of analytical versus numerical insight required into spatiotemporal dynamics as climatic conditions change, and data availability for model calibration and validation. Other considerations may include computational resources (e.g. IBMs and climate models are very computationally intensive) and known uncertainties (or variability) in disease and climate inputs.

2.2 The role of modelling

In the context of understanding how global change will affect infectious diseases, both statistical and mathematical models have important roles to play. Statistical models use descriptive correlations between explanatory and response variables (here, climate and disease respectively) to predict the future state of systems based on past behaviour. Such models offer no explanations as to underpinning biological mechanisms driving predicted changes, although inferences are normally derived from the results obtained (see Section 3.2). Mathematical models, on the other hand, adopt a process-based approach, combining known biological, epidemiological and/or environmental processes to formulate assumptions that characterise the model. Future states of the system are predicted given the initial state and by comparing model output with observations on incidence, mathematical models offer explanatory power. We focus here on the role of dynamic mathematical models.

Models provide a useful bridge between individual-scale processes, behaviour and environmental conditions and population-level observations on disease spread. As such, key principles underlying relationships between climate and disease may be elucidated, interactions between components affecting transmission may be better understood and patterns of prevalence may be explainable in terms of underlying processes. Model calibration and validation may provide a means of reliably predicting short and long-term disease dynamics, both under the assumption of unchanging model processes and where extrapolation of current observations to future scenarios is required when factors driving transmission change. Such models offer a major advantage over statistical models in this respect, which rely on the relationship between response and explanatory variables remaining constant. Extrapolation is based on current background conditions and the strength of existing associations between explanatory and response variables, an assumption that is questionable over the timescales characteristic of climate change.

Mathematical models also allow us to better understand the dynamics of complex systems involving interactions and feedbacks between multiple non-linear processes. Climate models are frequently associated with extreme sensitivity to initial conditions, while chaotic behaviour has also been observed in disease models (e.g. Bolker & Grenfell, 1993), and models may be used to overcome difficulties in our intuition at understanding the behaviour of systems with complex, non-linear and chaotic phenomena. This is particularly relevant to climate-driven infectious disease systems because of the complex behaviour that external drivers of dynamics, which climate variables embody, can introduce into disease transmission such as cyclical or chaotic dynamics (see below). Well-validated models may be used for short and long-term prediction, testing hypotheses and potentially acting as early warning systems for disease outbreaks in response to climatic phenomena (e.g. ENSO). They may also provide the basis of sensitivity analyses, enabling a better understanding of the response of disease dynamics to changes in model parameters, either epidemiological or climatic, as well as enabling identification of areas where improved data is required.

Perhaps most importantly, mathematical models may be used in scenario analysis to better understand (a) the impact of climate change mitigation on transmission, (b) how the interaction between climate and vector-borne, water-borne and other infectious diseases may influence climate change adaptations and (c) the influence of climatic variables and other drivers of disease on intervention dynamics. Such analysis may be used in long-term planning of disease control programmes, as well as utilising models as a means of quantifying uncertainties in disease and climate knowledge (see Section 4) and how this translates into uncertainties in the effectiveness of proposed intervention strategies.

3. Disease models in the context of climate change: The need to incorporate complexity

3.1 Large-scale effects of climate on disease transmission

Climatic variables affect processes associated with transmission in numerous ways and these may be broadly categorised as:

a. Direct effects on physical and physiological processes (e.g. changes in vector survival and the rate of blood meal processing with changing temperatures).
b. Indirect or intermediate effects on physical processes (e.g. hydrological processes affecting the creation and modification of vectors breeding sites through changing rainfall patterns).

c. Changes in human geography (e.g. land use changes such as deforestation, urbanisation or migration affecting the distribution of regions susceptible to emerging outbreaks).
d. Changes in the intensity, frequency or geographic distribution of extreme weather events such as droughts, flooding, heat waves and cold waves.
e. Changes in human susceptibility to diseases through immunosuppression due to factors such as changes in chronic cardiorespiratory diseases, malnutrition or water shortages.
f. Changes in intermediate host population dynamics (e.g. regional changes in vector abundance or bacterial proliferation causing increased water-borne or food-borne diseases).

Such effects raise important questions that realistic models, both mathematical and statistical, should address and both types of models, when used in combination, may provide powerful causative and descriptive links between climate and disease changes. As well as changes in the mean values of climatic variables, temporal variability is also likely to play a significant role (e.g. Zhou *et al.*, 2004), so assessing the effects of climate variability (and uncertainty) on transmission is vital. Temporal variability in disease models may arise from a number of sources (Grassly & Fraser, 2006), the basic mechanisms for which, in this context, arise from (a) changing contact patterns or behaviour over time (e.g. human behaviour in response to severe weather events or changing vector dispersal patterns), (b) temporal variability in environmental variables driving microscale processes (e.g. diurnal temperature fluctuations or longer-term land use changes), (c) fluctuations in intermediate host population dynamics (e.g. tick or snail abundance in response to changing environmental variables) or (d) changes in host immunity (Parham & Michael, 2011).

Models may also be used to address questions such as the appearance of disease thresholds in the context of system resilience and stability (Gambhir & Michael, 2008; Scheffer *et al.*, 2001), assessing the impact of climate mitigation and disease intervention measures, integrating economic considerations to assess the scale, nature and timing of control strategies given limited resources, and better understanding dynamic interactions between diseases. More specific epidemiological concepts may also be investigated such as the effects of climatic drivers on the basic reproduction number R_0 (defined as the average number of secondary infections generated per primary case (Anderson & May, 1991)), invasion properties (such as the probability of establishment (or fade-out) of outbreaks in newly vulnerable regions), the rate at which incidence increases and long-term disease persistence.

3.2 Examples of models to date

3.2.1 Statistical and semi-mechanistic-based approaches

Research to date developing integrated malaria models has included both statistical and biological (process-based) approaches. An early statistical model used fuzzy logic to quantify the suitability of different regions within sub-Saharan Africa for transmission given local temperature and rainfall conditions (Craig *et al.*, 1999), while Rogers & Randolph (2000) used a statistical approach to show that that the global malaria distribution may not change considerably by 2050. Other work has used spatial models and risk maps to demonstrate that changing population densities may be a crucial factor determining future malaria risk in Africa (e.g. Moffett *et al.*, 2007), while the impact of climatic drivers versus developmental variables (such as local infrastructure, income and land use changes) has been considered in India (Garg *et al.*, 2009). A semi-mechanistic modelling approach has also been used to analyse the role of rainfall in driving long-term malaria dynamics in the highlands of Kenya (Pascual *et al.*, 2008).

3.2.2 Mechanistic modelling approaches

The first mechanistic modelling to introduce climatic variables into integrated disease frameworks (and consider associated health impacts) was developed in the late 1990s (Lindsay & Birley, 1996; Lindsay & Martens, 1998; Martens, 1998; Martens *et al.*, 1995). Changes to the regions at risk of malaria, dengue or schistosomiasis under different emissions scenarios were assessed using the concept of epidemic potential (EP), defined as the inverse of the critical number of vectors per human required to ensure $R_0 \geq 1$, so that low EP indicates the need for either high vector numbers or low human densities (or both) for infection to establish and become endemic. The expression for EP arises from an underlying deterministic non-spatial ODE model at equilibrium and thus assesses infection risk using the statics properties of disease transmission. Vector and human population dynamics, as well as disease dynamics, are assumed to be at equilibrium and no dynamical influences on disease risk are assumed.

As well as illustrating the insufficiency of vector abundance and climatic conditions as sole indicators of disease transmission potential (since factors such as the impact of control measures and the characteristics of local human or vector populations should also be considered), this work illustrates the highest risk of disease invasion to regions bordering current endemic areas, as well as populations at higher altitudes (Martens *et al.*, 1995), although this risk is sensitive to local temperature and rainfall conditions under different emissions scenarios (Lindsay & Martens, 1998). This research is generalised by Janssen & Martens (1997) to consider the role of evolutionary insecticide and antimalarial drug resistance on the effectiveness of intervention measures. Areas of low endemnicity may suffer less severe consequences of resistance (incidence typically reduces with control measures) compared to regions with high endemic malaria, which may suffer increased incidence as a result of resistance, although the contrast between these cases depends on the climate change scenario. Results are based on a dynamic ODE transmission model for a human population at quasi-equilibrium (but assuming an equilibrium vector population). Frameworks developed in the early modelling literature are combined with comparable qualitative studies and generalised into an integrated assessment framework for understanding the effects of climate change on diseases in Chan *et al.* (1999), identifying the need to assess possible impacts due to ecological, biological and socio-economic factors.

While early modelling work on malaria, dengue and schistosomiasis make valuable contributions to the field, considerable limitations are apparent. Most notable of these are (a) consideration of only static aspects of disease transmission (and human and vector population dynamics) to assess infection risk, (b) limited or poor parameterisation of interactions between hosts, vectors and pathogens in terms of climatic (and other environmental) variables and (c) limited development of realistic disease transmission models beyond low-dimensional ODE approaches. To overcome the assumption of equilibrium vector populations, Shaman *et al.* (2002) develop a detailed dynamic simulation model, coupled to land surface hydrology, to model the abundance of *Anopheles*, *Aedes* and *Culex* mosquitoes, while Ahumada *et al.* (2004) use the concept of physiological age to develop a matrix population model of *Culex quinquefasciatus* dynamics under daily fluctuations in ambient temperature and rainfall conditions.

Of relevance to malaria is the discrete-time stochastic IBM of Depinay *et al.* (2004) who consider the effects of abiotic (temperature and moisture) and biotic (nutrient competition, predation and dispersal) factors on *Anopheles* ecology to predict adult abundance time series given daily variability in microclimates. Few other dynamic vector population models linked to climate have been developed to date, although those of note include the matrix model of *Aedes* dynamics by Schaeffer *et al.* (2008) and the fully-coupled hydrology and entomology model of Bomblies *et al.* (2009), which also links simulated vector abundance with local malaria risk.

Integrating better-parameterised and more realistic dynamical population and transmission models represents the current state of the art, although considerable difficulties and uncertainties remain (see Section 4). Arguably the most recent and comprehensive research in this respect is that of Hoshen & Morse (2004) (and Hoshen & Morse (2005)), recently updated and improved in terms of model parameterisation, calibration and validation (Ermert *et al.*, 2011a, 2011b), who use a discrete-time model (based on physiological age) to better understand the link between vector dynamics and malaria transmission under different environmental conditions. Such models may be used for better understanding static and dynamic aspects of transmission under future climate scenarios, particularly when combined with mapping work elsewhere (e.g. Hay *et al.* (2009)), and the use of multi-model ensembles to improve model confidence (Hoshen & Morse, 2004) represents an approach that has already been integrated in climate modelling (see Section 4). Few other integrated dynamical studies currently exist (although see the entomological model linked to climate in Ruiz *et al.* (2006)), but work focussing on static aspects of transmission have also made valuable recent contributions. These include the effect of diurnal temperature cycles on malaria risk under different mean climatic conditions (Paaijmans *et al.*, 2010), the role of the Normalised Difference Vegetation Index (NDVI) in driving seasonal transmission (Gaudart *et al.*, 2009) and the influence of temperature on malaria invasion under different climatic regimes (Parham & Michael, 2010).

Fewer modelling studies on the influence of climate change on other VBDs have been carried out to date, although this represents an emerging modelling field. However, some work has been carried out to date on the impact on schistosomiasis and dengue (e.g. Cross & Hyams, 1996; Hales *et al.*, 2002; Yang *et al.*, 2010), representing the two most likely VBDs to be affected by climate change behind malaria (Martens, 1998; McMichael *et al.*, 1996). Other modelling studies have included those on Lyme disease (Brownstein *et al.*, 2005) and TBE (Randolph & Rogers, 2000).

4. Conclusion

Despite considerable progress in the last decade in our understanding of the link between climate change and the consequences for human infectious diseases (and other health risks) (McMichael *et al.*, 2006), considerable work remains, particularly in better understanding the role of environmental drivers versus other epidemiological factors known to drive transmission. Current uncertainties may be categorised as those related solely to epidemiological aspects independent of climate, those related to uncertainties associated with climate models themselves and those related to the interaction between disease and climate. Understanding, quantifying and improving our knowledge in each of these areas is vital if we are to better understand the challenges that lie ahead.

Understanding vector population dynamics represents an important area requiring considerable further research. For *Anopheles* mosquitoes transmitting malaria, for example, a major cause of mortality in immature stages is thought to be predation and other density-dependent effects (Juliano, 2007; Mogi *et al.*, 1984; Service, 1977), while similar effects have been reported in *Aedes* (Dye, 1984) and *Culex* (Lundkvist *et al.*, 2003) mosquitoes. Data availability (and quality) with which to parameterise density-dependence in population models, however, is currently sparse, partially due to the difficulty in undertaking experiments replicating realistic field environments (Service, 1993) and partially due to the qualitative nature of many field observations (e.g. on predator-prey interactions).

Intra-species and inter-species competition is often observed between vectors (Kirby & Lindsay, 2009; Paaijmans *et al.*, 2009), with associated impacts on predators' species preference in the presence of multiple prey (Bradshaw & Holzapfel, 1983). The limited quantitative data available on *Anopheles* rarely distinguishes between the behaviour of species within the *An. gambiae* complex and *An. funestus* (or indeed clarifying stage-specific immature behaviour). Indeed, taxonomy issues often complicate parameterisation of vector population models using historical data (Lane & Crosskey, 1993; Mattingly, 1977). More recent experiments on vector species can also introduce taxonomic uncertainty owing to time or resource constraints (e.g. Fillinger *et al.*, 2004).

Thus, detecting, measuring and modelling density-dependent effects is extremely challenging (e.g. Hassell, 1987; Solow & Steele, 1990), even if species-specific data is available, and understanding such effects in adult vectors is even more difficult, with few studies to date (e.g. Charlwood *et al.* (1995) for the limited research to date on effects in adult *Anopheles*). Given the strong influence of such biotic effects on vector abundance, and hence VBD transmission, this represents a major source of uncertainty, particularly since such effects may not even be consistent across all habitats for the same species (Juliano, 2007).

In addition to biotic uncertainties with vector (and bacterial) population dynamics, understanding the influence of abiotic effects, such as those from climatic and other environmental variables, is key. In the case of VBDs, environmental factors are likely to affect each component of the disease triangle of hosts, vectors and pathogens, although the magnitude (and timescale) of the effects on each remain uncertain. Reliable parameterisation of the effects of temperature, rainfall, RH, wind patterns and other climatic variables on the range of possible disease vectors requires further experimental studies (e.g. Depinay *et al.*, 2004; Ermert *et al.*, 2011a, 2011b). Research to date has shown that these interactions may have important non-linear influences on vector and pathogen dynamics, which will strongly affect disease dynamics when incorporated within realistic disease transmission models.

Improved parameterisation of microscale interactions between climatic and epidemiological processes affecting the disease triangle thus represents a major source of uncertainty in current climate-driven disease models, although these have served to highlight where improved data is required. In addition, little research has considered the interaction between biotic and abiotic factors affecting transmission, but predation and other density-dependent effects, for example, may depend on climatic and other environmental variables (e.g. Sunahara & Mogi, 2002). Temperature effects on mosquito mortality, development and activity may affect the population dynamics of species in upper and lower trophic levels, changing the nature of predator-prey interactions (Service, 1977).

Considerable heterogeneities also exist across the disease triangle and these include variability in the nature of climate and disease relationships for VBDs, for example, by vector species (e.g. variability within the *An. gambiae* complex and between other *Anopheles* species) and parasite strain (e.g. different temperature responses of the malaria parasites *Plasmodium falciparum* and *P. vivax*). Understanding heterogeneity in risk factors for human susceptibility to diseases affected by climate change is also important and the presence of non-communicable diseases (e.g. cardiorespiratory disorders) may contribute to increased risk of infectious diseases in vulnerable populations, as well as changes in human behaviour, movement and land use. Other epidemiological uncertainties (independent of environmental factors) also remain (e.g. immunological responses, issues of cross-immunity and multiple infections), as well as the need to integrate epidemiological and environmental factors into frameworks incorporating socio-economic considerations, social factors and the impact of intervention measures to assess current and future disease risks.

As well as improving our understanding of the interactions between population, disease and environmental processes (and uncertainties therein), understanding the impact of climate change on infectious diseases also requires knowledge of the uncertainties in climate modelling. Uncertainties surrounding the development, reliability and performance of GCMs, downscaling to regional climate models (RCMs) and the use of climate model ensembles have been considered elsewhere (e.g. Knutti, 2008; Murphy *et al.*, 2004; Slingo *et al.*, 2009). Types of from uncertainties include structural (e.g. arising from the type of climate model used), process-based (e.g. assumptions regarding sub-grid and neglected processes), parameterisation issues (e.g. regional variability in model parameters), choice of initial conditions (and boundary conditions for RCMs) and variability between emissions scenarios, together with issues such as the choice and stability of numerical algorithms used to solve model equations.

Quantifying uncertainties in climate model predictions is vital if we are to translate these into the implications for global and regional disease risk using transmission models, themselves possessing uncertainties. Understanding the sensitivity of disease models to uncertainties in model inputs and how these propagate into uncertainties in model predictions represents an important area. Understanding the limitations of current climate-driven disease models given climatological unknowns (and limitations in computational power) is important if we are to improve the reliability of future models and the robustness of predictions under climate change. The use of multi-model ensembles in climate modelling has already become an established technique (e.g. Palmer *et al.*, 2005; Tebaldi & Knutti, 2007) and although some disease modelling has incorporated ensemble climate model predictions (e.g. Morse *et al.*, 2004, 2005), ultimately we may require full integration of multi-model ensembles of climate and disease models to improve our understanding of future changes in disease spread and the implications for mitigation, adaptation and control.

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4

Climate Change and Population Health: Possible Future Scenarios

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1. Introduction

There is little doubt the earth's climate is changing and will continue to change over time. Predictions suggest higher temperatures, and more frequent heat waves, heavy rains, floods, droughts and severe storms. Among the consequences may be detrimental health effects, to the extent that climate change has been termed the "biggest global health threat of the 21st century" (Costello et al., 2009). Primary health effects may include changing patterns in temperature- and weather-related morbidity and mortality, whereas secondary effects may result from water and food insecurity, mental stresses and changes in transmission patterns of certain infectious diseases.

Disparities will be apparent in the vulnerability of individuals and populations around the globe, and despite contributing little to the cause of climate change, populations in poorer countries will be particularly vulnerable (World Health Organization, 2008). Currently various human societies are implementing various adaptation strategies. Such strategies are informed by the socio-political and religious institutions of societies. While the developed world emphasises the virtues of technology and sound socio-political systems in promoting future adaptation strategies to climate change, many countries in the developing world utilise grass-roots based social action. The use of a multi-faceted approach offers novel ways for dealing with future climate change scenarios and its potential impacts on human population health.

2. Human health and environmental temperature

Population health can be directly affected by ambient temperature. In most parts of the world the association between temperature and mortality follows a U- shaped relationship (McMichael et al., 2008). Generally mortality is lowest at moderate temperatures and increases with extreme cold in winter or extreme heat in summer. The effect of climate change on this pattern and temperature-related deaths in general is unclear, but it is likely the warming of global temperatures will result in a reduction in cold-related mortality. Whilst some believe overall mortality rates will therefore decline and effects could be beneficial (Keatinge and Donaldson, 2004) others doubt there will be decreases in cold-related mortality (Medina-Ramon and Schwartz, 2007) and the health benefits will likely be exceeded by an eventual increase in heat-related mortality (Bambrick et al., 2008). However, net impacts as yet remain uncertain (Ebi et al., 2006).

The harmful health effects of hot weather can be partly explained by the body's physiological response to the surrounding thermal environment. Core body temperature is maintained between 36.1 and 37.8°C, and upon detecting an increase of about 1°C, receptors on the skin or within the body trigger signals that send messages to the brain where the hypothalamus (the body's temperature regulatory centre) initiates processes to cool the body (Matthies et al., 2008). In response to a rise in core temperature, heat dissipation involves an increase in cardiac output and blood flow to the skin where heat is distributed to the environment in one of four ways – conduction, convection, radiation, or via the evaporation of sweat (Matthies et al., 2008). Whilst less efficient in environments with high humidity, the evaporation of sweat is the only mechanism which is effective when air temperature exceeds skin temperature (Matthies et al., 2008). An awareness of being in an uncomfortably hot environment prompts behavioural reactions such as moving to a cooler place, decreasing activity, and drinking fluids. These actions are an important part of behavioural thermoregulation which in some individuals can be impaired for physical or cognitive reasons (Faunt et al., 1995; Kalkstein and Sheridan, 2007).
High temperatures and heat waves can also affect concentrations of air pollutants such as ground level ozone and particulate matter (Matthies et al., 2008), both of which can be detrimental to health. Ozone is formed by the action of sunlight on nitrogen oxides and volatile organic compounds, and concentrations increase with higher temperatures (Kinney, 2008). Windblown dust in arid regions and smoke from heat-associated bushfires can also elevate airborne concentrations of particulate matter. Whilst much remains unknown about the health effects of climate change, it is thought that levels of aeroallergens such as pollens and moulds will be affected with consequences for allergic disease sufferers (Kinney, 2008), and that the combined effects of warmer temperatures and altered concentrations of air pollutants on human health may be additive or synergistic (Luber and McGeehin, 2008; Matthies et al., 2008).

2.1 Heat-related illnesses

Exposure to extreme heat, strenuous physical exercise or a combination of the two, can overwhelm the body's ability to adequately dissipate heat, leading to hyperthermia and possibly heat-related illness, particularly if the individual is dehydrated (Simon, 1993). The continuum of heat-related illnesses range from mild to life-threatening and include heat rash, heat oedema, heat cramps, heat stress, heat syncope, and heat exhaustion (Matthies et al., 2008). Heat stroke is the most serious heat-related illness characterised by hyperthermia and central nervous system dysfunction. Due to subsequent multiorgan dysfunction, heat stroke is often fatal, and survivors can have ongoing health consequences or permanent neurological damage (Bouchama and Knochel, 2002). 'Classic heat stroke' usually affects the aged, whereas 'exertional heat stroke' is often seen in younger people as a result of exercising or working in the heat.

2.2 The epidemiology of heat waves

The Intergovernmental Panel on Climate Change predicts heat waves will increase in frequency, intensity and duration as a result of climate change (IPCC, 2007) and in the absence of adaptation or interventions, the consequences for population health may be considerable. Whilst there is no universal definition of a heat wave (Tong et al., 2010), generally city- or area-specific conditions determine local definitions of unusually high and prolonged temperatures. Studies in Adelaide, Australia have defined a heat wave as being three or more consecutive days of maximum temperatures of 35^{o}C or above (Hansen et al., 2008a; Hansen et al., 2008b; Nitschke et al., 2007) whereas other studies have experimented with a range of definitions (Tong et al., 2010).

In recent decades intense and deadly heat waves have occurred around the world, with dire consequences for population health. The most serious heat wave occurred in Europe in August 2003 encompassing several countries, the worst affected being France where approximately 15,000 excess deaths occurred (Fouillet et al., 2006). Prior serious heat waves occurred in Athens, Greece in 1987 (Katsouyanni et al., 1988), Chicago, United States in 1995 (Semenza et al., 1996) and India in 1998 (Kumar, 1998). More recently deadly heat waves have occurred in California in 2006 (Ostro et al., 2009), Australia in 2009 (Victorian Chief Health Officer, 2009), and Russia in 2010 (Osborn, 2010). Often people in cities are worst affected during heat waves as a result of the urban heat island effect whereby the high thermal mass of concrete and bitumen surfaces in cities causes heat to be retained, resulting in higher temperatures during the day and night (Luber and McGeehin, 2008).

Numerous epidemiological studies investigating these heat waves have assisted in the identification of patterns of morbidity, mortality and heat-susceptibility within populations. As the process of maintaining heat balance can place physiological strain on the body in vulnerable individuals, adverse health events can be triggered, particularly in those with underlying chronic conditions, and generally cardiovascular, respiratory and cerebrovascular diseases are the main causes of deaths during heat waves (Basu and Samet, 2002). Additionally, studies have found that the instances of renal disease and acute renal failure increase during heat waves (Hansen et al., 2008b; Knowlton et al., 2009; Semenza, 1999), a likely indication of electrolyte imbalances and dehydration on the renal system. During the French heat wave of 2003, apart from deaths directly related to heat and dehydration, an increase in mortality due to cardiovascular, respiratory and nervous system diseases, mental disorders, infectious diseases, genitourinary diseases and ill-defined disorders was reported (Fouillet et al., 2006). As well as mortalities, ambulance callouts, emergency department presentations and hospital admissions tend to increase during heat waves (Fouillet et al., 2006; Knowlton et al., 2009; Nitschke et al., 2007; Semenza et al., 1999; Semenza et al., 1996), indicating the broad impact extreme heat can have on population health.

Those at the extremes of age are amongst the most vulnerable to the effects of heat due to underdeveloped or impaired thermoregulatory systems respectively. The elderly are particularly vulnerable for several reasons relating to poor fitness and physical and mental health, multiple co-morbidities that often accompany ageing, reduced social contacts and some medications that can affect heat dissipation (Luber and McGeehin, 2008; Matthies et al., 2008). Global warming and the demographic shift to an older population is a combination that will provide a challenge to public health in years to come (Saniotis and Bi, 2009).

Having an underlying chronic health condition can increase an individual's susceptibility to heat and persons with mental health conditions are vulnerable for a number of reasons (Bark, 1998; Hansen et al., 2008a; Semenza et al., 1996). Deficits in cognition affect the ability to adjust one's response to the thermal environment and the awareness of the need to modify behaviour, clothing, or fluid intake; certain psychiatric illnesses such as schizophrenia are thought to involve neurotransmitters in the brain that are also involved in temperature regulation; and antipsychotic medications can impair thermoregulation (Bark, 1998). Climate change may impact on mental health as communities struggle to cope with, and recover from, the social, emotional and economic consequences of weather related disasters such as heat waves, droughts, bushfires, storms, extreme rainfall events and floods (Berry et al., 2010).

Many outdoor workers in industries such as agriculture, construction, and mining are particularly vulnerable to heat stress and this risk will be increased with the higher ambient temperatures and extreme heat events associated with climate change scenarios. These conditions can produce an unsafe thermal working environment and affect productivity, particularly for workers in low and middle-income tropical countries (Kjellstrom et al., 2009). Other climate–related hazards facing these workers include extreme weather, air pollution, ultraviolet exposure, and vector-borne diseases (Schulte and Chun, 2009).

3. Adaptation and acclimatisation in a warming climate

The degree to which the health of a population will be affected by a warming climate will be tempered by its ability to acclimatise and adapt. Acclimatisation, the ability to adapt to commonly experienced climate patterns (Basu and Samet, 2002), is a physiological process whereby the body adjusts over time to the thermal environment via regulation of the cardiac, renal and pulmonary systems (Ramphal, 2000). Although more rapid in the young (Faunt et al., 1995) an average person can take up to two weeks to adapt to extreme temperatures (Ramphal, 2000).

Adaptation strategies that focus on preparedness and an increase in community-based resilience to weather-related disasters will be required to reduce the burden of climate change related health outcomes (Keim, 2008). As heat-related illnesses are preventable, the importance of adaptive behaviours and preventive measures during heat waves has been realised in recent years. Preventive measures may include rescheduling activities during the heat, increasing non-alcoholic fluid intake, wearing appropriate clothing and avoiding direct sunlight, and where practicable, locating to an air conditioned environment (Luber and McGeehin, 2008).

Heat wave watch/warning systems are a form of adaptation that has been introduced in many cities following major and deadly heat waves. The multi-level warning systems are triggered when oppressive conditions that could negatively affect health, are forecast for upcoming days (Kalkstein et al., 1996). These heat-health alerts use the general principles of emergency response to describe the hazard and when it will occur, and provide information and advice to the public and local authorities about appropriate adaptive behaviours (Kalkstein and Sheridan, 2007; Matthies et al., 2008).

A study in Perth, Australia, predicts that by 2070 there will be 15-26 days per year (compared to one day per year at present) when manual labour will be dangerous to perform for even acclimatised people (Maloney and Forbes, 2011). Adaptive strategies in the workplace may include information to workers about the risks of heat stress, recognition of symptoms and methods of prevention (Matthies et al., 2008), increased shading at worksites, or adjustment of working hours to avoid the hottest part of the day, the latter being more suited to indoor than outdoor workers (Kjellstrom et al., 2009).

Although populations will undergo some adaptation, those in low and middle-income countries will be particularly vulnerable to the effects of climate change (McMichael et al., 2008) whereas countries like the Unites States will have a greater capacity to implement effective adaptation measures and limit impacts on health (Ebi et al., 2006). Nevertheless in most situations, adaptation will be enhanced by education, early warning systems, responsive government, and an adequate health care sector able to respond to local climate-sensitive health problems (Woodward, 2011).

4. Infectious diseases and human population health

Climate conditions affect the transmission of vector/rodent-borne diseases in three ways: altering the distribution of vector species and their reproductive cycles; influencing the reproduction of the pathogens within the vector organism; and affecting human behaviours and activity. Malaria, dengue fever, Ross River virus (RRV) infection and Haemorrhagic Fever with Renal Syndrome (HFRS) are the most commonly investigated climate-related vector/rodent-borne diseases.

Many studies across the world indicate that increases in the incidences of malaria and dengue fever are strongly associated with higher temperatures and increased rainfall. Increasing temperatures with climate change will bring about more malaria and dengue fever cases in the future (Zhang et al, 2010; Tanser et al, 2003; Bi et al, 2003; Bi et al, 2001). Furthermore climate modelling shows that global warming will enlarge the potential range of the vector for malaria for example, which by 2030, could extend to a location 800 km south of its present limit in Australia (Bryan et al, 1996). This will bring about a serious public health issue to this current malaria-free country. Similarly, a slight increase in temperatures could result in epidemics of dengue in the world. In Australia, by 2100, if no effective policy and public health measures have been developed, the zone of potential transmission of dengue fever may expand 1,800 kilometres south, as far as Sydney. In contrast, by markedly constraining greenhouse gas emissions immediately, this southward extension could be limited to 600 km (Woodruff et al, 2006).

In terms of the relationship between RRV infections and climate variability, studies found that variations in rainfall, temperature and tides have been positively associated with the incidence of RRV infections (Harley et al, 2001; Tong et al, 2002). In addition, climate variability might be a contributor to the spatial change of the disease in Queensland, Australia over the past years (Tong et al, 2001). Examination of the relationship between rainfall and the incidence of HFRS in a low-lying region of eastern China showed a significant inverse association between the amount of precipitation and the incidence of HFRS when the density of rodents and the opportunities for human contact were considered, suggesting heavy rainfall in these low-lying areas could reduce the density of mice and thus the incidence of the disease (Bi et al, 1998; Bi et al, 2002). However, rainfall, land surface temperature, relative humidity and ENSO with lags of 3–5 months were positively associated with HFRS in northeastern China (Zhang et al, 2010).

Temperature and relative humidity may impact on the rate of replication of the pathogens and the survival of enteroviruses in the environment, animal reservoirs and host behaviours. It may affect eating habits, the type of food prepared in households and the meat industry. Rainfall, especially heavy rainfall events, may affect the frequency and level of contamination of drinking water. Moreover, climate change may influence water resources and sanitation so that water supply is effectively reduced. Such water scarcity may necessitate using sources of fresh water of poorer quality, such as rivers, which are often contaminated. All these factors may result in an increased incidence of food-borne and water-borne diseases.

The relationship between enteric infections and environmental temperature has been studied in Europe (Kovats et al, 2004, 2005; Tam et al, 2006; Bentham and Langford, 2001), Australia (D'Souza et al, 2004; Bi et al, 2008; Zhang et al, 2010), the USA (Curriero et al, 2001), Canada (Fleury et al, 2006), and Asia (Zhang et al, 2008). Most of these studies indicated that there was a positive association between temperature and enteric infections such as *Salmonella* infections and *Campylobacter* infections as well as Bacillary Dysentery. Studies have shown that a 1°C increase in temperature is associated with a 5%-15% increase in the risk of severe diarrhoea (Zhang et al, 2008; Kovats et al, 2004).

Emerging and re-emerging of vector-borne, rodent-borne, food-borne as well as water-borne diseases due to climate change will create huge health challenges for both developed and developing countries, especially for vulnerable populations such as the elderly, Indigenous communities, lower socioeconomic status groups and homeless people. It will particularly challenge the population health in developing countries such as China, India, Indonesia, and African countries etc, given their already overloaded and inadequate healthcare systems, high population density, inadequate infrastructure, lower level of health literacy, etc. For instance, the summer diarrheal diseases in Bangladesh due to flood and summer rainfall have made significantly negative impacts on the population health there, especially among children. Further climate change with more irregular extreme weather events will lead to more health issues for both developed and developing countries including more cases of relevant infectious diseases.

Therefore, relevant public health adaptation measurements should be taken immediately to reduce the negative impact of climate change on population health including infectious diseases. These should include:

1. To conduct health education and promotion among communities to build community resilience capacities to deal with the health challenge due to climate change, which include self-protection measures for infectious diseases among communities;
2. To improve infectious disease surveillance system, especially in developing countries so more accurate and updated communicable diseases intelligence could be obtained in a timely manner for decision-makers to take relevant actions;
3. To establish an early warning system to prevent infectious disease outbreaks due to climate change, requiring multidisciplinary collaborations;
4. To strengthen infectious disease control including the provision of vaccines for vulnerable groups and vector control before and during the epidemic seasons; and
5. To promote medical services, especially the roles of primary health care services, i.e., using General Practitioners to play an important role in the battle against the infectious diseases due to climate change. These may include health education, vaccination and effective diagnosis and treatment.

5. Asia and Africa: Climate change, human population health and adaptation responses

Populations vary in their vulnerability to climate change and this section will discuss the predicted impact on population health in Asia and Africa. It will also propose adaptation strategies to climate change in Asian and African countries. Due to its large population and widespread environmental degradation much of the Asian region will be particularly vulnerable to future climate change and global warming. From 1999, China contained 21% of the world's population and India contained 16% (Levy, 1999). A report by the

International Energy Agency (IEA) predicts that global CO_2 emissions will rise by between 30 and 42% by 2010, with China and India accounting for an "increase larger than all OECD countries combined" (Fu et al., 1998). Greenhouse emissions in Asian cities will also continually escalate due to increasing populations. Some 13 out of 21 Asian cities now exceed 10 million in population putting increasing demands on fuel food and water resources (Fu et al., 1998).

According to climate change projections there will be general warming over Asia and South-East Asia. Climate modelling of the Asian region predicts temperature rises from 0.5–2°C by 2030 and 1–7°C by 2070. Predicted temperature rises for Africa by 2100 range from 3 to 6^0C (APF, 2007). Such temperature rises for Asia and Africa will lead to adverse population health effects including increases in vector borne diseases.

Climate projections for Asia and Africa predict a variety of adverse weather patterns which will burden population health. These will include increasing cyclonic activity and flood severity in low-lying countries in Asia and South-East Asia, such as Bangladesh, China, Philippines and Thailand. Central parts may have diminished precipitation causing severe water stress which may lead to desert expansion and depletion of arable land. This may cause diminished agricultural output in many Asian and African countries which may have adverse social consequences such as and increase in food prices leading to famine and widespread hunger. Sea level rises in low-lying countries may have a tremendous impact on population health due to environmental refugees and increasing spread of communicable diseases due to unsanitary conditions.

5.1 Schistosomiasis transmission in China

In China, climate change may lead to higher transmission of schistosomiasis, which is caused by the parasite *Schistosoma japonicum* (Zhou et al., 2008). Research into schistosomiasis revealed the correlation between temperature rise and changes to the parasite's life cycles. Zhou et al used predictive models in order to simulate the spread of schistosomiasis by 2050. They found that average temperature increases for China will be in the range of 0.9°C by 2030 and by 1.6°C by 2050, predicting that schistosomiasis will cover an additional 8.1% of the Chinese mainland, and with the intensity increasing in areas which currently have schistosomiasis (Zhou et al., 2008).

Approximately 12 million people are at risk particularly in the Jiangsu province. It was found that even a temperature rise of one or two degrees can increase flooding in the Yangtze River, aiding in the transmission of disease-carrying snails. These snails then carry the disease to other areas. Adaptation strategies to mitigate the spread of schistosomiasis have included the creation of more efficient sanitation systems, the supplanting of water buffalo for machines, and the use of sensitive diagnostic tools (Zhou et al., 2008). The Chinese have also been using United States inspired technology in order to monitor the movements of snails via maps and a geographic information system (GIS) which predicts areas of predicted snail infestation.

Water supply, sanitation and contamination are on-going issues in many parts of China. Major river systems have been transformed in order to supply power to China's rapidly growing urban centres. In rural centres, there is a self reliance for people to manage water resources. However, rural people cannot finance larger water sanitation programs. What is needed is greater support by local and provincial governments to finance water resources which would also control the spread of schistosomiasis. In this way, adaptation strategies would take the form of much better co-ordination between local and provincial governments and rural people for controlling water resources.

5.2 Water and disease: population health

Climate change predictions have noted that many regions in Asia and Africa will suffer from water shortages and large water abundance due to flooding will cause adverse health problems. For example, flooding in Asian and African countries may result in soil run off and sewerage system overflows causing the spread of Cholera and diarrhoeal disease (Ahern et al., 2005). Low lying countries such as Bangladesh which is already prone to heavy flooding will bear a greater burden of diseases due to water abundance. Already, Bangladesh has had Cholera outbreaks along its coastal areas which have been linked to plankton and sea surface temperatures which are ideal reservoirs for the Cholera pathogen (Nerlander, 2009; IPCC, 2007). Much of Africa is also prone to flooding, particularly in the south, central and eastern Africa where approximately 14 African countries are prone to flooding. Flooding has had adverse social and economic impacts in recent floods in Algeria, Kenya and Mozambique. In Mozambique, the 2000 flood affected 2 million people and displaced over three hundred thousand. It also destroyed crop production (Urama & Ozor, 2010).

Alternately, water scarcity is currently being experienced in many Asian and African countries being affected by water stress. For example, approximately 75% of African countries and many central Asian countries are zones with minimal precipitation. It has been estimated that up to 250 million people will be exposed to water stress due to climate change (APF, 2007). Acute water shortages are being experienced in North African countries which have high populations (APF, 2007). Use of underground water reserves has also depleted the water tablelands in many countries. Lack of water availability increases the incidence of diarrhoeal disease and diseases linked to poor hygiene (Nerlander, 2009). Moreover, lack of water is a reason for population shifts which may cause overpopulation in areas of water availability.

Currently, there has been little done in creating efficient adaptation strategies for allocating water resources. One reason for this is due to the difficulty in controlling areas in flood prone areas. While this is not impossible, it would need considerable infrastructural measures. According to Nerlander (2009), long term infrastructural investments to infrastructures such as water sanitation plants are needed are needed in urban areas. In addition, city planners need to co-operate with water managers in order to ensure water availability throughout the year (Nerlander, 2009). In relation to extreme weather events, early warning systems need to be implemented in order to "enable the health sectors to preposition stocks enabling water purification" (Nerlander, 2009).

Another adaptation strategy would be to monitor ground water in order to ensure that water supplies are no longer compromised. Currently, there needs to be much more control of ground water resources. Local people will need to be at the forefront in monitoring ground water systems. Important progress can be achieved by regional governments improving policy and implementing various kinds of incentive frameworks and programs. The use of fiscal reforms may be instrumental in more efficient use of water, land and energy resources. Such reforms would also enable public funds to be freed up and invested in vulnerable groups (The World Bank, 2011). The maintenance of water inventories would be an important adaptation strategy for assessing the quantity and quality of groundwater resources. This would include:

1. Identification of different water sources.
2. Monitoring of water needs of users.
3. Water supply assessments for surface and ground water in relation to use by agriculture and industry.

4. Benchmarking water monitoring consistent with international standards (Urama & Ozor, 2010).

It is imperative that disaster management becomes an "integral part of adaptation and development process" (Urama & Ozor, 2010). This can include implementing proper infrastructure in order to reduce impacts, and "mitigating the problem among poor community and spreading it more widely through market mechanisms such as global insurance and capital markets" (Urama & Ozor, 2010). This would enable poorer communities to protect vital water resources.

5.3 Vector-borne diseases

Climate change research has shown that malaria and dengue disease vectors are especially affected by temperature increases. Changes in precipitation patterns affect breeding sites of vectors. This is particular the case with flooding which increases the prevalence of malaria. Malaria is prevalent in the sub-Saharan Africa, with over 90% of malaria cases originating from Africa, accounting for more than 40% of public health expenditure. Presently, almost 20 African countries are implementing efficient anti-malarial strategies such as reducing or eliminating taxes and tariffs on insecticide-treated nets (ITNs), to make them affordable to poor people. ITNs are being promoted as an effective anti-malarial adaptation strategy and improved vector control. While ITNs provide effective vector control African countries need to adopt other vector strategies due to on-going climate change. Such strategies include mitigating the rate of deforestation which increases vector borne diseases such as malaria and African trypanosomiasis (sleeping sickness). Ecological maintenance will ensure that the transmission of vectors can be controlled. However, this is a difficult proposition due to high populations in sub-Saharan Africa.

Efficient adaptation strategies to climate change will depend on health infrastructure of vulnerable countries. Many African countries are particularly susceptible to a diversity of vectors. This has the potential to precipitate multiple disease epidemics (Githeko et al., 2000). The onset of flooding which leads to population movement and displacement may also aid in the transmission of vectors and diseases caused by lack of sanitation. Far more infrastructural investment is needed in Africa in order to control vectors.

5.4 Heat wave events and population health

The occurrence of heat wave events in Asian and African regions may be a concomitant symptom of climate change. Many Asian and African countries suffer from lengthy heat wave events. For example, many Asian countries were affected by a heat wave event which occurred in May and June of 2007. In North India temperatures exceeded 40 degrees Celsius. In 2010 China experienced a heat wave during which temperatures in parts of Hebei and Shandong provinces reached 40 degrees Celsius. Research on heat waves in the Chinese city of Shanghai indicates a relationship between mortality and duration of heat wave events. In the two heat wave events pollution may also have contributed to human mortality (Tan et al., 2007).

In 2003 Shanghai experienced its hottest summer in 50 years and a heat wave impacted on people with co-morbidities such as cardiovascular disease and respiratory illness (Huang et al., 2010). The elderly (>65 years old) were especially affected by the heat wave. The 2003 heat wave was exacerbated by China's rapid urbanisation which is affecting local climate in ways which include increasing the heat island effect in urban areas, and affecting urban infrastructure and housing quality (Huang et al., 2010). There has been a dearth in studies researching on the heat island effect in Asian cities and this is an area where public health programs can be initiated.

Future adaptation strategies may include the extended use of air conditioners and fans during hot weather, housing changes to better accommodate for hot weather, increased urban green spaces, larger living areas, and higher levels of heat awareness (Tan et al., 2007). Initiating such changes will be problematic due to the already large influx of rural people in Asia's urban centres.

6. Conclusion

Climate change affects not only the environment, it is a major issue that can affect environmental health on a worldwide population basis (Costello et al., 2009). Whilst not all impacts will be detrimental, it is believed overall the negative effects on health will outweigh the benefits (World Health Organization, 2008). Changing patterns of temperature related morbidity and mortality, water and air quality, food supplies and infectious diseases transmission are the likely consequences of global warming that impact on human health and wellbeing in the developed and developing world. Furthermore, Asian cultures have been able to implement various culturally based adaptation strategies in order to combat climate change and biodiversity loss. Adaptation is a culturally based strategy which incorporates many levels of learning. While the rhetoric of climate change is relatively new this does not mean that adaptation strategies are in their nascent stages. What is evident is that different societies have the capacity for implementing novel and significant kinds of adaptation responses to climate change. This will continue to be the case in the future with predicted global warming and environmental degradation.

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5

Climate Variability and Population Health in China: Updated Knowledge, Challenges and Opportunities

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1. Introduction

With remarkable economic growth in the past three decades, China has already overtaken the USA as the largest single emitter of carbon dioxide since 2007 (United Nation Statistics Division, 2009) and encountered many environmental challenges such as climate change, which significantly affects population health. According to the latest assessment report by the Intergovernmental Panel on Climate Change (IPCC) (Cruz et al., 2007), an evident clear warming trend has been observed in most areas of China during the last 50 years. Moreover, since the 1990s, China has experienced frequent extreme weather events, such as a 40-day episode heatwave in Shanghai in 2003, the longest heatwave being recorded for the last 50 years (Tan & Huang, 2004). The recent severe drought in Yunan Province of southwest China highlights the climate threat in China (Qiu, 2010). Under a medium–low greenhouse gases emission scenario, an annual temperature increase of 1.5°C by 2020 is projected in China (relative to the mean annual temperature of 1961–1990) and the figure will go up to 4.5°C by 2080s (Chinese Academy of Agricultural Sciences, 2009). More extreme weather events will likely occur more frequently and intensively (Cruz et al., 2007). The impacts of such climate variability should be better understood in order to develop adaptation strategies at all levels of government as well as practice guidelines for service providers to build climate change resilience for citizens.

Study of the association between climate variability and human health has been largely neglected among Chinese researchers in the past decades as argued in two recently published editorials (Kan, 2009, Wang & Chen, 2009). Given the largely affected population size, various regions with different climatic characteristics, and a diverse socio-economic status across China, it is necessary to understand and recognize the updated knowledge of health impact associated with climate variability in China, and to identity the opportunities available to meet further challenges. However, there has been no such complete picture presented in China to date. This study has systematically reviewed the research examining the association between climate variability and population health in China. The aim is to provide evidence for policy makers and practitioners which will assist in the reduction of health risks of climate change and the development of national and regional adaptation strategies to deal with the health impacts of future climate change.

2. Methods

Indicators of climate variability included temperature, rainfall, relative humidity, air pressure, wind speed, hours of sunshine, evaporation and the Southern Oscillation Index (SOI, an index of El Nino/La Nina events). Extreme weather events, i.e. heatwave/extreme heat, flood, draught and typhoon, were also included. Direct and indirect impacts of climate variability on population health were reviewed, including communicable diseases and non-communicable conditions. Indoor exposures and clinical case reports and studies solely on the health impacts of air pollution were excluded.

Studies published during the last 30 years between 1st January 1980 and 31st December 2010 were included as few studies before the 1970s could be found due to the Great Cultural Revolution in China. Publications in academic journals, conference proceedings, and reports from governments and professional organizations written either in English or in Chinese were included. The key words, in both English and Chinese, included "climate or weather or temperature or rainfall or El Nino or heat wave" and "health or mortality or morbidity or death or hospital" and "China or Chinese". In addition to PubMed, Web of Science, Scopus, and Google Scholar, major Chinese literature search engines in China were used, including the China National Science and Technology Library (NSTL), China Knowledge Resource Integrated Database (CNKI), VP info (VIP) and Wanfang Data. Although meta-analysis is not recommended for this review due to the large variance of the data sources, study designs and quality of research, the spatial and temporal distribution of the reviewed studies were described. In addition, the strength of the association between climate variability and health outcomes were qualitatively indicated based on the number of studies which show a significant relationship.

3. Results

In total, 270 original studies were identified with 77% of them published in Chinese journals with a majority having an English abstract. There were only 4 relevant studies published before 1990 and over 90 articles in 2009 and 2010. These studies were conducted in different regions across China with most in major cities such as Beijing and Shanghai. The health impacts include indirect impacts on communicable and non-communicable diseases and direct health impacts of extreme weather events. The strength of the association between climate variability/extreme weather events and the health outcomes is summarised in Tables 1 and 2, while the tempo-spatial distribution of the number of studies is presented in Figure 1.

3.1 Indirect impacts

3.1.1 Communicable diseases

Communicable disease is still a major public health problem in China. In 2009, there were 5,898,415 newly notified cases of infectious diseases, which was a 9.2% increase comparing to that in 2008 (Ministry of Health in P. R. China, 2009). For some infectious diseases, climate variability such as temperature, rainfall and relative humidity could be one of the driving causes of their transmission. The studies of the association between climatic variables and infectious diseases in China mainly focused on vector-borne disease, water/food borne disease and airborne disease.

	Temperatures	rainfall	relative humidity	air pressure	wind speed	Evaporation	hours of sunshine	El Nino
vector-borne diseases								
malaria	+++	++				+	+	
dengue fever	++	+	+		+			+
schistosomiasis	+++	++				+		
typhus	+	+		+				
Japanese encephalitis B	+	+		+		+		
hemorrhagic fever with renal syndrome	++	++	+	+	+	+	+	+
water/food borne diseases								
bacillary dysentery	+++	+	+	+	+	+	+	
cholera	+	+		+			+	
hepatitis	+		+	+				
typhoid	++	+		+		+	+	
other enteric infections	+	+			+			
airborne diseases								
severe acute respiratory syndrome	+++		+	+	++		+	
asthma	++		+	+				
pneumonia	++		+	+				
influenza	+		+	+				
chronic bronchitis	+			+				
measles		+		+		+		
scarlet fever					+		+	
pulmonary tuberculosis	+		+	+				
non-communicable conditions								
hypertension	+			+				
cancer mortality	+			+				
chronic liver disease	+							
cardio cerebral vascular disease	+++							
respiratory disease	+				+			
Total mortality	+++		+					

Table 1. Strength of the association between climate variability and health outcomes in China (Number of studies showing a significant association: + 0-5, ++ 5-10, +++ >10)

3.1.1.1 Vector-borne diseases

Malaria, dengue fever, schistosomiasis, Japanese encephalitis, hemorrhagic fever with renal syndrome and typhus were examined in China with regard to their associations with climatic variables.

	extreme weather events			
	heatwaves/ extreme heat	flood	drought	typhoon
vector-borne diseases				
malaria		+		
schistosomiasis		+		
Japanese encephalitis B		+	+	
water/food borne diseases				
bacillary dysentery		+	+	
typhoid		+	+	
airborne diseases				
measles		+		
non-communicable conditions				
chronic liver disease			+	
cardio cerebral vascular disease	+++			
respiratory disease	+		+	
Total mortality	++	+		+

Table 2. Strength of the association between extreme weather events and selected health outcomes in China (Number of studies showing a significant association: + 0-5, ++ 5-10, +++ >10)

Malaria is the most studied mosquito-borne disease related to climate variability. There has been a recent come back of malaria in China and climate variability might be one of the drivers. Studies, using empirical data, showed a positive association between temperatures and incidence of malaria in different areas of China with a lagged effect ranging from one to two months (Bi et al., 2003, Hui et al., 2009, Xiao et al., 2010). Increase in rainfall could also lead to more malaria cases in southern China but may not be an influencing factor in northern region with temperate climate (Wang et al., 2009, Zhang et al., 2010). Moreover, malaria transmission can be related to other meteorological variables, such as the effect of fog with an one-year lag time and the impact of El Nino (Tian et al., 2008, Bi et al., 2005).

Dengue Fever is a tropical or subtropical disease occurring only in three Provinces in southern China. Minimum temperature, rainfall, and relative humidity could affect the density of *Aedes,* the vector of dengue in China. These variables therefore play a role in the transmission of dengue fever (Yi et al., 2003a, 2003b, Yu et al., 2005). An empirical model using average vapour pressure projected that the epidemic area of dengue fever in southern China may extend to northern areas due to the effect of population growth and climate change (Hales et al., 2002). If temperature increases about 1-2°C, some non-endemic tropical regions in China may suffer from dengue fever epidemics in future (Chen et al., 2002).

Schistosomiasis has re-emerged in southern China despite great success of the disease prevention and control programs over the last 50 years. There are more than 800,000 chronic schistosomiasis suffers in the seven southern Provinces with about 3,000 new cases being notified each year (Ministry of Health in P. R. China, 2009). In 2009, the incidence increased nearly 20% compared with that in 2008. Since the late 1990s, there have been several studies identifying both favourable and unfavourable effects of the changing environment, including climate variability, on the transmission of schistosomiasis due to the construction of the Three Gorges Reservoir (Zheng et al., 2002, Xu et al., 1999, Xu et al., 2000). Results from other studies also indicate that increase in temperatures could lead to more schistosomiasis cases (Yang et al., 2005a, 2005b, 2006). With consideration of the biological activities of host snails, a study suggested that expansion of schistosomiasis transmission into currently non-endemic areas in the north is possible, with an additional risk area of 783,883 km² by 2050 due to climate change (Zhou et al., 2008).

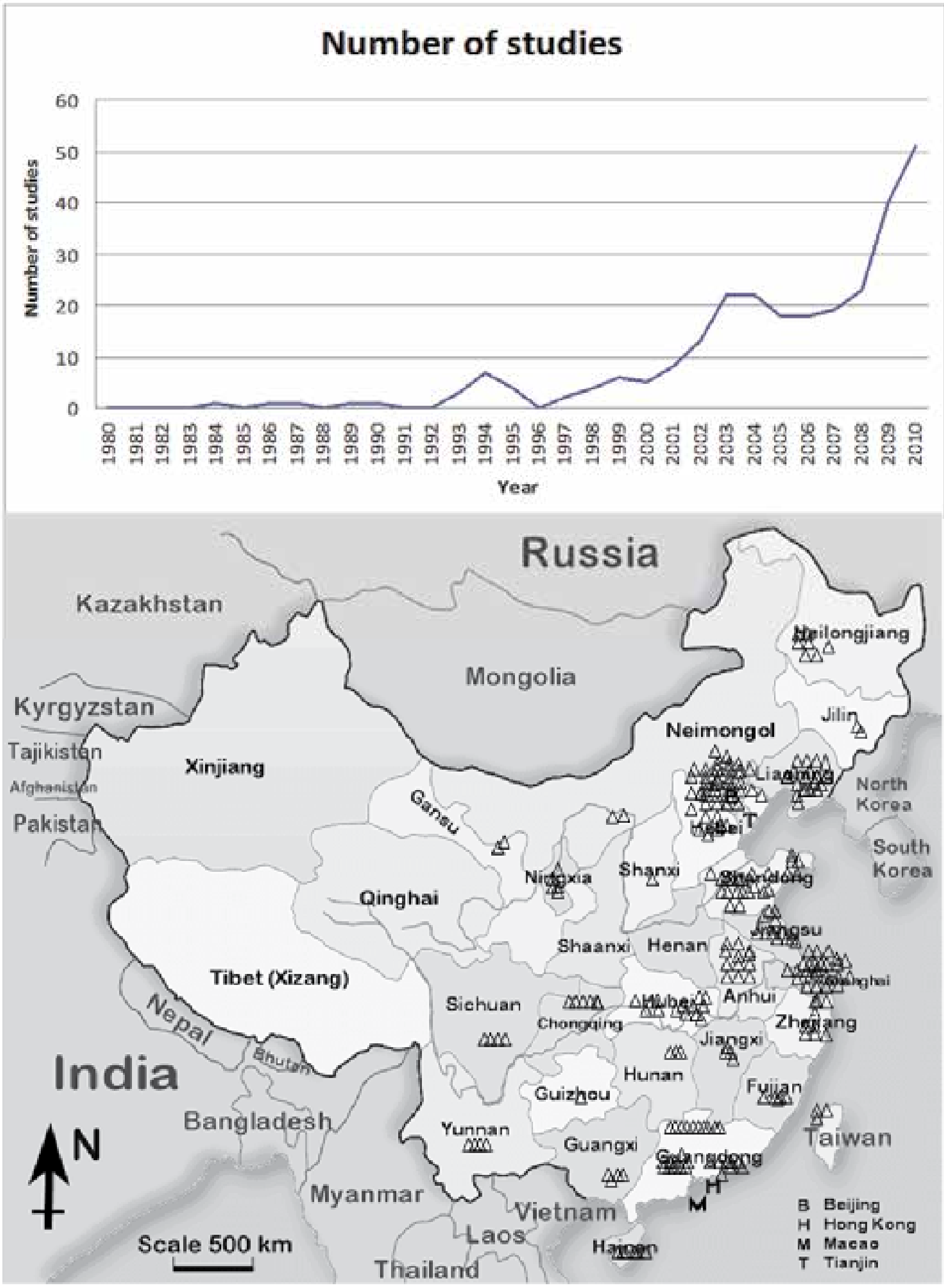

Fig. 1. Tempo-spatial distribution of the reviewed articles in this study (Each Δ represents one study)

Japanese encephalitis (JE) is another major mosquito-borne disease in China with 3,914 new cases notified in 2009. Evidence suggested that temperature and precipitation had a significant relationship with the transmission of JE with an one-month lag effect and a threshold of 25.2 ºC for maximum temperature and 21.0 ºC for minimum temperature were also detected in a northern city (Bi et al., 2007b, Liu & Du, 2008, Qu et al., 2006). Its incidence may also be negatively related to air pressure (Qu et al., 2005). In addition, mosquito density in conjunction with pig density were used to forecast JE epidemics (Hsu et al., 2008).

Hemorrhagic fever with renal syndrome (HFRS) is caused by Hantaviruses, with rodent as the host. Although great achievements have been made for the disease control since the 1980s, there are still around 9,000 new cases notified each year (Song, 1999). Using different models, studies suggest that the density of rodent and autumn crop production were positively associated with the incidence of HFRS while rainfall and Huai River water level were negatively associated with the incidence in low-lying epidemic areas (Bi et al., 1998, Bi et al., 2002, Hu et al., 2007). A positive relationship between HFRS and temperature, precipitation and relative humidity was also reported in northeast China (Guan et al., 2009). Recent studies in northern China indicate that rainfall, temperature and relative humidity play a significant role in HFRS transmission (Zhang et al., 2010, Lu, 2007).

Typhus is caused by Rickettsiae and transmitted by rodent and mite. A negative relationship between air temperature or land surface temperature and the incidence of scrub typhus was reported (Qu et al., 2004a, 2005). However, the analyses of annual dataset rather than monthly or weekly data may affect the accuracy of the study results.

3.1.1.2 Water/food borne diseases

Less attention has been paid to water/food borne diseases, compared with vector-borne diseases. The most common water/food borne diseases that have been studied are infectious diarrhoeal diseases, including bacillary dysentery, cholera, hepatitis, typhoid, and other enteric infections.

Bacillary dysentery suitable climatic conditions are high temperature and high humidity in Chengdu, southwest China, and Shaoxing, northern China (Liao et al., 2009, Tan & Chen, 2003, Lu et al., 2009, Zhou et al., 2009, Sun et al., 2008, Huang et al., 2009). Possible impact of El Nino on the transmission of bacillary dysentery in Shandong, north China, was reported (Zhang et al., 2007). In addition to weather factors, a study in Beijing also included socio-economic factors. The results indicate that less rainfall, less hours of sunshine as well as a higher number of refrigerators per 100 households were related to lower incidences of bacillary dysentery in urban areas in Beijing (Jia et al., 2009).

Cholera is an acute enteric infection transmitted by contaminated drinking water or food. However the number of cases in China has reduced dramatically in recent years due to effective disease prevention and control programs. The association between meteorological variables and the incidence of cholera has been reported by a very limited number of studies in China. Results from these ecological studies indicate that high temperature, high rainfall and low air pressure might increase the number of cases of cholera (Yang, 2003, Tan et al., 2003, Li et al., 2006, Tan, 2004).

Typhoid fever and paratyphoid fever have decreased significantly in China due to health promotion and improvement of environmental hygiene. However, there was an increase of new cases in China with 16,938 notified cases in 2009, 8% higher than that in 2008 (Ministry of Health in P. R. China, 2009). Back-Propagation Neural Network models were developed to examine the relationship between meteorological factors and Typhoid Fever or

Paratyphoid Fever (Zhang et al., 2009a, 2009b; Qu et al., 2004b). These results indicate that meteorological and geographic factors may contribute more than 80% of the transmission of typhoid fever in China.

Other enteric infections

In 2009, there were more than 650,000 new cases of 'other infectious diarrhoeal disease' notified to the Ministry of Health in China (Ministry of Health in P. R. China, 2009). A medical-meteorological forecast model of infectious diarrhoeal disease was developed to be able to provide a better service for Olympic Games 2008 in Beijing (Zhang et al., 2008). Preventive measures with consideration of climate variations were discussed in a study in Nanjing regarding intestinal communicable disease in general (Cheng et al., 1995).

3.1.1.3 Airborne diseases/respiratory diseases

Similar to water/food borne diseases, the association between climate variability and airborne diseases has not been well addressed in China. After the 2003 pandemic of severe acute respiratory syndrome (SARS), several studies raised the question that if meteorological factors could be one of the drivers of this pandemic, particularly by studies in Beijing, Guangdong Province and Hong Kong, where most of the cases came from (Yip et al., 2007, Tan et al., 2005, Chan et al., 2009, Zhang et al., 2004, Ye et al., 2003, Chen et al., 2004, Huang et al., 2004, Lin & Zheng, 2004, Tang et al., 2010, Bi et al., 2007a). Temperature, relative humidity, and wind velocity were identified as the three key meteorological determinants affecting the transmission of SARS in Guangdong (Yuan et al., 2006). A negative association between temperature and daily number of cases was reported (Lin et al., 2006, Bi et al., 2007a) and a certain range of temperature (14-28°C) was identified suitable for development and transmission of the SARS virus (Chen et al., 2004, Tan et al., 2005).

The relationship between weather variables and other respiratory diseases, including asthma, pneumonia, influenza, chronic bronchitis, measles, scarlet fever and pulmonary tuberculosis (TB), were also analysed in some areas in China. A study in a coastal city Qingdao, for instance, reported that high air pressure, low temperature, and low humidity were favourable weather conditions for asthmatic attack among children in the urban area (Liu et al., 2007). A study of pneumonia in children indicates that low air temperature could increase the epidemic of respiratory syncytial virus (RSV), one of the main factors causing pneumonia in children (Wang et al., 2005). Furthermore, a time-series analysis for hospitalised children with pneumonia 1970-1990 in Heilongjiang Province in northeast China also found the association with temperature, air pressure and humidity (Wang et al., 1994). Influenza was mainly investigated in Hong Kong and Shenzhen in southern China (Chan et al., 2009, Zhai et al., 2009b, Lin & Zheng, 2004, Zhai et al., 2009a, Fang et al., 2005, Tang et al., 2010) as well as in Beijing (Liu et al., 2002). An international study indicated that relative humidity was associated with the incidence of influenza A while mean temperature was the key climate variable associated with the incidence of influenza B in Hong Kong (Tang et al., 2010). A study of 200 older patients with chronic bronchitis suggested that decreased temperature and high air pressure were related with increased number of cases in Nanjing in southeast China (Li et al., 2008a). A study in a drought area in northeast China suggested that incidences of epidemic measles and cerebrospinal meningitis were correlated to annual mean air pressure, precipitation, and evaporation (Qu et al., 2004a). Wind speed and daily sunshine hours were reported being positively related to the incidence of scarlet fever in Beijing (Li et al., 2007). Furthermore, a significant positive relationship between temperature and pulmonary TB was reported in Nanjing, which may provide more evidence to encourage development of national TB control programs (Liu & Sun, 2009) as TB is a major public health problem in China with more than 270,000 new cases in 2009 (Ministry of Health in P. R. China, 2009). However, more studies need to be conducted to confirm the findings.

3.1.2 Non-communicable conditions

The association between weather conditions and hypertension, cancer mortality, chronic liver disease, cardio-cerebral vascular disease, respiratory disease and total mortality were reported in China. Several studies used meteorological variables to develop artificial neural net models predicting incidence of hypertension, indicating that temperatures, particularly large variations between seasons, were key factors for prediction (Ma et al., 2003, Li, 2004, Zhou et al., 2008, Gu et al., 2001). One study analysed weather conditions and cancer mortality, indicating an increased mortality of lung cancer and a decreased mortality of liver cancer may be related to high temperatures (Li et al., 2005). Two studies applied Chinese traditional medicine to study the relationship between climatic factors and liver cirrhosis (Cai & Wang, 2005) and chronic virus hepatitis (Wang, 2002), suggesting that temperatures, particularly cold seasons might be a trigger of upper gastrointestinal bleeding in cirrhosis. Based on 42,005 cases from four major hospitals in Wuhan from 1994 - 1998, eight cardiovascular and respiratory diseases were analysed and four meteorological forecast models of daily hospitalisation of each disease were developed based on a set of indices in different seasons, especially the weather process of cold front (Chen et al., 2001). In addition, an association between temperature, air pressure, humidity and incidence of cardio-cerebral vascular disease including stroke was reported in various regions in northern and southern China (Liu et al., 2004, Liu et al., 2008, Han et al., 2008, Wang et al., 2001, Yu et al., 2008, Meng & Li , 2004, Lu & Li, 1997, Zhao et al., 2000, Cheng et al., 1994, Guo et al., 2000, Yang et al., 2009, Zhu & Chen, 2008a, Li et al., 2009, Zhu & Chen, 2008b, Chen et al., 1993, Zhao et al., 1998, Cheng et al., 2000, Wu & Ge, 1990). These studies have focused either on hospital visits or mortality with most of them using time-series analyses. However, one of the key limitations is that the impact of seasonality and potential long term trend were not adjusted in most of the analyses. The relationship between climate variability and total population mortality was reported in studies in southern China (Du et al., 1987, Li et al., 2009). In addition to the seasonal variations in mortality observed in Wuhan, the results indicate that the excess mortality would increase by 12% for 1°C increase in temperature and by 4% for 1% decrease in relative humidity in Chongqing, southwest China. However, they did not attempt to identify a threshold temperature of the association.

3.2 Direct impacts

Although China has experienced frequent and severe extreme weather events in recent years, research on the impacts of these extreme weather events on population health is very limited.

Heat-related mortality was the mostly investigated health outcome due to the impact of extreme heat (Hajat & Kosatky, 2010). The health impacts of heatwaves in Shanghai have been reported recently (Tan et al., 2006, 2007, 2010). Results from these studies indicate that high temperature is associated with increased mortality. Furthermore, air pollution and urban heat island effect could worsen the adverse health effects from exposure to extreme heat. However, a lower mortality was observed in 2003 than that in 1998 in Shanghai, which may be due to the introduction of a heat-health warning system implemented in 2001 (Tan et al., 2004), along with the improvement in living conditions and socio-economic status (Tan et al., 2007). A V-shape association between heatwave and mortality was also reported in another coastal city, indicating 1ºC degree increase in temperature may lead to relative risk of mortality increase by 3.6% but a threshold temperature was not reported (Chen et al., 2009). A U-shape relationship between temperature and mortality from coronary heart disease and cerebral infarction in elderly Chinese was reported in Taiwan (Pan et al., 1995). It was found that in the elderly, the risk of cerebral infarction at 32ºC was 66% higher than that at 27-29ºC while the mortality from cerebral haemorrhage decreased with increasing temperature at a rate of 3.3% /1ºC. An international study indicates that among the four studied countries, the United States, Canada, China and Egypt, the greatest increase in heat-related mortality would occur in China, particularly in areas with irregular heatwaves (Kalkstein & Smoyer, 1993). Another international study conducted by researchers in Japan also reported that climate change would significantly increase excess heat stress mortality in China, if no adaptation or mitigation efforts were made (Takahashia et al., 2007).

Heat-related morbidity has not attracted sufficient attention by Chinese scholars, even though morbidity should be more sensitive as a heath indicator comparing to mortality. The association between heat stress and cardiovascular disease was reviewed by a Chinese researcher but interestingly not one reference was cited from China (Cheng & Su, 2010). The characteristics of disease spectrum in internal medicine outpatients during the period of extremely high temperature and drought were investigated in Chongqing, reporting the health impacts varied by age and sex and respiratory disease was the most affected by extreme high temperature and drought (Yu et al., 2009b).

Health impacts of other extreme weather events, such as drought, flooding, and typhoon, were examined by a very limited number of studies. The interactions of drought and extreme heat on infectious diseases, including digestive infection, malaria and Japanese Encephalitis, were reported (Long et al., 2009, Qu et al., 2009, Yu et al., 2009a, Yu et al., 2004). Using a synthetic evaluation model, a significantly higher loss of life in flood season was observed than that in the no-flood season (Li et al., 2007, Tan et al., 2007). Typhoon Saomei in August 2006 hit southern China and an epidemiological study reviewing more than 3,000 residents in a village in Fujian suggested that risk factors of injuries in typhoon include wind speed and failure to take specific preventive measures (Shen et al., 2009).

4. Discussion

4.1 Increased concerns among Chinese scholars

The lack of studies on climate change and human health in China has been clearly reflected in the latest 2007 IPCC fourth assessment report. Two sections discussed the association between climate change and human health in China. One is in Chapter 8 (Confalonieri et al., 2007), a chapter reviewing the worldwide human health impacts, vulnerability and adaptation to climate change. The other is the human health section in Chapter 10 (Cruz et al., 2007), which very briefly summarised the risks to human health and adaptation in Asia. It is not surprising that, among the over 570 cited articles from both sections, only two studies were specifically about climate change and human health in China, which included a study of the health effect of heat and a study of climate variations and schisotomiasis (Yang et al., 2005 , Tan et al., 2004).

Based on our review, however, a clear increase in the number of studies in this research field in China has been observed, particularly since 2000. Researchers from the China Medical University, Beijing University, Chinese Academy of Sciences, Chinese Center for Disease Control and Prevention, Fudan University, Shanghai Urban Environmental Meteorological Research Centre, Nanjing University, Chongqing Medical University, Hong Kong University, have conducted important studies that are of significance to improve the understanding of the complex relationship between climate variations and human health in Chinese settings. Based on the map in Figure 1, it is interesting to see that most of the studies were conducted in major cities along the east coast and the Yangtze River region. It could be due to the research capability of local institutions and the increased concerns about the environmental and ecological change related to the construction of the Three Gorges Reservoir region over the Yangtze River. This distribution reflects the increased concerns not only about the climate change per se but also about the ecological sustainability due to other environmental changes in China, which may have implications for other developing countries that have similar environmental issues.

A global study recently initiated by the United Nations Development Programme (UNDP), entitled "Piloting Climate Change Adaptation to Protect Human Health" will allocate more than 20 million US dollars to improve the adaptive capacity in health sectors in seven countries (UNDP, 2009). As one of the participating countries, the Chinese government has promised to make a great effort to tackle climate change. It is expected that with the implementation of this global study, a strong link between climate monitoring and the health surveillance system will be established and more quality research on climate change and human health will be published to provide evidence for policy making regarding the protection of human health from climate change.

4.2 Advances and limitations in previous studies

It is recognized that previous studies have identified some important associations between meteorological variables and human health in China. There are some advantages of these studies. For example, in addition to ecological time-series models, various statistical models were applied to quantify the association between climatic variables and diseases, such as back-propagation neural network models, Bayesian models and grey relational analysis. Results from these advanced models confirmed the impact of climate variability on diseases, particularly at a local or regional level. Several projective studies have also been conducted to predict the potential health risks due to climate change. In addition to climatic variables, modified effects with other environmental factors, such as urban heat island and air pollution, were included by some of the previous studies in examining the health impacts of heatwaves.

Some of the research gaps are summarised as follows.

a. Health impacts of climate change have not been systematically assessed, i.e. there is not a national or state study presenting the overall distribution of the vulnerability to future climate change. Previously covered study regions and populations are limited given China has a very large population and area with distinct climatic zones. Some regions, such as Tibet and Xinjiang in western China, are obviously neglected, although residents in these regions may even be more vulnerable due to their low economic status and poor adaptation capacity. There is also a lack of studies on sub-groups who are more vulnerable to climate variations, particularly children, elderly and the people living in rural areas.

b. Studies on the health impacts of extreme events, such as heat waves and flooding, are limited. Only association between extra mortality and heatwaves or flooding was analysed in southern China. Other adverse health outcomes, e.g. the impacts of heatwaves on mental health and renal disease, have not been examined, while some evidence indicates significant associations exist (Hansen et al., 2008a, 2008b).
c. There is a lack of studies on risk factors for the vulnerability to climate change. Most of previous studies focused on heath impact assessment with few of them exploring the risk factors associated with these extra health burdens. However, this information would be of great value to develop effective intervention programs with focuses on vulnerable groups.
d. Although a survey of coastal residents in China, Japan and Korea in 2006 indicates global warming was perceived as one of the higher environmental risks (Zhai & Suzuki, 2009), there is an obvious lack of studies on risk perceptions among individuals and stakeholders, a lack of investigating any adaptation barriers as well as cost-benefit analysis of potential intervention programs. However, results from these studies would be very useful to build resilience to climate change in local communities.
e. There is a lack of solid evidence to form a base for decision making, given the limitations in quality of previous studies in China. Few studies can be transferred into policy and public health practices, such as direct evidence (e.g. threshold temperature identification) for developing early warning and emergency response systems to adapt to future climate change.

4.3 Challenges for conducting research in this field

Possible barriers and challenges in conducting quality studies in this research field in China and other developing countries may include the following issues.

a. Data quality issues: Reliable and complete data, either from surveillance systems or project based, are the key to conduct research on climate change and human health. Similar to other developing countries, data quality could be a problem for Chinese researchers. Although Chinese government established an infectious disease notification system in the 1950s and after the pandemic of SARS in 2003, the infectious disease notification system has been improved dramatically to ensure accurate and quick reporting of new cases to the Ministry of Health, data quality is still not comparable to those from developed countries that may have over 100 years established disease surveillance systems. Moreover, data of non-communicable disease have not been routinely collected in most regions of China. However, by acknowledging the challenges, it should not be an excuse for not doing any research in China and other developing countries.
b. Issues on data availability and sharing: In addition to a short period of reliable data availability, most health surveillance data and environmental data are not open to the public and not free available to researchers. Problems also lie in the management and exchange/sharing data between relevant departments, such as meteorological bureau and public health departments. This reflects little collaboration between health departments and other relevant environmental departments, which is essential for research on climate change as this is not a task that one single department can fulfil.
c. Research capacity: There is a lack of experienced scholars with advanced knowledge and skills in this field in developing countries. As an emerging research field, research on climate change and human health requires the latest, advanced and cross-

disciplinary knowledge and analytic skills to address this global exposure with various local impacts. Therefore, it is agreed that developing countries, including China, do need support from colleagues in developed countries to build research capacity in effective collaboration.

d. Knowledge transfer between languages: English is one of the big obstacles for Chinese researchers to access up-to-date literature and communicate with colleagues from other countries. Some excellent literature review of overseas studies have been written and published in Chinese (Li et al., 2008b, Qin & Zhang, 2009 , Tan & Huang, 2004, Tan & Zheng, 2005) but only a very small proportion of the Chinese studies have been published in international journals and most Chinese journals cannot be accessed by overseas scholars. One of the aims of this review is to summarise the results from studies published mostly in Chinese to provide more evidence for developing a global adaptation strategy.
e. Research funding and government support: Although there are more climate-health studies being published in recent years, compared with the funding for conducting research on meteorological modelling and the impact of climate change on agriculture, ecology and nature protection, the research funding for examining health impacts of climate change is significantly less. At the time of writing this review, by searching "climate change" in the National Nature Science Foundation of China, the main research funding source for Chinese scholars, among the 202 supported climate change projects between 2008 and 2010 only one project is related to human health, which is to study the interactive impacts of air pollution and climate change on short-term mortality in major cities (Pan, 2009).

4.4 Opportunities and recommendations

China issued its first National Environment and Health Action Plan (2007-2015) in 2007, aiming to develop an efficient system for environmental health by 2015 (Ministry of Health in P. R. China, 2007). The plan addresses some of the important issues regarding environment and health, such as the need to develop relevant laws and regulations, to establish nationwide surveillance networks and early warning systems and to share information among different government agencies and stakeholders. This plan also recognizes the importance of a supportive coordination mechanism by placing environment and health "in the list of government priorities", which is a great positive change of the Chinese government's attitude to environment and health. Research on climate change and health is mentioned in one paragraph of this strategic plan and is identified as one of the research priorities to provide technical support capacity on environment and health (Ministry of Health in P. R. China, 2007).

It is no doubt that more systematic research should and will be conducted in China to have a better understanding of the relationship between climate change and human health and to better adapt to future inevitable climate change. The causes of vulnerability to climate change in the Asia Pacific region, e.g. destructive growth, poverty, political rigidity, dependency and isolation, were summarised in a paper in the late 1990s, indicating that climate change would bring an extra health burden to the currently over-loaded health system in these regions (Woodward et al., 1998). In China, the largest country in Asia with a very high population density and relatively low socio-economic status, environmental health risks have not had a high priority in public health practice. More research is necessary to provide robust evidence to policy makers to address this global exposure with various local impacts.

Potential research directions for further studies in China, perhaps for other similar developing countries as well, may include:

a. Improving early warning systems for infectious diseases by integrating meteorological variables, with consideration of different categories and subcategories of infectious disease in regions with various geographic and climatic characteristics;
b. Examining health impacts of climate variability on more health outcomes that have local importance, particularly non-communicable diseases;
c. Identifying risk factors among vulnerable subgroups and regions with higher risks that would be most vulnerable to climate change in the future;
d. Modelling future health burden of disease that can be attributable to climate change or can be avoidable by effective interventions;
e. Developing intervention studies and programs with a focus of local communities with high risks and conducting cost-effective analysis of any mitigation programs, which would be more appealing to policy makers;
f. Formulating research on disaster preparation in terms of public health response systems; and
g. Integrating multi-disciplinary research on climate change adaptation to increase resilience of local communities, which should be systematically conducted as early as possible to deal with future climate change.

It is acknowledged that government support and international collaboration would be crucial to the success of research in this field. Support from government at all levels is extremely important in terms of providing research funding and opportunities for capacity of research building in Chinese institutions. In addition, collaborations with colleagues in developed countries would be significantly helpful in transferring knowledge and skills and sharing information, particularly that young researchers should be encouraged to communicate at an international platform. It is expected that Chinese scholars can recognize these risks/opportunities and are willing to devote themselves in such a challenging and rewarding research area for the health benefit of ourselves, our next generations and our planet.

5. Conclusion

This systematic review has identified the current research status about climate variability and population health in China, suggesting that climate variability could play a role in some of the major public health problems in China. Recommendations for further studies have been provided not only for Chinese scholars but also for researchers in other developing countries. It is expected that in order to reduce the health risks of future climate change, further research should be conducted with sufficient support from governments to fill up the identified research gaps so as to assist in evidence-based policy-making process in public health within a changing climate.

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6

Climate Change and Sustainable Development of Water: Sub-Saharan Africa

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1. Introduction

Current scientific consensus predicts that continuing and significant climate changes arising from increasing greenhouse gas emissions will occur in coming decades, likely resulting in widespread alterations to hydrologic conditions. Hydrologic alterations are challenging for sustainable development of water resources, because of the direct reliance on the hydrologic cycle for adequate supplies of water and the cycle's inherent vulnerability to change of temperature, precipitation, and streamflow.

According to the IPCC, African countries are more vulnerable to changes of climate and resultant effects due to lack of capacity and economic development. 200 million people already water-stressed in Africa. Providing access to adequate supplies of water has been a high priority on the agenda of organizations working in the international development community. Progress has been made, but some of the greatest challenges that developing nations continue to face include providing access to water, while successfully managing it as an environmental resource, and mitigating the potential effects of climate change as this resource continues to be developed.

Development and management of water resources has long proceeded under the assumption of a relatively constant climate, subject to some natural fluctuation. Critical water infrastructure in developed countries, such as the Colorado River System, are designed to buffer variability in precipitation and streamflow over time scales of a few years to a decade. Water infrastructure in the developing countries of sub-Saharan Africa is struggling to provide adequate water to inhabitants. Variability in precipitation and streamflow, in the form of a drought, has had devastating consequences.

Access to water affects complex feedback loops between natural resources, land use, hydrologic and climate cycles, policy, population growth, agriculture, socio-economics of development, and stakeholders. The combination of rapid population growth, extreme climate, and uncertainties of inadequate data will have a disproportionate effect on Africa. Already, environmental and human crises have results from inadequate, or mismanaged, access to water in both developed and developing countries. As Sub-Saharan Africa continues to grow, climate change poses uncertainties for resources.

This chapter reviews aspects of population growth, agriculture, and development within the feedback loops; what is known and projected with respect to climate change; hydrologic alterations of surface water and groundwater; caveats; and planning and the path forward.

2. Feedback loops

2.1 Population growth

Sub-Saharan Africa has some of the highest growth rates in the world ranging from 1.6 to 3.1 % per year (Taylor et al., 2009). The population is expected to double in the next thirty years. In general, the African population does not have adequate access to water. Local governments and agencies have been working to improve access to water, and progress has been made. At the current rate of work, the Millenium Development Goal of halving the proportion of people without access to water by 2015 will be not met in 2040 (Stampini et al., 2009). The rate of work cannot keep up with population growth and urbanization.

Groundwater is increasingly developed as an economically viable solution to meet demand for water resources. In Uganda, for example, 70% of water supplied to 782 small towns is groundwater piped via deep boreholes (Mileham et al., 2009). Reasons for developing groundwater include: ease of developing hand-pumps in remote locales; availability during drought; superior chemical and biological quality (compared with surface water sources); and relative low price compared with methods of treating surface water (Dapaah-Siakwan and Gyau-Boakye, 2000; Gyau-Boakye, 2001). In the latter case, for instance, costs of treating water derived from surface sources is approximately twice that of groundwater for communities of less than 5,000 people (Gyau-Boakye, 2001).

Surface water sources are also being developed via small dams and impoundments, but may become less reliable. Per capita surface water supplies in Mali, for instance, are projected to decline by 52% due to an increase of population and a predicted decrease in rainfall. It is anticipated that the per capita decrease in freshwater sources will intensify stress on groundwater resources. If downward climate projections reported for precipitation and surface water availability continue, there may be negative implications for long-term supply of groundwater resources.

2.2 Agriculture

Climate change and resultant alterations to hydrologic conditions affects agriculture via food security. The 75 to 250 million people in sub-saharan Africa could be exposed to increased water stress due to climate change and rain-fed agriculture could be reduced by 50% (Edmunds, 2009). Agricultural production may be severely compromised due to increases in temperature, evaporative demand, and rainfall. Unreliable and declining rainfall already threatens smallholder, subsistence family farms, which form the backbone of most local economies. These small farms are estimated to account for 70% of agricultural production.

To have more reliable, and potentially increased, crop yields for self-sufficiency or export, "efforts should be intensified to support water resource and small-scale irrigation development" (Perret, 2006). Mechanized systems, already in place at some boreholes that access groundwater, can be optimized to extract groundwater for agriculture at much higher rates than for domestic use alone. In Ghana, for instance, there a nationwide drive towards extracting groundwater resources for irrigation of vegetables throughout the year, since over 50% of the country's gross domestic product comes from the agricultural sector, which is primarily rain-fed (Banoeng-Yakubo et al., 2009).

Use of surface and groundwater for agriculture has had varying results. In the US, for example, irrigation for agriculture has led to no issues of food security, but over-extraction of groundwater resulting in groundwater declines, land subsidence, drying up of ecosystems, sea water intrusion, and degradation of groundwater quality (Kinzelbach et al., 2003). In perspective: at the global scale, the largest user of water is irrigated agriculture. Worldwide, the agricultural sector accounts for 70% of water extraction, while less than 5% of African land is currently being irrigated (Taylor et al., 2009). In order to mitigate the effects of climate and combat food security, the African agricultural sector may shift from 5% to 70% of land being irrigated by extracted water.

2.3 Development

Climate change and resultant alterations to hydrologic conditions affects development on multiple socio-economic levels. Achieving the social and economic interest of the population includes providing each community member with opportunities to access water for human health and to experience economic development via agriculture and/or industry. The need for improved access for human health cannot be disputed. On a daily basis, diseases related to poor water or lack of sufficient water kill an estimated 14,000 to 30,000 people in developing nations, of which many are children (Gleick, 2000). Beyond human health, inadequate access to water impacts educational outcomes, and productivity. Absence from school and work due to water-related illness contributes to substandard school performance and productivity, respectively (UNDP, 2006, UNICEF, 2006). Lack of access to water essentially keeps developing nations from developing.

The minimum amount of safe water suggested for improved human health is 50 liters per capita per day (lpcpd), which includes use of safe water for washing, bathing, food preparation, etc (Gleick, 1996). Surveys of water use in rural areas, however, reveal that domestic use accounts for 55% of the total volume extracted, while the remainder is for livestock and gardening (Gleitsmann et al., 2007). The total per capita amount, then, in rural areas is approximately 90 lpcpd (50 lpcpd domestic and 40 lpcpd livestock and gardening).

Rural areas reflect only a portion of the population, as the doubling of population is not evenly distributed. Urbanization is a rapidly increasing trend and urban population is expected to triple between 2000 and 2050. In Mali, for instance, population growth is proportionate to the size of communities: 3.6% for those with more than 5,000 inhabitants, 1.3% for those with 2,000 to 4,999 inhabitants, and 0.6% for those with less than 2,000 inhabitants (N'Djim and Doumbia, 1998). Urbanization increases domestic consumption due to availability of water from a growing pipe network; water use in an urban house (with garden) can be up to 400 lpcpd.

Compounded with urbanization, the demand for water is intensified by mechanized groundwater development. In Uganda, for example, mechanization of groundwater wells expanded dramatically since 2003 (Mileham et al., 2009). These mechanized wells are extracting water for urban areas or a combination of several rural communities. Additionally, these wells may be used for irrigated agriculture, as already discussed.

Finally, development of industry increases demand for water. In the US, for instance, water extraction was 700 cubic meters per person per year at the turn of the century, increasing to 2,300 by the early 1980s, and a subsequent drop to 10% below peak despite continued increases in development (wealth) and population (Gleick, 2000).

For a water supply to provide these socio-economic benefits of development, it must yield sufficient volume to meet all domestic needs, be deemed safe for human consumption, reliable all throughout the year, reasonable distance to fetch water, and maintained by the community. It must also provide sufficient volume for development via agriculture or industry.

3. Climate hange

3.1 Observed and projected

Observed global mean temperatures have been increasing during the last hundred years, with the rate of warming accelerating more recently (IPCC, 2007). There is decreasing frequency of cold days, cold nights, and frost events and concurrent increasing frequency of hot days, hot nights, and heat waves, especially in the latter half of the past century. The increase of temperature observed across the globe is also observed across Africa, with the rate of warming also accelerating during the latter half of the last century. During the last century, Africa warmed by 0.7°C while rainfalls have increased 5 to 10% (IPCC, 2001, 2007). On a sub-continental scale, there are regional variations of temperature trends. For instance, warming is observed in southern and western Africa, and the tropical forests, while cooling is observed near lakes or coastal areas (Boko et al., 2007).

Projections for changes of temperature across Africa vary by scenario. In general, projected increases for temperature are between 3 and 4 °C by the end of this century as compared with the end of the last century (Carter and Parker., 2009; Boko et al., 2007). Warming for Africa is projected to be to be 1.5 times the global mean (Christensen et al., 2007) and, as with observed trends, regional and temporal variations are expected. In general, projections predict up to 40% reduction of rainfall in arid and semi-arid areas but a marginal increase in tropical and equatorial areas (Boko et al., 2007; IPCC, 2007).

Increases of temperature and precipitation are likely to have resultant effects on climate and hydrology, but the ability to accurately predict the impact of temperature increases is currently limited. In the absence of precipitation changes, warmer temperatures alone would likely lead to less streamflow, mainly due to higher evaporation. Considering precipitation also, warming increases the water-holding capacity of the atmosphere and may increase the frequency of very heavy rainfall events, especially in the tropics (Allen and Ingram, 2003; Trenberth et al., 2003).

A variety of methods have been used to evaluate the effect of temperature increases on climate and hydrology, resulting in a broad range of projections. Some of these projections include: increase of annual rainfall and subsequent runoff; decrease of annual rainfall and subsequent runoff; increased evaporative demand; higher evapotranspiration combined with shorter rainfall seasons resulting in persistent soil moisture defecits; soil moisture defecits leading to reduced recharge to groundwater; increase of intense rainfall events; increase of evapotranspiration may negate some of the effects of increased rainfall; increase of arid and semi-arid lands by up to 8%; increases and decreases to recharge of groundwater, varying regionally by up to 53% (Challinor et al., 2007; Olago et al., 2009; Christensen et al., 2007; Milly, 2005; Milham et al., 2009). A regional example is increase of recharge for Sahel and decrease of groundwater recharge to south-west Africa (Kundzewicz and Döll, 2009). On a more ominous note, the warming of the Indian Ocean is projected to disrupt rainfall in eastern and southern Africa, resulting in an additional 50% increase in undernourished people by 2030 (Funk et al., 2008).

With respect to the increase of rainfall intensity and evapotranspiration, evidence suggests that extreme events, such as floods and droughts, are occurring with increasing frequency and duration (IPCC 2007; Peduzzi, 2005). Although extreme weather events often recall images of landscapes desiccated by drought or inundated by flood waters, the reality of extreme event occurrence can be less dramatic. While dramatic types of events are relatively easy to identify in the hydrologic record, other events occur over a wider range of timescales and are not as obvious. Extreme events include high and low precipitation intensity, duration, frequency, or spatial extent; high and low temperature intensity, duration, and frequency; or high and low discharge intensity or duration (Tebaldi et al. 2006). Projected increases in intensities will exacerbate drought and flood events both of which threaten crops yield and food security (Challinor et al., 2007).

3.2 Alterations to surface water and groundwater

Extended departures of streamflow, temperature, and precipitation from historic mean annual values will affect availability, and quantity of water. Volumes of water resources developed as surface water and groundwater are often estimated, since surface waters are not always adequately monitored and hydrographic networks are shrinking, while groundwater networks are scarcest of all (Kundzewicz and Döll, 2009).

Surface water and groundwater sources are both dependent on precipitation. Rainfall variability is high, with multi-year events of higher and lower than average rainfall. In some instances, inter-annual variability is such that 95% of annual rainfall totals deviate between 16 and 45% from the mean (Cater and Parker, 2009). Large trends of decreasing rainfall were widespread in the Sahel from the late 1950s to the late 1980s with some recovery through 2003 (Nicholson, 2005; Dai et al., 2004), and to-date it is not clear if drought conditions have ended. Inter-annual variability of rainfall is linked with inter-annual variability of surface water (runoff) such that wetter periods observe greater volumes of stream flow surface water and drier periods observe reduced volumes of surface waters. Relationships between reduced rainfall and declining stream flows have been observed for streams in the Central Kenyan Rift, Volta River Basin, and Niger River Basin (Olago et al., 2009; Mahe 2009).

Relationships have also between observed between reduced rainfall, declining stream flows, reduction of recharge to groundwater, and subsequent decline of groundwater levels. The relationship between rainfall and recharge is not necessarily linear, with the possibility of recharge occurring sporadically on regional and temporal scales. In the Ethiopian highlands, for instance, recharge from monsoonal rains is released by spring and seeps in the dry season but this monsoonal recharge does not necessarily contribute to inter-annual groundwater storage (Walraevens et al., 2009).

Contributing to the non-linearity of the relationship between rainfall and recharge, some studies suggest that a certain threshold of rainfall (annual or event-driven) must be reached before any recharge to groundwater occurs. The large inter-annual variability of rainfall, thus, may lead to large inter-annual variability of recharge (Eilers et al., 2007; Edmunds, 2009; Olago et al., 2009). Insignificant recharge is thought to occur when rainfall is generally less than 200 mm yr^{-1}, though some recharge during individual intense events less than that amount (Scanlon, et al., 2006; Edmunds 2009). One study observed recharge taking place approximately every 10 years for a duration of a 3-year pluvial event (Olago et al., 2009). Individual intense events, in general, may be contributing more to recharge than the sum of all daily rainfall events (Taylor and Howard, 1996; Eilers et al., 2007; Owor et al., 2009).

The decline of groundwater levels has been observed during periods of sustained annual reduction of rainfall such as during drought. Complete dewatering of certain aquifers was observed in Ethiopia during drought (Walraevens et al., 2009) and decline of groundwater levels observed during drought in Burkina Faso (Thiery et al, 1993) and in the upper Niger Basins (Bamba et al., 1996). It is suggested that the volume of groundwater extracted should not be greater than the volume recharged (Kinzelbach et al., 2003), and probably much less.

In arid to semi-arid regions, Saharan regions, significant recharge events occurred about 5,000 years ago (Edmunds et al., 2004), so it must be recognized that substantial recharge has likely not occurred recently and that groundwater resources are essentially non-renewable (Edmunds 2009).

4. Caveats

There is inherent uncertainty in the GCMs for projections across the globe. There is "substantial" uncertainty in the projections and resultant climate and hydrologic effects for Africa (Taylor et al., 2009). Perhaps some of the greatest uncertainty is for the latter part of this century for the West African Sahel, as some projections predict larger rainfall while others predict longer, intensified drought (Lebel et al., 2009). Uncertainty is, in part, due to varying time frames, assumed socio-economic standards, difficulties linking hydrologic models to GCMs, land-use changes, and the lack of understanding of the climate-water relationship.

Uncertainty may also be attributed to the shortage of available historical and current observational data. A study linking climate and hydrology in Uganda evaluated trends in temperature and discharge, but could not determine trends in precipitation with the caveat that only one precipitation station was available for study area (Nyenje and Batelaan, 2009). In general, there is a paucity of available climate and hydrologic data for the Africa continent, even though these are of great importance for sustainable water resources management (Baisch, 2009). Demand for water during droughts of the 1970s and 1980s, placed emphasis on rapid development of water sources. As a result, studies of groundwater, surface water, and rainfall were often not prioritized and balance of the local water resources is not well understood. Recently, there has been more effort to study and characterize aquifer parameters, extraction rates, seasonal groundwater level fluctuations, rainfall, and relationships between groundwater and surface water, but it will take time to close the knowledge gap.

Computational technology has allowed for models of surface water and groundwater to be used in scientific research with output potentially used for decision making by policy-makers. These models are useful for forecasting the potential impacts of climate change projections and especially useful for testing and evaluating alternative resource management strategies. Models range from simple spreadsheets to complex codes and, depending on complexity, computing capacity makes it possible to run many models on a desktop system. As a case study, a spreadsheet multicriterion decision analysis model was used to analyze sensitivity of stages of drought on the Niger River and impacts to priorities of decision-makers (Traore and Fontane, 2007). Results have been attained from simple models to analyze natural groundwater level variation (Thiery et al., 1993), lumped models to estimate evapotranspiration (Ardoin et al., 2001), water balance approaches to evaluate water resources (Asomaning, 1992), and water balance approaches via groundwater models such as MODFLOW (Lutz et al., 2007; 2009; 2011).

Most recently, remotely-sensed data have been used to fill in gaps of the historical and current observational data. Satellite data from the Gravity Recovery and Climate Experiment (GRACE) has been used to develop estimates of freshwater storage for a water balances in the Congo (Crowley et al., 2006) though technical challenges remain for using the GRACE data (Taylor et al., 2009). Evaporation is an extremely difficult parameter to measure, requiring expensive field equipment that. Remotely-sensed data and has been used to estimate evapotranspiration in the Volta Basin of Ghana (Compaoré et al., 2008), and to estimate streamflow, lake, and marsh height in the Lake Chad Basin (Coe and Birkett 2004).

5. Path forward

The combination of demand for access to water from development, irrigation for agriculture, and growing population are already challenging for developing nations. And, compounded with mitigating the potential effects of climate change projections, there is growing growing concern over the availability of water resources (Ndjim and Doumba, 1998; Taylor et al., 2009).

The caveat of data availability and implications for modeling has already been discussed. A further caveat is data availability and implications for complex feedback loops between natural resources, land use, hydrologic and climate cycles, policy, population growth, agriculture, socio-economics of development, and stakeholders. Inadequate understanding of water resources, failure of scientific community to research and convey new discoveries, and a lack of societal and political awareness to act on available scientific evidence (Edmunds 2009) causes difficulties for developing policies to guide water resources development. Information needed to asses water resource sustainability is not readily available, non-existent, or are not collected (Gleick, 1998). And, especially at the local scale, agencies often operate under constraints of limited expertise, funding, resources, and data.

Development of water resources, in particular groundwater, has historically been approached from a perspective that supply can be plentiful. And while hand-pumps do extract very little water with respect to the larger water balance (Lutz, 2007, 2009, 2011), increased water availability to Africa populations during the past few decades has already resulted in localized draw-downs of water tables and loss/damage to ecosystems (Edmunds 2009). Regional failure of an aquifer is unlikely, though increased demand may cause localized failure at a particular source of water. Unfortunately, few data exist upon which to base extraction policies (MacDonald et al., 2009).

Declines of groundwater due to drought, rather than abstraction, have been observed in the Khalahari Karoo/Stampriest Artesian Aquifer and Lake Chad Basin Aquifer System (Scheumann and Alker, 2009). Cooperative commissions have been formed on transboundary aquifers, but they are less developed than the commissions formed for transboundary rivers and lakes, such as the Lake Chad Basin Commission, and Orange-Senqu River Basin Commission (Scheumann and Alker, 2009).

Promotion of linkages among stakeholders is essential. Water planning and decision making is often left to a narrow range of people who do not necessarily include rural interests, minority groups, environmental groups, and academics, for instance (Gleick, 1998). Bureaucrats at the national ministerial level often have little or no knowledge on the impact of a program on the intended beneficiaries, suggesting that any attempt to assess the impacts of rural water supply programs in the developing world should solicit information from regional and district representatives (Akuoko-Asibey, 1997).

6. Conclusion

The assumption of a relatively constant climate has been increasingly called into question with the recognition that climate variability is greater than commonly perceived, and may

increasingly impact water resources. Furthermore, evidence suggests that extreme events, such as floods and droughts, are occurring with increasing frequency and duration. Stationarity of climate and hydrology should no longer be assumed for water resources planning. There is a growing need to consider susceptibility to, and planning for, more extended departures of streamflow, temperature, and precipitation from historic mean annual values.
The discussion of complex feedback loops between natural resources, land use, hydrologic and climate cycles, policy, population growth, agriculture, socio-economics of development, and stakeholders circles back to the impacts of climate change. Much effort is going on to close major gaps existing in the knowledge of climate and hydrology in Africa. The HAPEX-Sahel study Journal of Hydrology, the ongoing African Monsoon Multidisciplinary Analysis (AMMA) investigating tropical monsoon dynamics over West Africa, in particular the AMMA-Catch observing system monitoring land use/land cover and hydrology at sites in Benin, Niger, and Mali, and NCAR cloud seeding over Manatali Dam in Mali. These are just a few examples.
There is need for impact assessments at local scales and simple, but accurate tools and techniques to assess impacts to water resources is essential to mitigate climate change. Increased demand resulting from increase of population, potential for irrigation to agriculture, and development. Some of the greatest challenges that developing nations continue to face include providing access to water, while successfully developing and managing it as an environmental resource, and mitigating the potential effects of climate change as this resource continues to be developed.

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7

The Climate Change, Water Crisis and Forest Ecosystem Services in Beijing, China

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1. Introduction

Although the Earth's climate changes continually, as a result of natural processes, there is now a strong scientific consensus that global warming is occurring, that it is largely driven by greenhouse gas emissions due to human activity. The linear warming trend over the last 50 years is nearly twice that for the last 100 years, with average global surface temperature rising by 0.74 ^{0}C between 1906 and 2005 (IPCC, 2007). Climate change and its impact on human survival have been today's major challenge and key topics of discussion globally (Oli et al., 2008). The major observed evidence showed that, the trend of climate change in China was consistent with that of global climate change. As a developing country of responsibility, China attaches great importance to the issue of climate change, and has taken a series of policies and measures to mitigate and adapt climate change effects (NDRC, 2007). Beijing, the capital of China, is characterized by a warm temperate continental monsoon climate. In the context of global warming, the observed changes related to climate in Beijing include an increase in annual average temperatures, possible reductions in average rainfall and runoff, and more heat waves and less frost (Wang, 2008). Meanwhile, as a consequence of rapid population growth and economic development, Beijing is facing a water crisis, with rapid deterioration of water quality, serious water shortages, and reduced availability of groundwater. Therefore, it is noticeable that Beijing's actions should focus not on climate changes in isolation but on interactions between climate change and other stresses on the city growth and development. This chapter draws together evidences from a series of researches on climate change, water crisis and forest ecosystem services in Beijing, and provides a reference point for international research institutions, government agencies and other organizations to respond to these issues. The rest of the chapter is organized as follows. Firstly, the evidences for climate changes in Beijing, including temperature, precipitation, heat island effect and extreme weather events, are introduced. Secondly, the water resource situation and water scarcity risk in Beijing are analyzed. Finally, Beijing's forests and their services in the mitigation and adaptation to climate change are explored. I hope this chapter can provide some insights in the importance of urban forest under future climate change, and will help the global audience with similar issues.

2. Climate change in Beijing

2.1 Temperature

Based on the major observed evidence of climate change in China, the annual average air temperature has increased by 0.5-0.8 ^{0}C during the past 100 years, and the warming trend was more significant in western, eastern and northern China in the south of the Yangtze River (NDRC, 2007). Beijing is in the north of China and in the temperate climatic zone with a perennial mean temperature of 12 ^{0}C (Li et al., 2005). Under global warming background, the annual average air temperature in Beijing presented a fluctuating increasing tendency (Xie and Wang, 1994; Wang et al., 2009a). During the past 32 years, the annual average temperature in Beijing has increased by 1.7 ^{0}C, from 11.6 ^{0}C in 1978 to 13.3 ^{0}C in 2009 (see Fig.1). Moreover, the trend of climate warming in China will further intensify in the future. The nationwide annual mean air temperature would increase by 1.3-2.1 ^{0}C in 2020 and 2.3-3.3 ^{0}C in 2050 as compared with that in 2000 (NDRC, 2007).

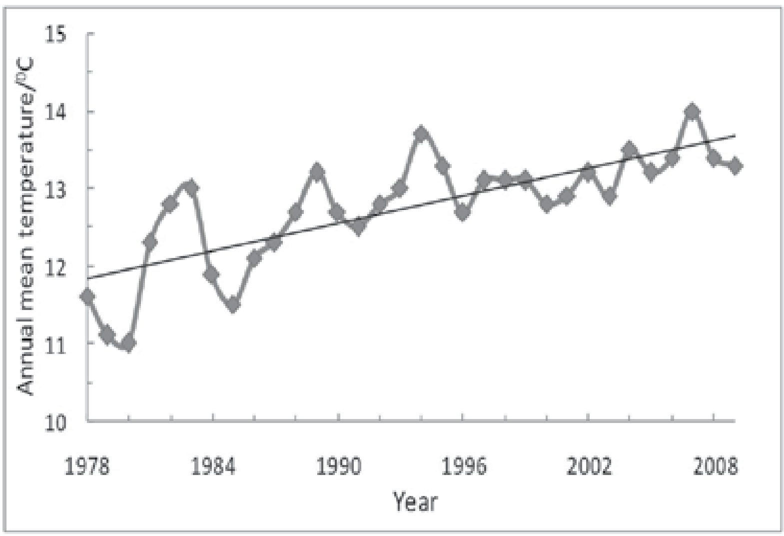

Fig. 1. Annual average temperature in Beijing from 1978 to 2009

2.2 Precipitation

Although there was no obvious trend of change in annual precipitation in China in the past 100 years, the decrease in annual precipitation was significant in most of northern China, eastern part of the northwest, and northeastern China, averaging 2-4 mm/a, with decrease in northern China being most severe (NDRC, 2007). Beijing is located in the northern tip of the North China Plain and in arid region with an annual average precipitation of 640 mm (Li et al., 2005). The annual precipitation in Beijing decreased gradually since 1950s with an average rate of 41.9 mm/10a (Yue, 2007). Figure 2 also shows the decrease tendency in average precipitation in Beijing from 1978 to 2009. In addition, the precipitation on urban stations decreased faster and fluctuated greatly than that in rural ones, and the fluctuation intensity of rainfall increased the risk of flood and drought in Beijing area (Zheng and Liu, 2008).

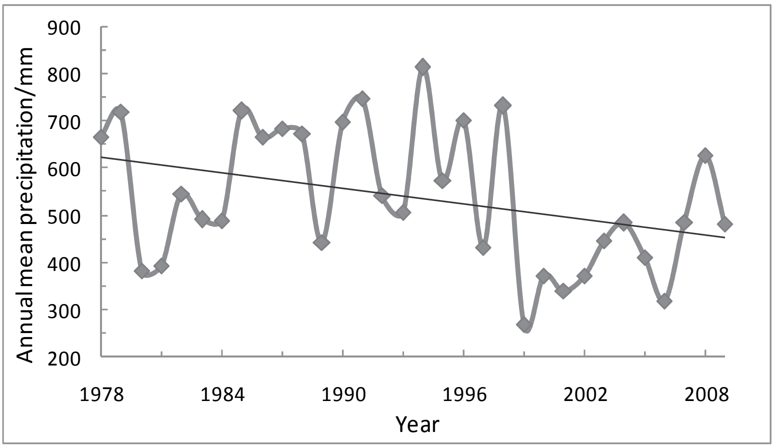

Fig. 2. Annual average precipitation in Beijing from 1978 to 2009

2.3 Heat island effect

The rapid development of urbanization causes the urban heat island to become a more and more serious problem. Urban heat island effect is due to the temperature difference between urban and its' surrounding suburban rural areas (Du et al., 2008). In recent years, the urban heat island in Beijing region has been constantly observed (Zhang et al., 2002; Song et al., 2003; Lin and Yu, 2005; Zhang et al., 2006). Based on the climate observation data collected from 11 weather stations, Wang et al. (2009a) reported that the temperature difference between urban and rural area in Beijing was increasing fluctuately from 1961 to 2008 (see Fig.3).

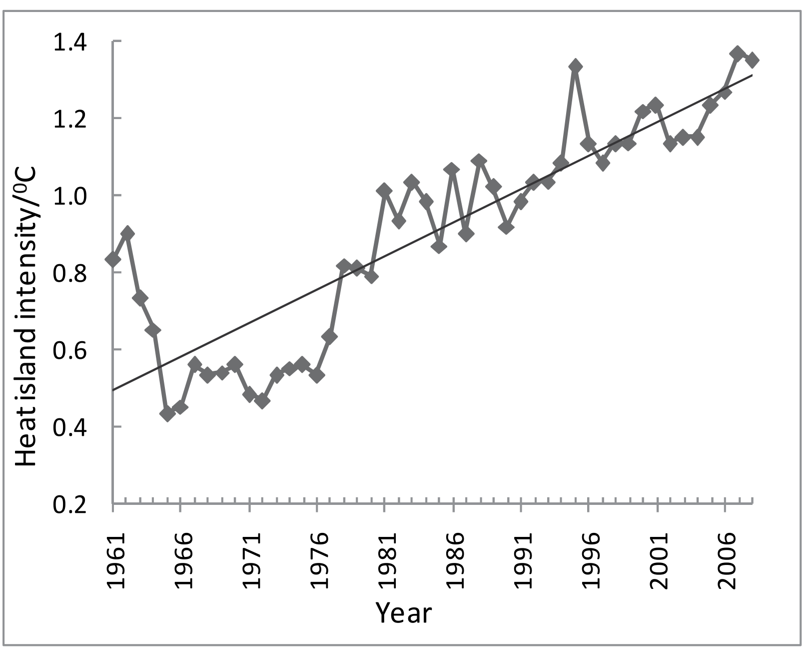

Fig. 3. Temperature difference between urban and rural area in Beijing from 1961 to 2008

Furthermore, there was a closer relationship between land-use and the surface urban heat island of Beijing, and the spatial pattern of urban heat island was turned to be more separate and a lot of cool spots appeared in the center city from 1987 to 2005 (Peng et al., 2007). In addition, urban heat island effect arose in summer and autumn and was the most intensive in summer (0.6-1.5 ^{0}C) (Yan et al., 2008).

2.4 Extreme climate/weather events

Apart from the meteorological debates, there is evidence that economic damage as a result of extreme weather events has dramatically increased over the last decades (Vellinga and van Verseveld, 2000). Many cities in the world are suffering from the increasing frequency and intensity of extreme weather events such as heavy rainstorms, floods, droughts, fires, and hurricanes due to climate change. The daily weather observation data from 1951 to 2003 showed that, the high temperature and frowzy events in Beijing had an increasing trend in the last 30 years, but low temperature, strong wind, thunderstorm and thick fog represented a decreasing trend (Zheng and Zhang, 2007). In addition, the events of high temperature, frowzy weather, low temperature, strong wind and thunderstorm have a remarkable annual change but faint periodicity, the rainstorm and sand storm's variation are periodical, their main period are 10 years and 8-10 years.

3. Water crisis in Beijing

Climate change is expected to produce higher temperatures and direr summers and wetter winters (Charlton and Arnell, 2011). Reductions in water availability are also expected as a consequence of climate change (Arnell, 2004), with implications for a reliable supply of water to customers. China is a country in water shortage and its average water resource capacity per person is only 1/4 of the world. Due to the economic and social development as well as the global warming effect, the problems of water shortage and water pollution have become important factors in hindering the future economic and social development in China. As the capital of China, Beijing has also been suffering from such water issues as water resources scarcity, water quality deterioration and over-extraction of groundwater. Even worse, the critical situation regarding water crisis in Beijing will still exist in the future (Zhang et al., 2010a; Tong, 2010).

3.1 Water resource shortage

Beijing is, an international metropolis, and has a residential population of 17.55 million in 2009 (Beijing Municipal Statistical Bureau, 2010). During the past several decades, the demand for water in Beijing has increased dramatically due to the rapid urban population growth and economic development (Wu and Zhang, 2005). At present, the total amount of water resources in Beijing is 2.18 billion cubic meters (Beijing Municipal Water Conservancy Bureau, 2009), the average water resource per person is only 125 cubic meters, which is far lower than the severe water shortage standard of 1000 m^3/person (Wang et al., 2009b). Figure 4 shows the amount of water resource, surface water and ground water from 1988 to 2008, which all representing a decreasing tendency. The scarcity of water resources has significantly compromised the social economic sustainable development in Beijing (Zhang, 2004).

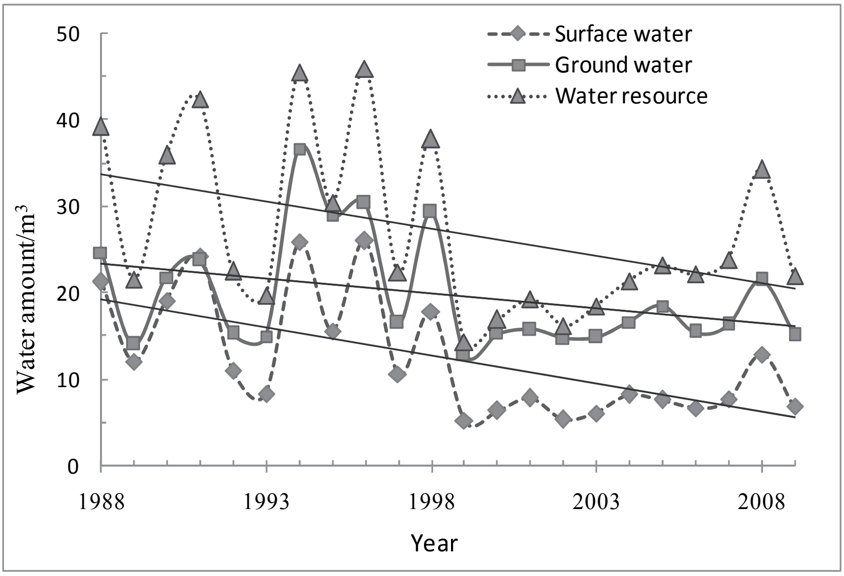

Fig. 4. Water resource amount in Beijing from 1961 to 2008

According to the projections of the water supply plan of Beijing, water use will increase by 3.42% while the population increases by only 1% (Zhang et al., 2007). During the 11th five-year plan period (2005-2010), the residential population in Beijing increased by an annual average of 520 thousand persons. And it is expected that the population will continue to increase to 21-26 million persons by 2020. With system dynamics method, Tong (2010) found that the carrying capacity of Beijing would decline if current water supply and use standard and structure were unchangeable (see Table 1). Consequently, both growing demand and declining supply are contributing to the serious water shortage that Beijing has faced. During the past several years, however, the situation has steadily deteriorated, with little evidence that scarcities will be alleviated in the future.

Year	Scenarios 1		Scenarios 2		Scenarios 3	
	Carrying capacity of water use for life activity	Carrying capacity of total water use	Carrying capacity of water use for life activity	Carrying capacity of total water use	Carrying capacity of water use for life activity	Carrying capacity of total water use
2015	913.21	991.68	719.63	1506.51	1690.98	1506.51
2016	905.77	973.98	589.09	1485.85	1676.72	1485.85
2017	898.44	956.89	453.17	1465.88	1655.69	1465.88
2018	891.24	940.39	311.36	1446.53	1658.29	1446.53
2019	884.14	924.45	163.09	1427.73	1654.96	1427.73
2020	877.16	909.04	296.17	1520.53	1800.64	1520.53

Table 1. Population carrying capacity of Beijing under various scenarios (Tong, 2010)
Unit:10^4 persons

3.2 Over exploration of underground water

Groundwater in urban environments is an important and valuable resource for portable water supply and industrial use (Yang, et al., 1999), but is at risk from over-exploitation and polluting land use (Lerner, 1990). In Beijing, two-thirds of the municipality's total water supply comes from groundwater. The Beijing Water Bureau estimates that its available groundwater ranges from 2 to 2.45 billion cubic meters per year. As recently as 30 years ago, Beijing residents regarded groundwater as an inexhaustible resource (Probe International, 2008). Now hydroeologists warn it too is running out (He, et al., 2005; Yue, 2007; Tian, 2010). The over-exploration of underground water caused serious ecological and environmental problems, such as land subsidence, sea water intrusion, waste water seeping into groundwater, and ecosystem deterioration, of which the declining of water table was the most serious. Figure 5 shows that the groundwater tables decreased greatly from -16.42 m to -24.07 m during the period of 2002-2009, due to the over exploration of underground water in Beijing city.

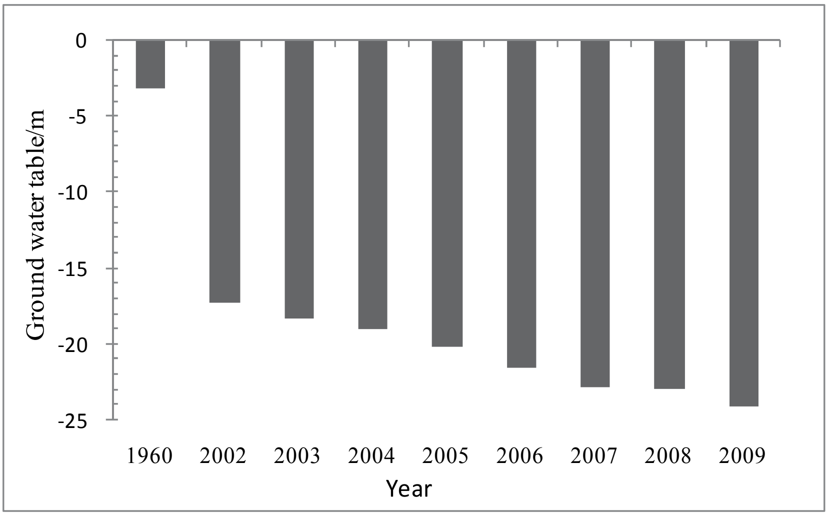

Fig. 5. Ground water level in Beijing from 1961 to 2009

3.3 Water quality deterioration

Although Beijing has made great efforts in recent years to improve water quality, there is serious pollution of surface water. According to the Quality Standards of Surface Water Environment (GB 3838-2002), only 46% of rivers in Beijing could reach the water quality requirement in 2009, the water quality in 1245.1 km of 2545 km of rivers being monitored were in the fourth and fifth grade or worse than fifth, which accounts for 53% of the total length of the rivers being monitored (Beijing Municipal Water Conservancy Bureau, 2009). There was 1.2 billion cubic meters waste water discharged annually in Beijing, about 0.9 million cubic meters of which from urban area, only 12% of which was treated through waste water treatment plants (Beijing Environment Protection Bureau, 1999). Figure 6 indicates that the amount of wastewater has being discharged and treated, and the treatment rate of wastewater in Beijing from 2003 to 2009. Untreated waste water discharged to the seeping wells, rivers and waste water ponds, is getting into ground water through seepage, which causes ground water pollution.

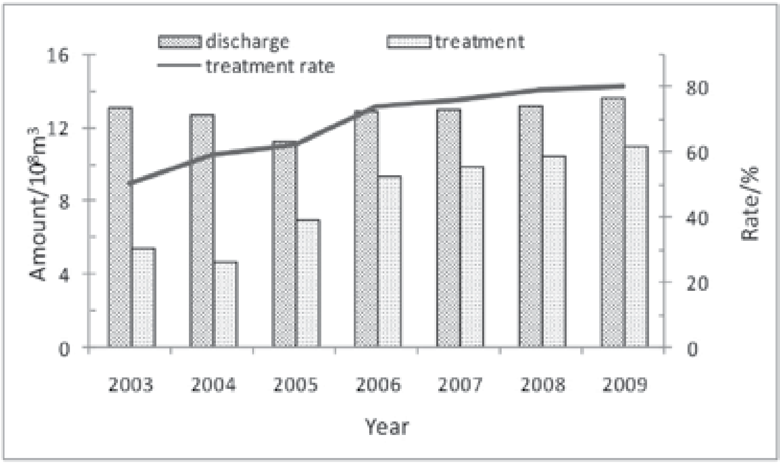

Fig. 6. Amount of waste water and treatment rate in Beijing from 2003 to 2009

3.4 Loss of stormwater runoff

Rapid urban expansion leads to the replacement of native vegetation areas, which provide rainwater interception, storage, and infiltration functions, with impervious surfaces, which often results in an increase in the rate and volume of surface runoff of rainwater (Whitford et al., 2001; Mansell, 2003). Climate change may further increase these fluctuations and the flood risk (Villarreal et al., 2004). Since the Reforms and Opening-up policies were implemented in the 1980s, Beijing has undergone rapid urbanization. The urban area was 183.84 km^2 in 1973, and it increased to 1209.97 km^2 in 2005; the built-up area has increased by 1026.13 km^2 during the past 32 years, having expanded at a rate of 32.07 km^2 per year (Mu et al., 2007). Owing to the fast urbanization, natural ecosystems are being increasingly replaced by an impervious urban surface (Xiao et al., 2007). Impervious surfaces increase the speed and volume of water running off a site, while decreasing the quality of that water and highly modifying the hydrology of urban areas (Shepherd, 2006). A higher proportion of rainfall becomes surface-water runoff which results in increased peak flood. There was a significant rise (0.04–0.08) in the runoff coefficient before and after the 1970s in Beijing (see Fig.7). To reduce the high runoff during rainfall, a great deal of stormwater drainage system

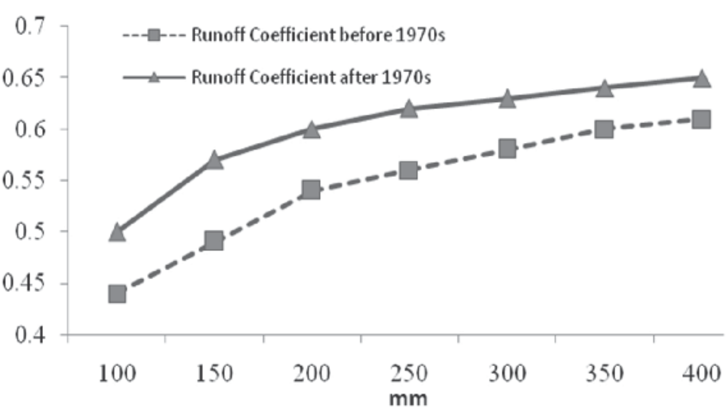

Fig. 7. Stormwater runoff coefficient in Beijing before and after 1970s

were constructed in Beijing. There was a constant increase in the total length of rainwater drainage pipes from 2999 km in 2001 to 4849 km in 2009 (see Fig.8).

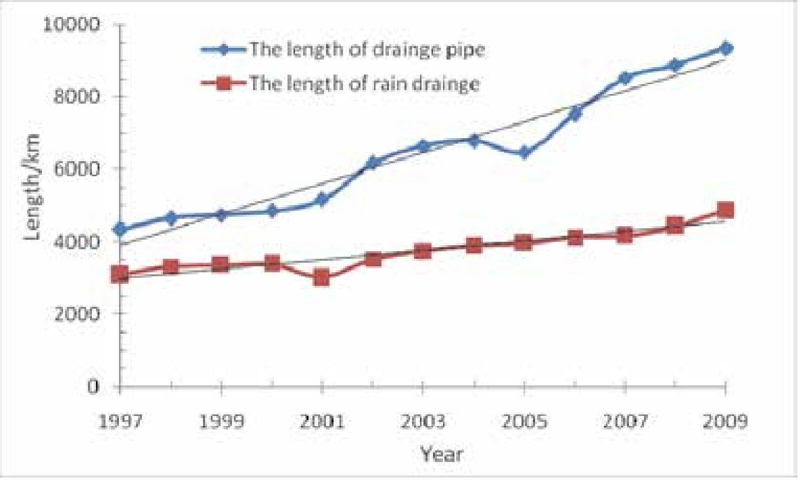

Fig. 8. Length of rain drainage pipes from 2001 to 2009 in Beijing

3.5 Beijing's policies of guaranteeing water supply

Nowadays, more and more people recognize that, water scarcity and conflict over supply has become a serious and common issue because of population growth, food needs and industrialization. Official responses to Beijing's drought and competing water demands attracts a lot of attention, and much effort is given (Probe International, 2008): (1) reallocate surface water from rural to urban consumers, (2) extract ever-deeper groundwater, (3) divert surface water to Beijing city from reservoirs and rivers outside Beijing municipality, (4) restrict water use in upstream Hebei, (5) Cut off river flow to downstream Tianjin, (6) shut down or relocate polluting and water-intensive industries. For example, the central government began arranging "emergency water transfers" from neighboring regions to Beijing city in 2003, of which is the massive South-North diversion project, which approved in 2001.

However, the construction of infrastructural projects to bring more and more water to the metropolitan area is neither sustainable, nor economically feasible, nor is it environmentally and socially desirable (Tortajada and Castelan, 2003). In a changing climate, the functionality provided by urban forest becomes increasing important. Especially the roles of forests in water supply (including quantity, quality, timing of release, flood reductions and low flow augmentation) should be given more attention. Maybe the creation and management of more urban forest is an answer to the recent calls for a more ecological and sustainable water management.

4. Beijing's forest and its roles in mitigating climate change and water crisis

In recent years, the forest area in Beijing has rapidly increased. According to the investigation data of Beijing Forestry Survey and Design Institute, the area of forest land grew by 20.2 % between 2000 and 2005, to a total of 105.4 million ha. The absolute annual expansion rates has increased to an average 20.8 thousand ha per year and relative rate grew somewhat to 4.04% over these five years (Zhang et al., 2010b). Based on the survey data of 2004, Beijing's forest ecosystem has a total area of 917 509 ha of which 14.95% is represented by coniferous forests, 42.59% by broadleaved forests and 7.42% by broadleaved-coniferous mixed forests, making a total forest area of 596 054 ha. The remaining 35.04% correspond to shrub forests. The dominant tree species include *Quercus dentasa*, *platycladus orientalis*, *pinus tabulaeformis*, *populus*, broadleaf tree, *robinia pseudoacacia, populus davidiana* , *betula platyphylla* and *Larix principis-rupprechtii*, which host a rich variety of other species of fauna and flora. The spatial distribution of forest resources in Beijing was showed in Figure 9.

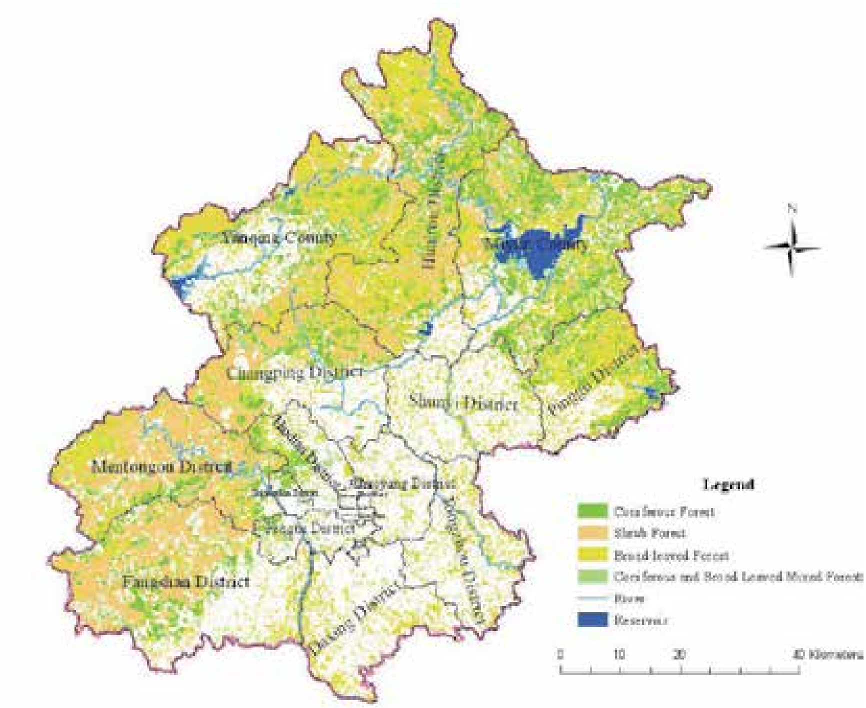

Fig. 9. Distribution of the forests in Beijing

Forest, one of the most important terrestrial ecosystems on the earth, provides fundamental services for human such as internal nutrient cycling, soil protection, biodiversity conservation, climatic regulation, and water supply (Nunez et al., 2006). Xie et al. (2010) estimated the magnitudes and economic values of the forest ecosystem services in Beijing at subplot level. The result showed that, the forests in Beijing supported a lot of ecosystem services to local and around communities, including primary products, water supply, gas regulation, hydrological regulation, environmental purification, soil formation and conservation, cropland protection, wind protection and sand fixation, biodiversity conservation, increasing employment, recreation, science and education. The economic value of forest ecosystem services in Beijing was estimated to be 19 billion RMB (Chinese Currency, 6.83 RMB=US$ 1) in 2004. In addition, the studies of Yu et al. (2002) and Wu et al. (2010) also reported that these ecosystem services to human welfare were much more important than what we had thought.

4.1 Water conservation

In the context of global climate change, the hydrological and meteorological role of forests has attracted much attention from the public (Bonell et al., 1993; Black et al., 1998; Vazken, 2004; Ian, 2007), and water supply provided an important argument for forest sustainable management and protection around the planet (Dudley and Stolton, 2003). In China, the term of water conservation often is described as a comprehensive regulation of forests on water resources through various hydrological processes, and grouped into three services, i.e., rainfall interception, soil water storage and fresh water provision.

Rainfall interception is the benefit provided by forests through reducing the risk of flood. In Beijing mountainous areas, the intensive rainfall events in rainy season often cause flood, debris flow and landslide. Forest ecosystem can intercept a proportion of rainfall by the plant canopy, forest floor and soil, to reduce the rainfall amount loaded on forest land in a short time, so that the occurrence possibilities of flood, debris flow, and storm related natural disasters can be reduced.

The results showed that, the maximum potential capacity of rainfall interception of the forest ecosystems in Beijing was approximately 1.43 billion cubic meters in 2004. And if all conditions were ideal, the forest canopies could intercept about 193.29 million cubic meters of rainfall, which accounting for 13.5% of total interception capacity; the forest litters could contain about 5.72 million cubic meters of water, only occupying 0.04% of total rainfall interception, and the forest soils could intercept rainfall nearly 1.23 billion cubic meters and constitute 86.1% of total interception capacity.

Soil water storage is one of the important regulating services provided by forests through maintaining constant soil moisture to reduce the impact of drought on agriculture and household livelihoods. Beijing has experienced a continuous low water period from 1999 to 2004 (Zhang, 2004), and suffered from enormous economic damage, which ultimately compromised its social and economic sustainable development. In forest ecosystems, the plant roots and microorganisms in the rizosphere increase soil porosity improving oxygen exchange and water retention capacity (Nunez et al, 2006). Consequently, forest soils can conserve a large amount of water in wet season, and slowly released them to maintain the proper soil moisture for the plants survival in dry season, and the service of soil water storage contributes to the effective utilization of water resource (Liu et al, 1996), and the drought risk reduction (Primack et al., 2001). It was estimated that nearly 278 million cubic meters of water could be stored in saturation state by the forest ecosystems of Beijing.

Fresh water provision is the benefit of freshwater resources, obtained from forests through 'filtering, retention and storage of water in, mainly, streams, lakes and aquifers' (de Groot et al., 2002). Forest ecosystems play an important role in helping to maintain water supply to major cities in the world, and a large amount of the water available for the world population as drinkable water comes from existing reserves in natural and artificial forests (Nunez et al., 2006). So the provision of fresh water contributes to the sustainable development of social economy and the relief of water crisis in Beijing. We estimated Beijing's forests provided about 287 million cubic meters of fresh water in 2004, corresponding to 27.8% of Beijing residents' water consumption (1.03 billion cubic meters) in the same year (Zhang et al., 2010b).

4.2 Water purification

Water quality would normally be expected to be good from forest. An exception may occur in high pollution climates where deposition rates of atmospheric pollutants may lead to catchment acidification and high nitrate concentrations in soil and groundwater (Calder, 2007). In urban environments, grassed areas are effective in removing sediment and nitrogen bound to the sediment (Deletic, 2005). Barrett et al. (1998) determined the reduction effect in suspended solid matter of two grassed strips alongside a highway to be 85%, and they found a 31–61% decrease in total phosphorus (P), total lead (Pb), and total nitrogen (N). Given continuous urban expansion and increased road use leading to more pollutants entering the stormwater system, this form of urban forest should be viewed as a valuable resource (Fam et al., 2008).

In China, a summary of several studies also reported that forest possess considerable adjusting and controlling ability over the non-point pollution (Lei, et al., 2000). Hillside forest can reduce 60% of solid pollutant and avoid the loss of nutrient up to 30-50%. Water temperature in the drainage area where the forest has been logged increases 0.2-0.4 ^{0}C, and the loss of N ranges from 4 $kg/hm^2 \cdot a$ to 142 $kg/hm^2 \cdot a$. Chen et al. (2002) found the buffering forest belts between farmlands and ditches can effectively stop and purify such elements as N and P in soil runoffs, thus controlling non-point source pollution of agricultural lands. Based on the investigation to water conservation forest and observation of surface water in Miyun county of Beijing, Li et al. (2004) reported that, the non-point source pollution caused by field fertilization had been reduced, which led muddy degree of surface water and the content of NH_4^+ to decline. The result showed the process of leaching, exchange, absorption, etc. between water conservation forest in valley of Miyun reservoir and precipitation can cleanse rainfall. In Beijing, the water quality in green areas also is superior to the runoff from roofs and roads (Hou et al., 2006), and it is often used as reclaimed water for green-land irrigation and vehicle washing. Since forests are key to clean water, the maintaining supplies of clean water and protecting watersheds are major reasons why public domain forests and rangelands should be reserved.

4.3 Microclimate regulation

The influence of urban forest on local microclimate is multidimensional and complex, including modification of solar radiation, wind speed, air temperature, relative humidity, and terrestrial re-radiation (Jim and Chen, 2009). In western countries, the public mainly focus on tree effects on cooling and heating energy saving at the local scale in low-density residential neighborhoods. In Chicago, an increase in tree cover by 10%, or planting about three trees per building lot, could reduce the total energy for heating and cooling by US$ 50-90 per dwelling unit per year (McPherson et al., 1997). Taha et al. (1997) found that urban trees could cool the city on the average by about 0.3-1.0 ^{0}C, and total annual energy savings could attain US$ 10-35/100 m^2 of roof area of residential and commercial buildings. The urban trees in Los Angeles could potentially save about US$ 93 million of energy use per year and could reduce peak power demand by 0.9 GW (Akbari, 2002).

However, Chinese cities usually focus on the evapotranspiration effect at the city level. Evapotranspiration process would significantly decrease the ambient air temperature, and raise the relative humidity in the vicinity of trees. Therefore, urban forests could produce an "oasis effect" to render the urban environment, specifically its bioclimatic conditions, more comfortable. Liu et al. (2008) testified the environmental effect of urban forest in Yuan-Da-Du Park in Beijing. They found that the tree-shrub-herbage mixture with higher coverage brought about a wider range of temperature and humidity effect, and had a greater effect on lowering temperature and increasing relative humidity, compared with lawn. Zhu et al. (2011) investigated six green belts with different width along the west fourth ring road of

Beijing and reported that, the temperature and relative humidity benefit increases as the width of green belts rise. The green belt of 6 m width has little effect on the decrease of temperature and unobvious effect on the increase of humidity. It has a comparatively obvious effect with the width of 16-27 m, and obvious effect with the width of 34 m; an extremely obvious and stable effect with the width of more than 40 m. Therefore, reasonable structure and composition of plant community could make the urban forest better exert their effects in decreasing temperature and increasing humidity in summer.

5. Conclusions

Based on the above analysis, the present situation of water resources in Beijing is severe. If nothing will be done, the sustainability of water resources in Beijing will face serious challenge, and more and more people will suffer water scarcity in the near future. However, climate change predictions that link reduced precipitation with increased storm intensity may have a smaller effect on water availability to forest ecosystems than reduced precipitation, which could help forests' survival and maintain productivity even under drier conditions (Yaseef et al., 2010).

Beijing's forests affect water quantity by intercepting precipitation, increasing water infiltration rates, and transpiring water, which can materially reduce the rate and volume of storm water runoff, flood damage, stormwater treatment costs, and other problems related to water quality. Therefore, the effectiveness of the forest ecosystem in Beijing with such roles on watershed management is definitely very essential. Nowadays, throughout the world there is increasing interest in land and water developments and policies in which forestry is a central focus. There is evidence that the forest in Beijing can help urban areas adapt to the impact of climate change, and policies should be used to encourage the optimal structure and composition of urban forest through ecosystem management strategies. Especially urban forest plans should be integrated with watershed assessments and with watershed recovery plans.

6. Acknowledgements

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Evaluations and Perceptions of the Climate Change in the State of Veracruz (Mexico): An Overview

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1. Introduction

The State of Veracruz (Mexico) is a strip of continent oriented from North-Norwest to South-Southeast on the Gulf of Mexico slope, with a surface area of 72815 km^2, and 7.5 million inhabitants. Its latitudinal width ranges between 46 km and 156 km. The Pico de Orizaba mountain (5747 m altitude), is located in the middle of the State and it is part of the mountain range that crosses Mexico from West to East around the 19°N parallel. This complex orography causes a very large spatial variability of climates and geographical configurations over this coastal State (figure 1).

The State is crossed by several rivers. The more important are, in the north, by the Panuco, Tuxpan, Cazones, Tecolutla and the Nautla rivers; in the center of the State the Actopan, La Antigua, and the Jamapa river, and down the south, the Papaloapan and the Coatzacoalcos rivers. All together, they transport 25% of the surface water that crosses over Mexico. The State also has some important lakes, such as the Tamiahua (880 km^2, on the north coast), the Lagoon of Alvarado (62 km^2, center-south at delta of Papaloapan river) and the fresh water Catemaco lake (75 km^2, south coast). The State has more than 750 square kilometers of coasts in front of the Gulf of Mexico, as well as a flat surface formed by the continental coastal flatland to the north, and another from the center to the south-center, and at center full of mountainous surfaces that go up to 5200 meters of altitude in less than 200 kilometers of width (see table 1), all of which exposes it to frequent disastrous weather phenomena. In the semester around winter, there are cold fronts with winds blowing at over 70 km/h for 35 days a year in average. This provokes temperature declines of more than 10°C within 24 hours; and in the summer, due to tropical flow, sometimes in the form of a storm, flooding occurs on the lower parts of the State as well as landslides (Tejeda et al. 1989)

Fig. 1. Main rivers and human settlements of the State of Veracruz.

Altitude (m)	Area (km2)	Percentage
0 to 200	52827	72.5
From 201 to 1000	13092	18.0
From 1001 to 2000	4988	6.9
From 2001 to 3000	1748	2.4
Over 3000	160	0.2

Table 1. Percentages of area corresponding to different altitude intervals for the State of Veracruz.

The years 2005 and 2010 have been especially upsetting. Four tropical storms affected the State in 2005, causing 1.5 million storm victims, 130 thousand affected houses, 170 road disruptions, but there were no human losses. Nevertheless, six years before, on October 1999, just one tropical storm, produced 200 thousand storm victims, 12 thousand affected houses, 20 road disruptions, and left 20 dead. The difference in deaths was because in 2005 a rudimentary but efficient early warning system was started.

2010 was a specially long and intense year regarding floods. For example, the city of Tlacotalpan (18.62°N, 95.66°W and 10 m above sea level), which is located on the riverside of the Papaloapan river -and considered cultural heritage of the humanity because of its XIX century architecture-, was flooded twice: the first time from August 28 to September 21 and the second time from September 28 to October 4. The level of the first flood was 2.7 meters above the river level and the second time 4 meters. Two hurricanes, Karl (September 17-18) and Mathew on the same month (September 26-27,) caused flooding on different parts of the State and losses for over five billion dollars - the State's budget in comparison is 7 billion dollars a year - and 20 deaths, but the for the entire State within the rainy season, there were 130 deaths accumulated in the year 2010.

In summary, the demographic growth –the State increased from 6.3 million inhabitants in 1990 to 7.6 million inhabitants in 2010–, the human settlements located in flood areas, and a policy lacking in preventive measures for disasters that only tends to emergencies, make this territory a laboratory for involuntary risks, increased by the ignorance of the patterns of atmospheric circulation at mesoscale and teleconnections as the main causes of climate variability, and of course adding the global warming.

And, by the way, Mexico emits approximately 2% of the world's green house effect gases. Of this percentage, because Veracruz produces oil, it emits 10%.

A first view of the complexity of this problem can be shown on the schematics of figure 2. What it expresses is that from an entirely atmospheric point of view (X axis) it is necessary to understand at least three moments: the meteorological moment, that allows for the realization of more or less accurate climate forecasts on a short term, the climate variability for the medium term (months) and the generation of climate change scenarios. And Y axis, the socio-environmental moment, requires a historical revision of the disasters and future

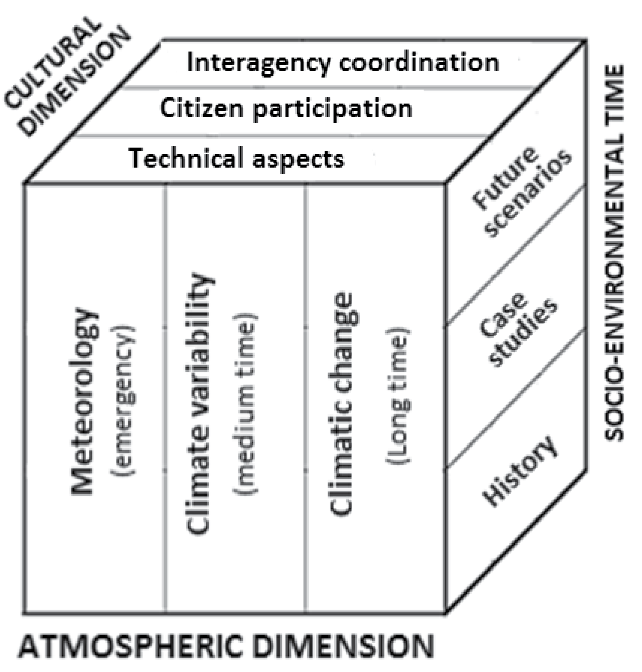


Fig. 2. Fundamental coordinates in the atmospheric, socio-environmental and cultural dimensions of the hydrometeorological phenomena.

projections, together with the study of special cases such as the ones mentioned in the years 1999, 2005 and 2010, for example.

Finally, what could be called the cultural dimension, must come from a solid technical knowledge regarding atmospheric aspects (climate and meteorological of a medium term), as well as the socio-environmental history, the most important cases and future projections. But this knowledge will be useless unless it corresponds to an inter-institutional coordination, which won't exist unless there is a highly participative society that forces the decision-makers to come into action.

This chapter will present a revision about the atmospheric teleconnections and their link to the local climate variability, as well as the evidence of the climate change and the tendencies of precipitation and temperature. Besides, some scenarios of the sea level rising will be commented on, plus the results of the perception of climate change poll in the two main urban centers in the State, and finally there will be a synopsis on an action plan to deal with the climate change.

2. Climate change and variability

The change over time of the atmospheric conditions is called climate variability, which has always existed as a product of the climate-ocean-continent interaction. In the process of understanding the climate at a regional scale (e.g.: the State of Veracruz) it is helpful to study the climate signals separately from the anthropogenic climate change.

Climate variability and change tests over the State will be presented to show that natural variability has a small relationship with atmospheric oscillations: El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO). Regional climate change signals were evaluated using the methodology proposed by the Expert Team on Climate Change Detection and Indexes (ETCCDI). The results show evidence of warmer conditions in recent years, with an increased frequency of hot days and a decrease on cool days. Although extreme precipitation indexes present non-significant changes on annual basis, a tendency of temporal concentration of rainfall was found.

The variability of precipitation in Mexico is in a good measure modulated by the El Niño/South Oscillation, ENSO (Seager et al., 2009). In the positive phase of El Niño phenomena, there are humid conditions during winter in all the Mexican territory, whereas during the summer, conditions are dry in the north and humid in the south. According to Magaña et al. (1998), winter rainfall intensifies during El Niño in the northwest and northeast of Mexico, but they decrease in the south. The El Niño winters are colder in almost all the country and the summers are warmer.

2.1 Data

In order to analyze the teleconnections between the atmospheric oscillations and the local precipitation variability, PDO index was used, which are available in the Washington University (http://jisao.washington.edu/pdo/PDO.latest); the optimum interpolated by Reynolds ocean surface temperatures and the index for the North Atlantic sea were obtained from the Unit of Investigation of the Climate of the United Kingdom (http://www.cru.uea.ac.uk/cru/data/nao.htm). The indexes of ENSO were obtained from the Hadley Center, also in the UK, through the British Centor of Atmospheric Data (http://badc.nerc.ac.uk/data/hadisst/). A common period was chosen for all the data between January of 1950 and December of 2001.

The daily data of maximum and minimum temperature and precipitation for the analysis of the changes in extreme climates were provided by the Mexican National Meteorological Service (2008) during the "Workshop on detection and indexes of climate change in the Mexican Republic", which was had on March 2009 in the city of Puebla, Mexico. Some series of data were updated with information provided by the *Organismo Cuenca Centro de la Comision Nacional del Agua*, and data by the observatory of the city of Veracruz were included.

The selection of these time series was made on the basis of the methodology proposed by the ETCCDI, using the RClimDex software as an auxiliary in the process of quality control, and the application of the information of the local climate in order to evaluate the extreme data marked as suspicious in the series. The sources consulted for the revision of the outliers and other mistakes were the printed meteorological bulletins, the climate dates for the main cold fronts, historical records of tropical storms, the directly registered observations on paper or the records from the previous and later days to the date analyzed.

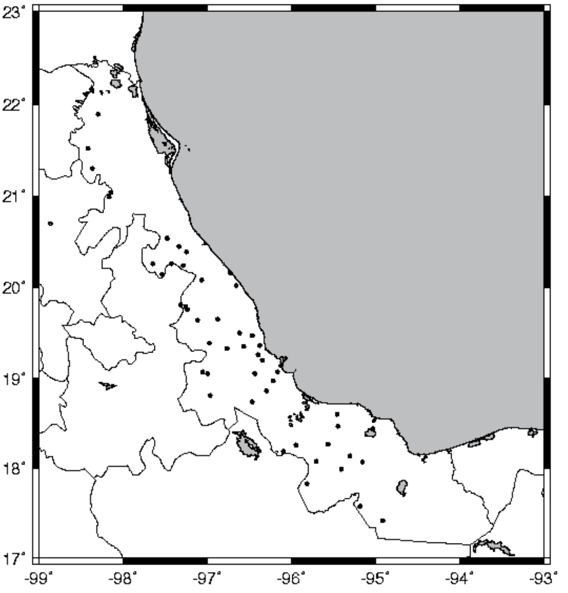
For each time series, a homogeneity test was performed with the software RHtesV2 developed by Wang and Yang (2007). It uses a regression in two phases in order to identify the changes of a median in the temperature data of the series of time intervals from each season.

From the quality control process and the homogeneity test, 50 series of precipitation and 30 of temperature were chosen because they were reasonably homogenous, they didn't have major mistakes, and they also had more than 90% of the data observed during the time period of 1963-2005. The climate stations cover geographically most of the State of Veracruz, with the exception of the northeast portion (21.0°-22.5°N y 97°-98°W) and the south of the State (17.0°-17.5°N y 94.0°- 95.0°W). See figure 3.

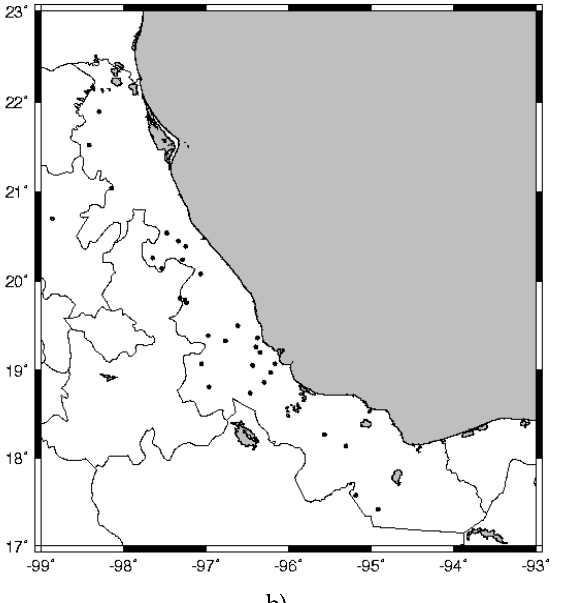
In summary, the State's series of maximum and minimum temperature were homogenized with the method used by Spaniard series (BRUNET et al., 2008), which are based on the Homogeneity Normal Standard test (SNHT; Alexanderson and Moberg, 1997), that detects the change points in the data, and establishes a pattern of correction, estimating the monthly adjustment of the series.

The series of time intervals allowed evaluating 24 climate change indexes proposed by the ETCCDI. The RClimDex software was applied for it. These indexes evaluate the diverse aspects of climate change such as intensity, frequency and duration of temperature and rainfall extreme events, duration of hot, cold, dry, gusts, maximum and minimum temperature during all the year, the number of very cold or very warm days, etcetera (Alexander et al., 2006). In this chapter important results will be shown, but for more details it is recommended that Torres-Alavez et al. (2010) be consulted.

The Gini index was used additionally in order to quantify the yearly variation in the concentration of rainfall (Martin-Vide, 2004) in 14 climate stations located in the State of Veracruz, which had continuous and good quality data from 1963 to 2005. This last index was compared to the simple index of daily intensity proposed by the ETCCDI, resulting in a quotient obtained by dividing the total annual rainfall between the number of days of rainfall.



a)



b)

Fig. 3. Geographical location of the climate stations used for the analysis of a) precipitation and b) temperature.

2.2 Correlations and trends

There were no important correlations found between the rainfall and the oscillation indexes. The only remarkable information was that the monthly accumulated rainfall reached its maximum correlation (0.14) with a ten month gap to the previous PDO.

When analyzing the relationships with the ENSO, it was found that the years in which El Niño happens are drier than those in which the conditions of La Niña present themselves, with a 0.05 statistical significance. The mid-summer drought (*canicula*) is the relative decrease of rainfall that occurs in the middle of the rainy season; its intensity is calculated as a deficit of the percentage of rainfall, relative to an ideal period with only a maximum of rainfall (Mosiño and García, 1966). It was found that approximately 16% can be explained as a relationship to the variations to the oscillations of the North Atlantic, while 9% can be explained as a relationship to ENSO.

When correlating the index of mid-summer drought with the annual medium of the indexes of the oscillations, it is concluded that El Niño (3.4) and the NAO of the Azores are the most highly correlated with respective values of 0.31 and 0.4 (the variation explained is of 9% and 16% respectively). In the case of the PDO and the AO, the correlation is imperceptible.

Regional series of maximum and minimum temperatures were generated for all the State, in which it is shown for both variables that there is a positive tendency starting from 1990 (figure 3). For the maximum temperature, the change in the linear tendency is 1.3°C along 1996-2005 decade, while the minimum temperature presents a change of 0.4 in the same period.

In the case of indexes for cold days, warm days and cold nights, the results agree with the results found by Vasquez-Aguirre et al., (2008). In many of the analyzed climate stations there is significant evidence of an increase in the happenings of hot spells (43% of the climate stations in figure 3a), and of the increase of the minimum extreme temperatures (50% of the climate stations in figure 3b).

The annual happenings of the hot spells (it is defined as when the hot temperature is over the 90 percentile for six consecutive days), as well as the minimum temperature show a significant increase in the entire region (figures 4a and 4b).

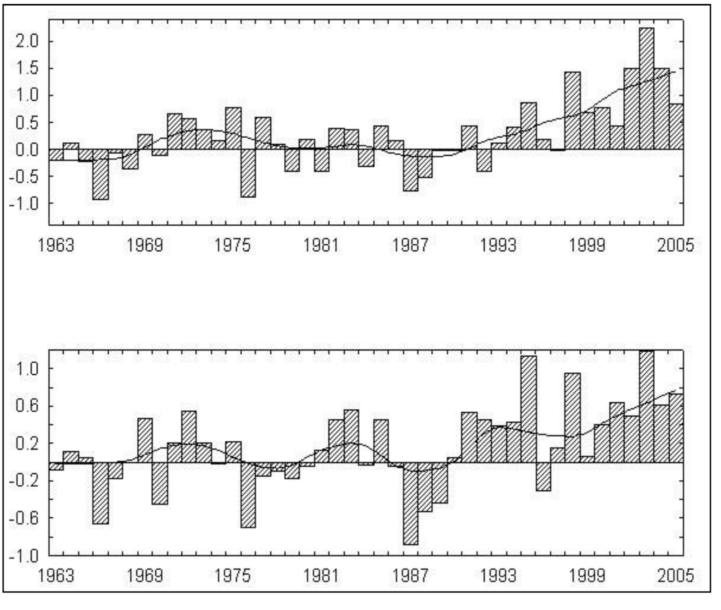


Fig. 4. Annual anomalies (1963-2005) of maximum temperatures (up) and minimum temperatures (below), of the base period 1963-1992 in °C.

Significant changes were observed in neither the total annual rainfall nor in the intense rainfall, although they were in the distribution of the time of rainfall, in which the number of consecutive humid days is reduced, while the dry spells show a slight increase (figure 5).

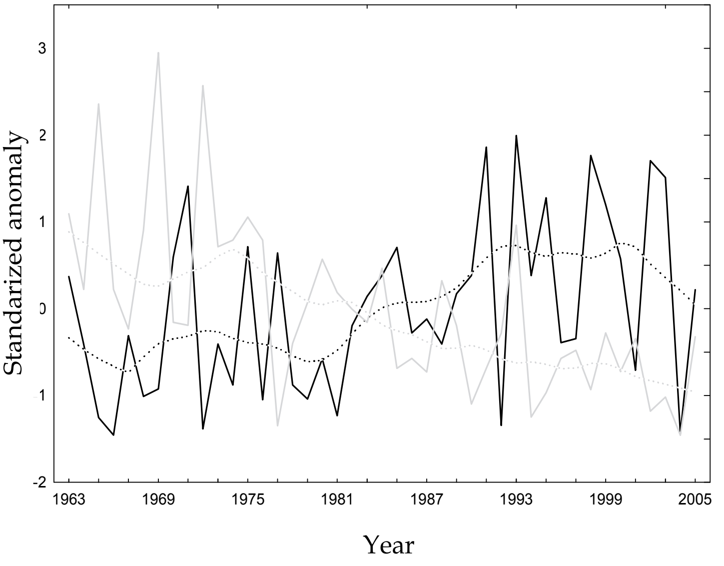


Fig. 5. Standard anomaly of consecutive humid days (continuous gray line) and dry consecutive days (continuous black line), both softened with a lowess (dotted lines).

The daily simple index (SDII) resulted in a cero tendency, due to both the rainfall and the number of decrease in rainfall days, while the Gini index showed a slight negative tendency (figure 6).

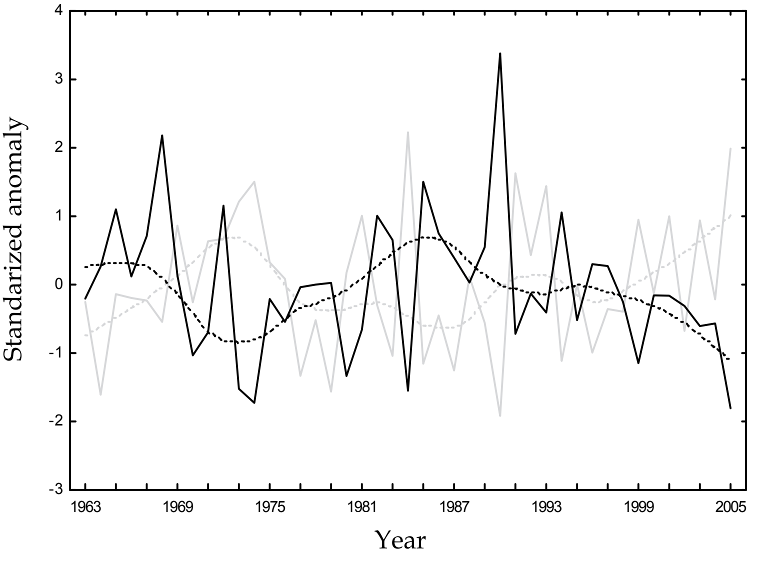


Fig. 6. Standard anomaly of the SDII (continuous gray line) and the Gini index (continuous black line), both softened by a lowess (dotted lines).

3. Sea level scenarios

On other side, climate change scenarios (temperature increases and rainfall modifications) for the rest of the century Veracruz State are similar to other tropical regions. The ocean level rise will be analyzed in order to prevent impacts on coastal towns and increase of the risk by flooding of rivers because 35% of the surface water of Mexico crosses through Veracruz State, mainly by five large enough rivers to flood 60% of land and towns with 3 millions of people.

The rise of the sea level represents a threat to the coastal settlements of Veracruz. The scenarios based on different numerical models indicate a sea level increase of 59 centimeters for 2100 (IPCC 4th Assessment Report, 2007) up until dozens of meters should Greenland's and the poles' ices melt. An exercise was performed calculating a scenario of a sea level increase from one to two meters for the coasts of Veracruz. 15 houses with 58 inhabitants would be permanently flooded. But what is more disturbing is the latent danger of a similar flood to the one that occurred in Louisiana, US with maximum registered rises of 8.5 meters with hurricane Katrina. This last situation, added to the two meters of the exercise performed in the climate change scenario (10-5 meters) shows a danger of flooding of 327 thousand houses (1.3 million people).

At the end of 2010 there was a State government change. The floods and the political campaigns for elections that year alongside with a propaganda overspending, left the government with a 3 billion dollar debt, with an annual budget of 7 billion dollars. Therefore the new government is pushing for an economic reactivation based mostly on beach tourism, which requires a minimal infrastructure investment.

Among the main touristic beaches of the State are Costa Esmeralda (figure 7), which is located 50 kilometers south of Poza Rica and north of Nautla; the Cazones, Tuxpan, and Tecolutla beaches are at the north of Costa Esmeralda; Palma Sola, La Mancha, and Lechugillas beaches are at center; Villa Rica and Mocambo beaches between Veracruz and Boca del Rio cities (Veracruz-BR, henceforth); Playa Escondida Beach at a side of Catemaco Lake and the zone of Coatzacoalcos city, among others. Next, some information will be presented to illustrate the potential vulnerability of the touristic zone. [1,2]

Even though these beaches cannot be considered to attract great numbers of tourism, they have an important infrastructure. For example, alongside Costa Esmeralda, there is an important hotel industry of categories ranging from 5 star hotels to economy, including camping sites as well as trailer-parks. The municipality of Tecolulta (22872 permanent inhabitants) had in December 2008 36 restaurants and one museum; 126 hotel businesses of which 89 are hotels, 25 are bed and breakfasts, 6 businesses are cabins and 6 trailer-parks, all of which have a total of 2164 hotel rooms, 248 house guest rooms and 114 cabins. Of the 126 hotels, one is a five star hotel, 11 are 4 star hotels, 27 are 3 star, 33 are two star, 13 are one star, and 41 have no category. Costa Esmeralda -located on the road that runs through Casitas, Monte Gordo, La Vigeta, Flores Magon and La Guadalupe towns, none of which is bigger than 3000 permanent inhabitants (figure 8)- count with 38 hotels that add up to more than 900 rooms.

The metropolitan area Veracruz-BR has an approximate population of 600 thousand inhabitants. The most important commercial port is found in the city of Veracruz (figure 8)

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[1] Tecolutla, http://www.tecolutla.gob.mx/ (Accessed August 2010)
[2] Totonacapan, www.totonacapan.com.mx/ (Accessed August 2010)

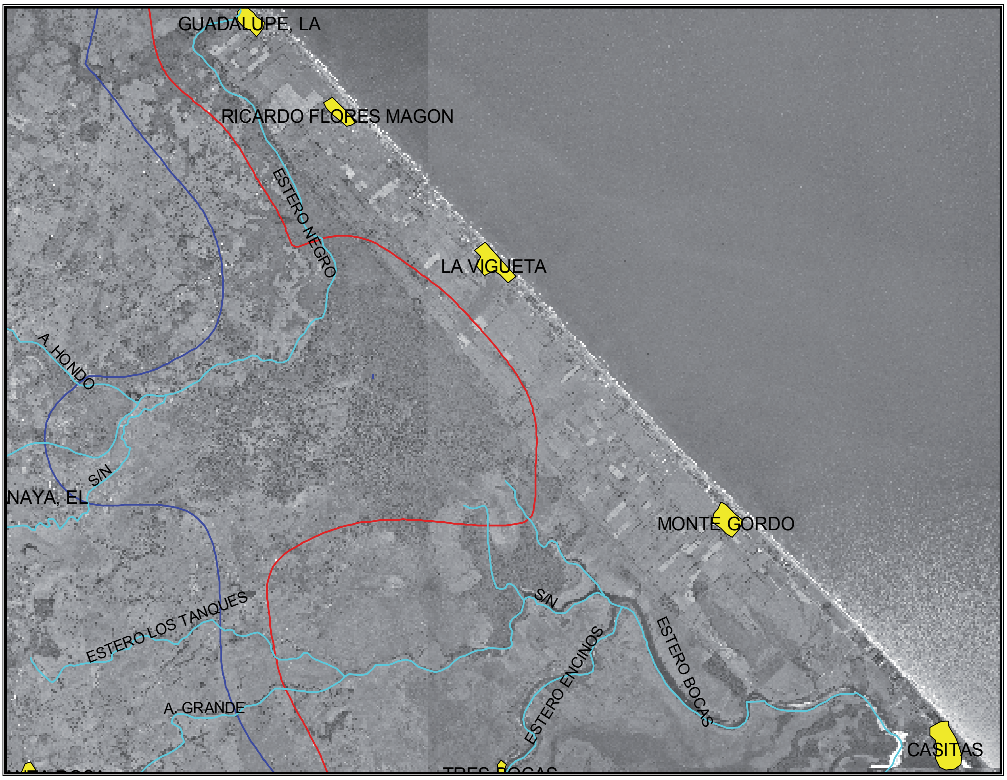

Fig. 7. The Zone of Costa Esmeralda, the red isoline is 7 meters above sealevel, the blue isoline is 11 meters above sea level, and the clear blue shows the rivers.

and the hotel infrastructure has 139 places of which 106 are hotels, 24 are motels, 6 are bed and breakfasts, there is an area of cabins and there are 3 suite complexes, all of which represent a total of 6037 rooms and/or hotel units. Of these, 5 are five stars hotels, 13 are two stars, 24 are three stars, 41 are two, and 14 don't have a category[3].

Regarding Boca del Rio (figure 9), its names comes from the shape of the Jamapa river when it flows into the Gulf of Mexico. The infrastructure of the hotel businesses is made up of 6 five star hotels, 23 four star hotels, 10 three star hotels, 15 two star hotels, 3 one star hotels and 5 without category, all of which give a total of 3215 rooms, plus bed and breakfasts and cabins; there are 10 suite complexes and a trailer-park. So, all the metropolitan area Veracruz-BR has an availability of approximately 10000 hotel rooms, that is, 17000 beds.

[3] State tourism information in www.inegi.org.mx/prod_serv/contenidos/espanol/biblioteca/Default.asp?accion=15&upc=702825159900 (Accessed August 2010)

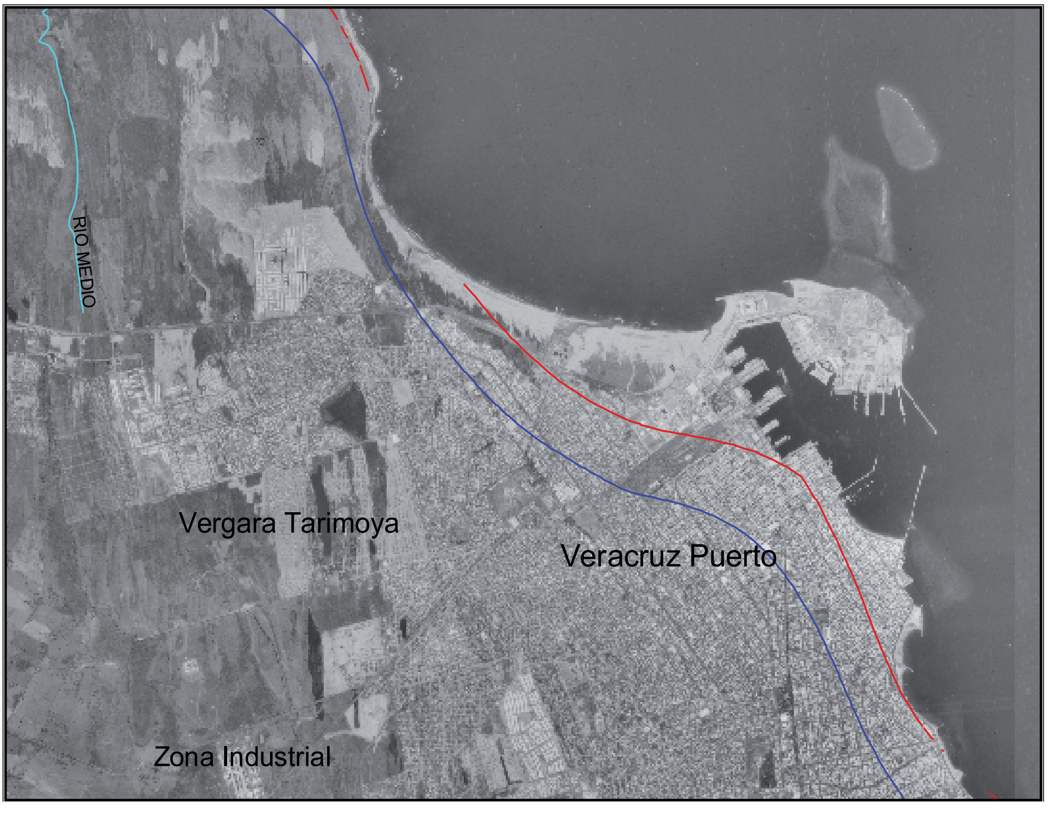

Fig. 8. The port of Veracruz, the red isoline is 7 meters above medium sealevel, the blue isoline is 11 meters and the light blue line shows the rivers.

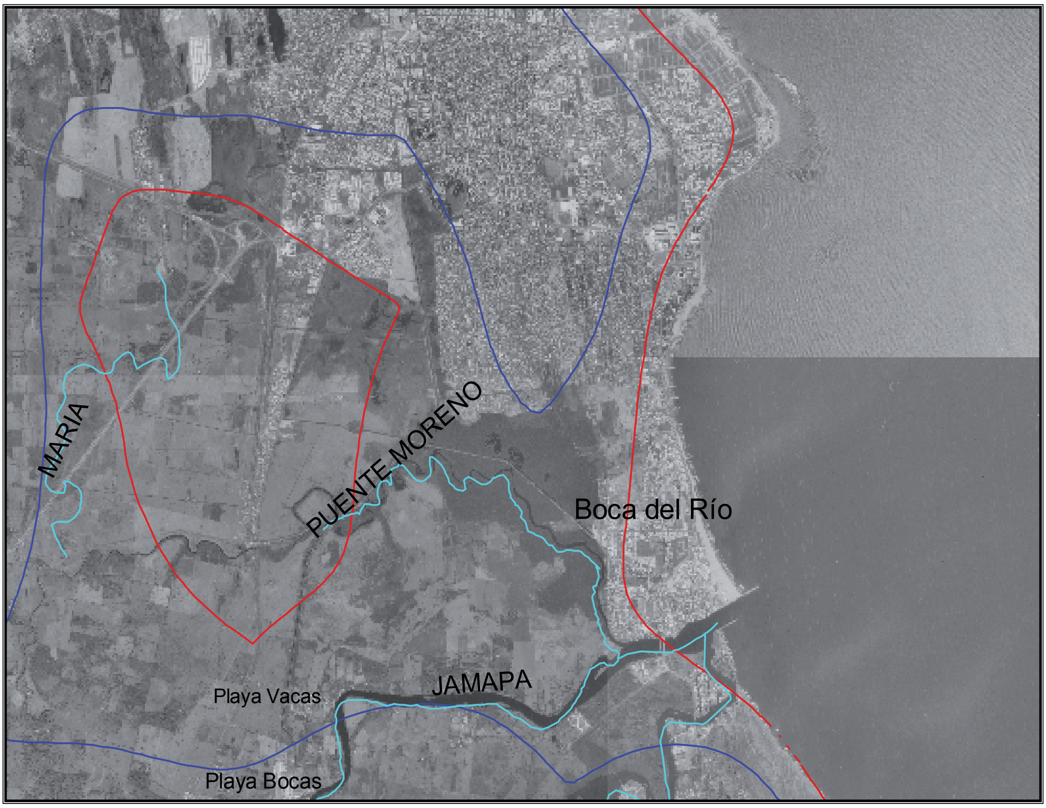

Fig. 9. Boca del Rio, the red isoline is 7 meters above medium sea level, the blue isoline is 11 meters and the light blue line shows the rivers.

3.1 Sea level scenario

By using the topographical information of the National Geophysical Data Center (NGDC) and the National Oceanic and Atmospheric Administration (NOAA), a global elevation model (ETOPO 1[4]) was applied to a grid of one minute latitude by one of longitude for the topography as well as for the bathymetry. It was interpolated using the Kriging geo-statistic method, which is appropriate when a spatially correlated distance or directional tendency of the data is known. This is frequently used in soil science and geology.

[4] ETOPO, http://www.ngdc.noaa.gov/mgg/global/global.html (Accessed August 2010)

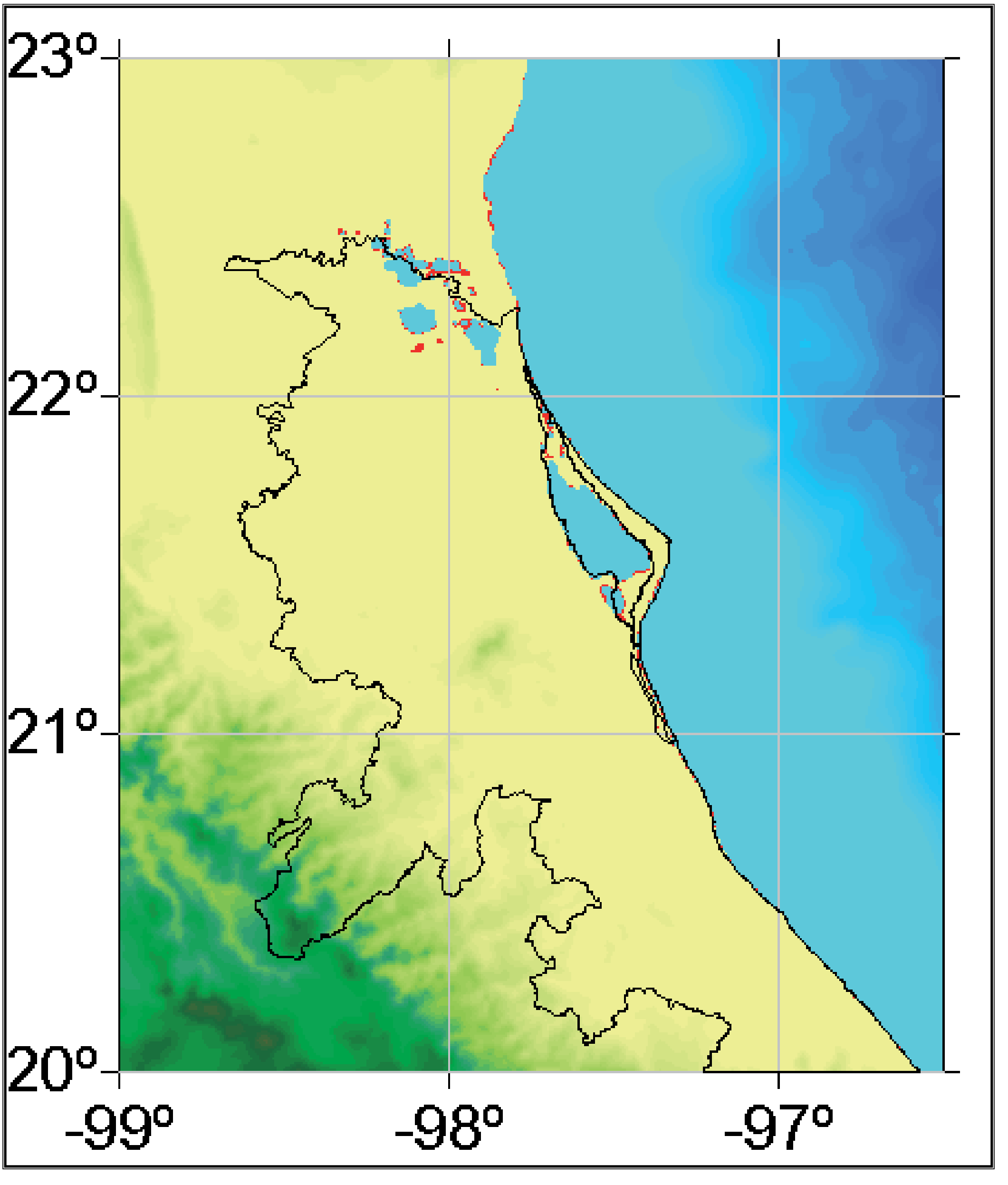

Fig. 10. The areas in red are those that would be flooded when the sea level increases one meter.

The coastal territories will be exposed to impacts due to the increase in the sea level, but mostly because of the higher exposure to extreme meteorological phenomena which will have the higher sea level as a platform to go deeper into mainland, settlements and infrastructure.

A scenario of sea level a rise for the State of Veracruz was calculated by one meter (figure 10) and by two meters (figure 11). The zones the most danger of being flooded were located, according to information from the National Institute of Statistics and Geography (INEGI[5]) stored in an IRIS hard drive version 4 of the year 2005 (IRIS V 4.0.1)

3.2 Potential risks

The data from INEGI 2005 shows seven settlements in danger of permanent flooding by the two meter sea level increase, because of global warming (figure 11). With a total of 76 inhabitants and 22 houses, these towns are called, Playa Palma Sola, Punta Delgada, Burgos, Playa Miranda, Puente Casitas, El Cristo and Rancho Los Cerritos (table 2). In figures 10 and 11, the red spots that are further south, go into the mouth of river Papaloapan; the population living in that strip of land within two meters over sea level is scarce, but the potential risks increase when considering a storm surge. Of course, if the risk of the extreme case of nine meters is considered, the red spot increases much more (figure 12).

Settlement	Local government	Latitude (°N)	Longitude (°W)	Altitude (masl)	Population (thousands)
Playa Palma Sola	Alto Lucero	19.8	96.4	2	11
Punta Delgada	Alto Lucero	19.9	96.5	2	5
Burbos	La Antigua	19.5	96.3	0	5
Playa Miranda	La Antigua	19.4	96.3	2	25
Puente Casitas	San Rafael	20.2	96.8	2	7
El Cristo	Tecolutla	20.5	97.0	0	20
Rancho los Cerritos	Tuxpan	20.9	97.3	1	3
					76

Table 2. Settlements in potential danger due to 2 m sea level increase (INEGI 2005).

It must be taken into consideration that the biggest danger of flooding in the coastal zones of Veracruz is for the effect of a storm surge, especially by tropical storms and hurricanes. Up until now, in the Gulf of Mexico coast the biggest flooding was caused by Katrina, a level 3 hurricane that by entering Buras, Louisiana on the 29th of August of 2005, into the Mississippi delta, it raised the sea level to 8.5 meters; and Camille, a level 5 hurricane that upon entry to the Bay of Saint Louis on the 17th of August of 1969, also into the Mississippi delta, it generated a 7.5 high tide.

The settlements in danger of flooding by storm surge or hurricane are found at a height of less than 8.5 meters. If 2 meters of sea level are added, the danger zone at the end of the 21st century is of 10.5 meters or less above sea level. In figure 13, the level curves for 9, 10, and 11 meters show the vulnerability of the river basins for the rivers, Panuco, Papaloapan and Coatzacoalcos. In the case of the coastal flooding of 11 meters, the number of people in

[5] www.inegi.org.mx

danger is 1.3 million with 327000 houses, because this includes the metropolitan area Veracruz-BR.

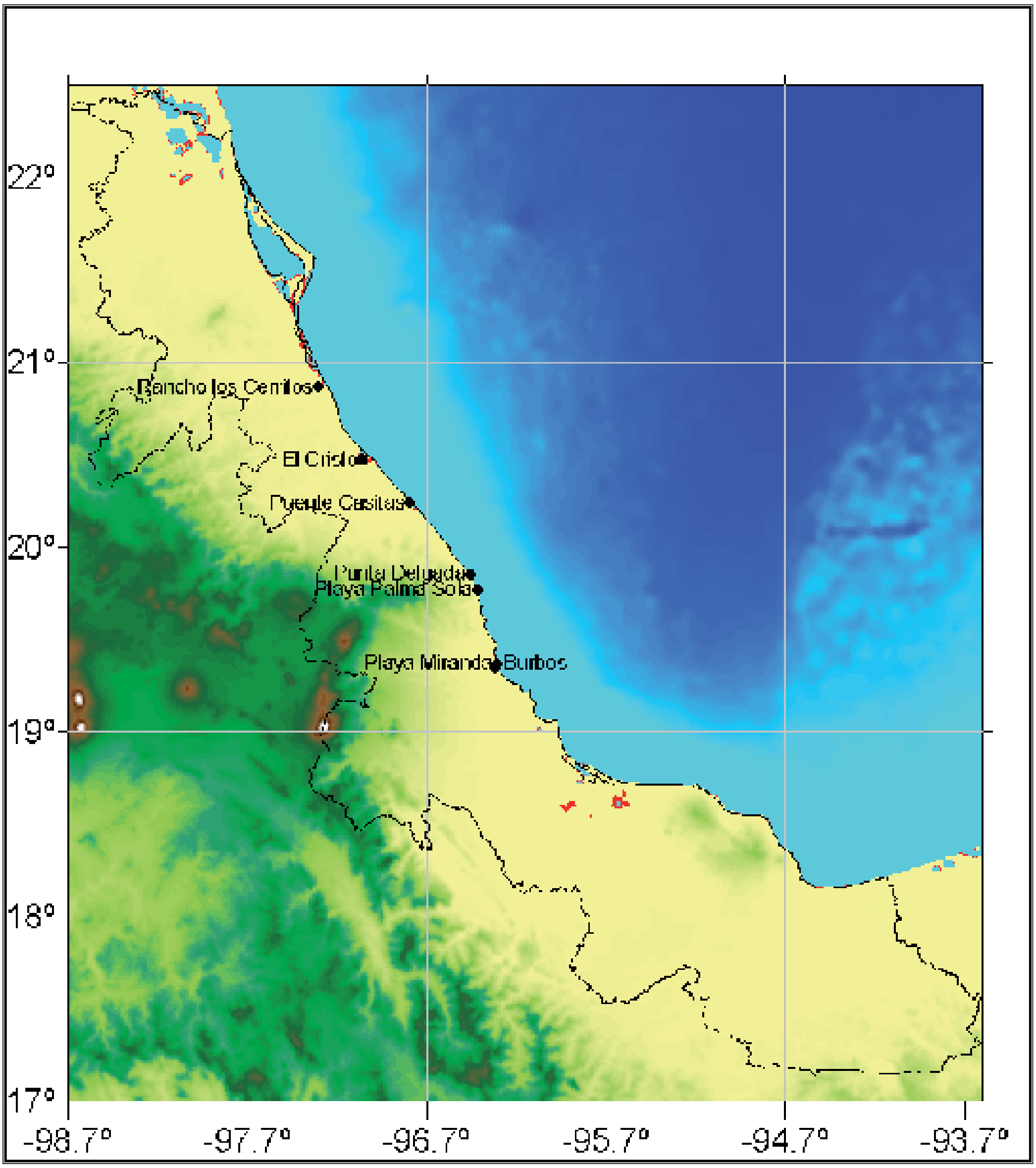

Fig. 11. The zones in red are at two meters or less above sea level. The black dots indicate the settlements that are located two meters or less below the sea level.

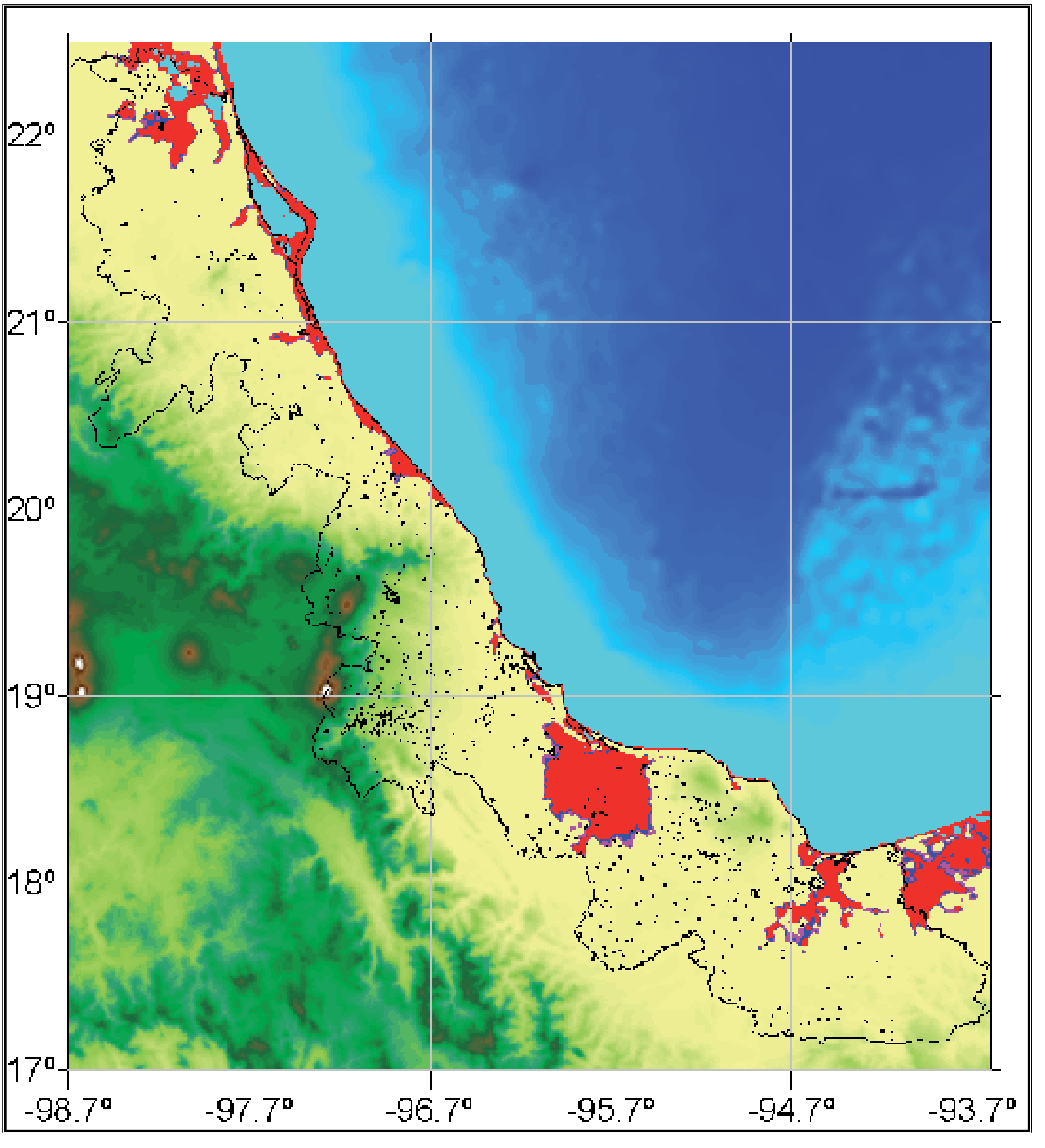

Fig. 12. The zones with a high level over the average sea level of less than 9 meters are in red. The blue zone is the 9-10 meters and the magenta is the 10-11 meters.

4. Climate change perception

The perception of climate change in the urban population is confused, according to polls applied during November 2010 in the capital of the State (Xalapa, altitude 1300 m) and the important marine port of Veracruz City, which total 1.1 million inhabitants.
The study of the public perception of the climate changes has developed significantly in the last two decades (Immerwaher, 1999; Bord, *et al.*, 1998, Brechin, 2003, Leiserowitz, 2006). It has been possible to establish some recurring trends in different studied contexts (Lorenzoni

and Pidgeon, 2006), such as the existence of a high concern for environmental issues and climate change, although climate change is considered less important than other personal and social problems (Dunlap *et al*., 1993; Bord *et al*., 1998; Immerwahr, 1999; Brechin, 2003; Norton y Leaman, 2004). Leiserowitz (2006) expressed about the American public, "despite the high concern about climate change, it is not perceived as an urgent challenge that can involve changes in its priorities and spending habits, but a problem that can be resolved by other actors." Stoll-Kleeman *et al*. (2001) have highlighted the difficulties of understanding that climate change poses to the public, due to the nature of the problem; and other studies State that the perception of climate change is a problem without solution (Immerwahr, 1999; Norton y Leaman, 2004), whose origin are very general issues such as human greed, which turn feelings into a lack of effectiveness of personal action. Thus, the combination of high concern with low awareness and personal effectiveness can lead to frustration and disinterest in the citizen (Immerwhar, 1999), as it will be seen with the populations surveyed in the conurbations of Xalapa (19.51°N, 96.9°W and 1400 masl), capital of the State of Veracruz, and Veracruz-BR (19.16°N, 96.14°W y 20 masl).

On the other hand, the study of images that people associated with climate change shows little connection with everyday life (Leiserowitz, 2005). Most people tend to associate climate change with distant phenomena such as the melting of icecaps, increases in temperature or different environmental problems, but it is rarely associated with aspects of everyday life.

Under these assumptions, the perceptions and attitudes of people in major urban centers are analyzed (Xalapa y Veracruz-BR; with 500 thousand and 600 thousand inhabitants) as not being expert of climate change; perceived risk, associated images, and self-efficacy to cope with climate change, among perceptions. Citizens play an important double role in climate change (Moser, 2006). On the first place, as actors involved in politics of climate change, because they can mobilize themselves to reach government policies, and in second place, individuals are resource consumers, for which reason they can initiate changes in the behaviors –favorable—to the reduction of them as well as adapting to change.

4.1 The pool

The survey was aimed at people over 18 living in both conurbations. To know the number of people to be interviewed, the methodology of the simple random sampling design for estimating a proportion was used. For the calculation of each sample, an error of 4% was considered and a 95% confidence level in the estimation of a dichotomized proportion. The calculated sample for the Veracruz-BR conurbation was 394, and for Xalapa, 384 questionnaires.

The sample was distributed in different Basic Geostatistics Areas (AGEB'S) of the cities into very high /high, medium and low/very low degrees of marginalization. For the location of the field researchers (IC) in the AGEB'S, maps were made with the program IRIS-SCINCE for each IC. The pool was conducted in electronic tablets-minimizing transcription errors-on November 13 and 14 of 2010, with trained IC in the areas of public opinion, statistics, and in the management and transfer of computer files.

The composition of the sample by gender was 54% women and 46% men in Xalapa, against 52% and 48% in Veracruz-BR. The age of the population shown in Xalapa was 43% between 18 and 34 years, 48% from 35 to 64, and 9% for over 65 (in Veracruz-BR the percentages were 40%, 48% y 12%). In the first city, schooling is divided into thirds between 1) primary and

secondary, 2) high school and 3) undergraduate and graduate school, while for Veracruz-BR it was divided into 28%, 36% and 21% with 5% non-response. Housewives, students and self-employed, each had with 20% in Xalapa, while employees have accumulated 34% and 6% unemployed. In Veracruz-BR proportions were covered by 22% housewives, 10% students, 22% of self-employed, 34% of employed and 12 unemployed.
It can see there are a variety of ages, education and occupations that allow us to infer that the survey responses are approximately valid for the respective cities.

4.2 Opinions of the citizens

According to the survey the most worrying problems were insecurity and drug trafficking (21% in Xalapa, Veracruz 18%), poverty (19% and 22% respectively), education and health (18% and 13%), unemployment (17% and 24%) and several others were about 16% for both cities. Climate change was noted in fifth place with 10% of the priorities in Xalapa and 6% in Veracruz-BR.
With regard to the opinion of the environmental problems that require further attention, water scarcity, water pollution, air pollution and climate change, each has a 15% in Xalapa, followed by the depletion of natural resources with 11% and the rest (29%) in many others.
In Veracruz-BR, air pollution is the biggest with 22% on concerns of respondents, followed by water pollution (15%), scarcity of water (12%), depletion of natural resources (11%), several other (34%) and climate change only reached 6%.
In Xalapa 85% agree that there is climate change, 9% do not and 6% do not know. In Veracruz-BR percentages are different, 73%, 23% and 4%. However, only 68% of respondents in Xalapa agree that climate change is already happening in the city (but it is 75% in Veracruz), which will occur over a period of one to ten years estimated at 16% in Xalapa 11% in Veracruz-BR, and that no claims will occur on 16% and 14% respectively. But there is near unanimity in both cities in terms of climate change affecting the family, community and country (80% to 85%) and that it will affect future generations (92%).
The main impacts identified in Veracruz-BR, are the recent floods (which occurred one month before the implementation of the survey), with 38%, higher temperatures by 20% and extreme atmospheric phenomena by 17%. In Xalapa these percentages are very different: 14%, 14% and 27%. Take into account that the annual average temperature in Vercruz-BR is 25°C (average relative humidity of 78%, with 120 rainy days/year totaling 1500 mm of precipitation) and for Xalapa it is 19°C (humidity on average 70%, 170 days and 1500 mm of rainfall per year).
What are the causes of climate change? Both in Xalapa and Veracruz-BR 75% of respondents pointed to air pollution, greenhouse gases, fossil fuel use and livestock, that is, more or less the causes identified by the experts, but 25% accused the ozone hole, the use of sprays and toxic waste. 6% at both sites defines climate change as the deterioration of the ozone layer and 7% didn't define it in Veracruz-BR and 2% did not in Xalapa.
Of course it is expected that about 90% of respondents agree that urgent measures and plans to face the phenomenon are needed, and they themselves say they are willing to change their habits to mitigate it. 44% in both surveys view that the sector that must take greater measures is the citizenry, the government is reported by 33% in Xalapa and 40% in Veracruz-BR, while corporate responsibilities are assigned by 23 % in the first and 16% in the second city.
The responses of the type of transport used by respondents do not reflect environmental awareness, but on the other hand the socio-economic, climatic and the urban circumstances,

do (Xalapa is warm Veracruz-BR is hot). In both cities, 60% use public transport; 26% and 37% own a car, in Xalapa and Veracruz, while in the first 14% say they favor walking and bike use, and only 3% Veracruz.

The television is the main source of information about the phenomenon in both Xalapa and Veracruz-BR (56% and 61%), followed by internet (13% in both), radio (9% and 13% respectively), newspapers (8% in both), family and friends reported by 8% and 3%, while the school only 6% and 2% in Xalapa and Veracruz-BR.

5. Concluding remarks and the Veracruz program for climate change

The variability of rainfall in the State of Veracruz is significantly modulated by the ENSO. During the years of El Niño, drier conditions prevail over the years than those of La Niña. The influence of the PDO is presented with a time lag of 10 months, but it has a very small relative influence of ENSO. For its part, the AO and NAO oscillations do not show a significant impact on the weather of the region.

The analyzed climate change indices corroborate the evidence of trend to warmer conditions in recent years in the State, an increased frequency of hot days and decrease in cool days. In precipitation no significant changes are seen, both in the annual rate as in the occurrence of extreme events, but a temporary increase in the concentration of this variable is noticed in most of the State.

Like other coastal cities in the world threatened by rising sea levels, measures to increase the resilience of the population and infrastructure in areas at risk should be taken, as well as the handling of financial security to adapt the building regulations housing to new changes in climate and extreme weather events. Modernizing water systems in these cities is imperative. Any amount of budget allocated to these adjustments will reduce the amounts paid, for example, by insurance companies in Cancun, Hurricane Gilbert, 1200 million in 1988 and 1781 million dollars to Hurricane Wilma in 2005 (AMIS, 2005).

Clearly the social concern about unemployment and public safety, together with environmental issues, seem to be in public awareness, positioning the environment as an immediate social problem directly related to the quality and life expectancy for each a citizen.

97% of the population indicates the need for a national, regional, State or municipal government to help tackle climate change, marking the importance of dissemination of plans and programs established and newly created at different levels of influence to strengthen the role of government as the institution capable and suitable for channeling citizen demands and strengthening its role in the solutions to the problem of climate change.

93% of respondents expressed their willingness to organize themselves to contribute to the mitigation of the causes and adapting to climate change impacts, individually and collectively. Now, only the approval and launch of the Veracruz Program for Climate Change (PVCC) is needed, as well as its immediate sector and massive spread throughout the population to start an organized united front to face this global phenomenon.

As it can be seen, in the State of Veracruz manifests the global warming trends of the accumulation of greenhouse gases; because of its particular geography, the State is susceptible to climate variability, which is not fully explained, together with its topography and coastal settlements, making it very vulnerable to the same variability and thus to climate change. Additionally, the population-at least in urban areas of Xalapa and Veracruz-BR-there is a perception that it favors the gradual implementation of a program to address climate change, which must necessarily go through a review of other social, environmental, and public policy issues, more or less following the scheme of figure 2.

Despite the fact that the State of Veracruz is one of the first Mexican states with a program and a law on climate change, and a Climate Change and Environment Ministry at the year 2010, polls show that public policies are perceived as unclear or non-existent. The Universidad Veracruzana in 2009 gave the State government the PVCC, which was developed by about eighty scholars who produced the technical and scientific bases contained in the eBook *Estudios para un Programa Veracruzano ante el Cambio Climático* (Tejeda-Martínez, 2009; Universidad Veracruzana, British Embassy, INE, 2009), which was the basis for the drafting of this section.

Among the basic considerations of the PVCC, it is estimated that the scenarios will show increases of the sea level up to 60 cm to 2 m coupled with storm surges.

In addition, climate change lead to an increase in water demand with the increasing temperature, which all together with the reduced rainfall, this induces saline intrusion in the groundwater of the coastal plains, which, in turn, generates most likely a decrease in the availability of water to meet future needs. This century the water storage is expected to decrease from 10 to 20% in irrigated agricultural areas, industrial areas and most densely populated centers.

In terms of biodiversity, in Veracruz there is virtually all vegetation types described for Mexico which shows the richness and complexity of the State. Just to mention it, the rich flora includes 7482 species of angiosperms and gymnosperms, which puts it in third place after the states of Oaxaca and Chiapas (Rzedowski, 1993). As for fauna, there has been the presence of 188 species of terrestrial mammals, over 660 species of birds, 85 species of amphibians and 209 reptiles (Challenger, 1998).

The biological wealth of Veracruz is at serious risk, since more than 72% of the State's area has been heavily transformed for agricultural and urban uses. If plant species are lost, this would affect significantly the provision of goods and services. This is the case of edible plants that are the native food support for local populations and which are widely used. Another is the availability of products that contribute financial support and are a means of maintaining rural populations (the herbalist vernacular, for example).

As in the case of plant species, Veracruz is considered one of the states with the highest diversity of fauna. The effects of global climate change can cause, in addition to the extinction of species and depletion of the distribution areas already discussed, conditions that favor the establishment of animal species in areas where they were not found before, the expansion of their distribution area and the creation of an enabling environment to increase their numbers, which unfortunately could occur with species considered harmful to humans, as is the case of insects that transmit pathogens that cause diseases (dengue, malaria, Chagas disease, etc.).

From the point of view of the economy, the PVCC considers that, if droughts occur in the north and floods in the southern State, the rural population could lose between 12 and 35% of income per capita by mid 21st century, which would exacerbate the crisis in rural areas.

As for the energy requirements of the population to cool buildings, this is expected to increase as the temperature increases. The average increases most significant user-compared to late last century, will occur in coastal areas: 10, 20 and 43%, corresponding to the decades of 2020, 2050 and 2080. This increase will tend to diminish in the villages located in

Scope	**Objetives to…**
1. Monitoring and knowledge generation	• provide the State of Veracruz with a proper legal and institutional framework to tackle climate change • substantially improve the knowledge about the effects of climate change and climate variability in the State of Veracruz • contribute to the creation of human capital in mitigating GHG emissions and climate change adaptation
2. Environmental protection system	• establish mechanisms and actions that promote the reduction of electricity consumption and to mitigate GHG emissions • contribute to the mitigation of GHG emissions through proper management of waste • reduce the GHG emissions generated by the transport sector • promote adaptation and mitigation measures aimed at conservation of biodiversity, as part of a strategy to tackle climate change • reduce the fragility of forest ecosystems (forests, forests and wetlands, among others) and increase their biomass and productivity, to assist in mitigating GHG emissions • reduce the effect of climate change on the development of pests and invasive species in production systems and natural • use wild life species that have traditional uses as part of a strategy to tackle climate change • reduce the pollution of major rivers and water bodies • forecast, in a timely manner, the increased flows and water levels in flood-prone areas, on one hand, and drought, on the other. • improve the efficiency of water utilities as a strategy to address the water shortage due to climate change • protect the Veracruz coast from the effects of climate change • monitor and to protect coastal aquifers to provide saline intrusion caused by over-exploitation of aquifers or by the sea level rise
3. Health and welfare	• reduce risk of the tourism, industrial and port sectors from the effects of climate change, chiefly from the sea level rise • reduce the effects of the climate change on the cattle sector • reduce the effects of the climate change on fishery • reduce the effects of the climate change on agriculture • increase the potential of the productive coffee systems as a measure of mitigation • reduce the negative effects of the climate change (the decrease in the thermal comfort and the hidric phenomena risks) on houses and buildings • implement a strategy for educational communication and government coordination in order to give viability to mitigation actions and climate change adaptation • consider the gender perspective in the development and implementation of adaptation actions to climate change and GHG emissions mitigation • strengthen the adaptive capacity of economic and geographically groups vulnerable to the impacts of climate change

Annex 1. Veracruz Program for Climate Change. Objectives

mountainous regions, but for the population of the coastal region, considering the overall population and temperature, could be expected to reach 25% by 2020, 91% by 2050 and 111% by 2080, while for the State of Veracruz as a whole it would be 35, 127 and 155% for the same periods. All this even considered the heat produced by urban heat islands, which should be incorporated in the cases of the cities that approach or exceed one million inhabitants. For its part, the effects of heat waves on the population of the hot zones will lead to more and more clearly the increased risk in death for people with heart and circulatory problems.

The impact of climate change on human settlements should be assessed as part of at least the change in water availability and climatic factors affecting people's bio-comfort, and threats of spreading diseases.

The government budget deficit the State already mentioned, doesn't allow for any further actions that would be clearly mitigation and adaptation to climate change. In the last five years the State government founded the Center for Climate Studies, the Ministry of Environment and Climate Change, and in September 2010 approved a State law on climate change, 70% stated in the objectives that PVCC are listed in Annex 1.

In short, the requirement is of a shift budget of 60 million dollars a year, but which must be supported by a clear government policy, which hasn't happened so far. However, the repeated occurrence of disastrous weather phenomena, the gradual rise of sea level change and the sudden storm surge, and a perception among the population ever more clearly that the phenomenon could be harm society, all this might make the government plan schemes considering climate change and other aspects as shown in figure 2, such as the outline of a strategy for disaster reduction.

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9

The Competitiveness of Selected New Members of the EU in the Environmental Products and Services Market

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1. Introduction

In 2005, the Commission laid the foundations for an EU strategy to combat climate *change. This document now sets out more concrete steps to limit the effects of climate* change and to reduce the risk of massive and irreversible disruptions to the planet. These short-term and medium-term measures target both developed countries (the EU and other industrialized countries) and developing countries (Communication from the Commission, 2007, COM 2007; final). One year before an environmental technologies action plan for the European Union was prepared by the European Commission in order to stimulate technologies for sustainable development (Communication from the Commission to the Council and the European Parliament, 2004, COM 2004; 38; final).

This action plan in favor of environmental technologies concerns technologies to manage pollution, less polluting and less resource-intensive products and services and ways to manage resources more efficiently. These environmentally friendly technologies pervade all economic activities and sectors. They cut costs and improve competitiveness by reducing energy and resource consumption and so creating fewer emissions and less waste (as above).

The Commission considers that the implementation of the priorities in the Action Plan is well underway, particularly in terms of establishing technology platforms and key orientation documents which should catalyze the development of environmental technologies, funding from the European Investment Bank (EIB) and the preparation for an international support fund. However, the Commission highlights the need to step up work in this area, in particular by mobilizing European risk funding, fixing environmental performance targets for products, processes and services, establishing an EU wide system for testing and verifying environmental technologies as part of work to revise the Guidelines for environmental State aids, defining market development and industrial performance indicators, setting up national implementing roadmaps and drawing up action plans for public procurement (Communication from the Commission-2005-COM 2005; 16).

While the United States and Japan take the lead in biotechnology and nanotechnology, the EU leads the way in environment-related technology (solid waste, renewable energy and

motor vehicle abatement), with Germany playing a very active role. Japan is second to the EU in all three environmental technology fields (*Highlights;* OECD,2007).
It can be also stressed that among the 6 Lead Market Areas in Europe (according to the *Lead Market Initiative)* especially 4 environmentally friendly goods and services markets have been identified as highly innovative, respond to customer's needs, having a strong technological and industrial base in Europe and depend more than other markets on the creation of favorable framework conditions through public policy measures. *Sustainable construction, recycling, bio-based products and renewable energies* belong to these lead sectors, characterized by high economic and societal value (*A lead market initiative for Europe* ; Communication from the Commission to the Council, 2007, COM 2007, 860, final).
CEE countries in their process of accession to the EU and adaptation to European environmental standards undertook significant steps in the 1990s to improve their natural environments, increasing their imports of goods designed to aid in environmental protection and technologies to implement "clean production" of export goods. These steps should improve the competitiveness of Polish, Czech, and Hungarian goods and products in the future on both the European and global markets. Research results confirm the pro-ecological emphasis of transition economies' restructuring efforts, particularly when read together with the significant increase in their foreign trade in pro-ecological goods and services.
In the case of firms with foreign ownership the effect of compliance with environmental norms and standards on their share of the domestic market was very slight, while the effect of compliance with environmental norms and standards on their share of the export market is somewhat greater, but still modest. An analysis of the results shows that most foreign investors do take environmental protection issues into account in making their decisions, but they do not consider them to constitute a major investment factor. A majority of the respondents favor centralizing strategies. This strategy seems advantageous for recipient countries. Firms with foreign capital frequently introduce environmental protection norms and take part in environmental protection programs. [1] Wysokińska Z,& Witkowska J, 2005, p.279).
At present supporting sustainable growth –for a resource efficient, greener and more competitive economy is one of 3 objectives of the Strategy Europe 2020-main EU's growth strategy for the coming decade (*Europe 2020*, 2010). Sustainable growth means first of all protecting the environment, reducing emission and preventing biodiversity loss, capitalising on Europe's leadership in developing new green technologies and production methods in order to build a more competitive green and low carbon economy that makes efficient, sustainable use of resources (as above) .

2. Characteristics of the market of environmental goods and services

The **environmental goods and services market** is among those world markets that has demonstrated one of the highest growth rates in demand over the past ten to fifteen years. Its volume was assessed at approximately USD 518 billion in the year 2000 and projections for the year 2010 assume its growth to approximately 600 billion (in *Trade and Environment Review 2003*, United Nations,2004, p.36.). The low and irregular share of foreign trade in environmental services and world export in environmental services over various years is at a level of barely 0.3%–0.4% of what is produced. For comparison, world exports in environmental products is approximately 20% of their production. This shows a high disproportion in the trading of environmental products between its products and services sections.

The **environmental industry** (i.e. industry "working" for environmental protection) was characterized by an average growth rate of more than 10% over the past ten to fifteen years. However, the dynamics of its growth in the highly developed countries had a significantly lower rate, which barely amounted to approximately 1.6%–2%. At the same time, the growth rate in developing countries was at a level of approximately 7%–8%. Analysts expect the expansion of industry working for environmental protection as well as of the environmental services sector to a volume of more than USD 600 billion by the year 2010. Projections show that such growth will be particularly characteristic of those countries and will amount to approximately 8%–12%. Compared with other markets, it may be stated that the environmental products and services market is not as large as the steel or agricultural markets. However, its size is comparable with the pharmaceutical or information technology markets. The environmental products market encompasses three main segments—equipment (technical equipment), environmental services, and natural resources. Technical equipment obviously encompasses the most advanced technologies, while environmental services include simpler, albeit more common ones. The predicted growth of more than 15% in the sales of environmental services over the past decade is an additional approximately USD 42 billion increase in demand on the world market providing employment for approximately 1–2 million workers. It is the highly developed countries that are the largest producers of environmental services (United States – approximately 38% of the world market, Japan – approximately 18%, and Germany, Great Britain, France, and Italy). A mere approximately 2% make up the share of Eastern Europe (inclusive of the European part of the CIS), where the share of Poland is between 0.3% and 0.4% (Wysokińska , 2009, p. 941-948.).

The environmental markets in highly developed countries are extremely competitive. They have an exceedingly specialized consumer rights protection base. However, they are experiencing low or even negative growth in many sectors and are very "sensitive" to economic cycles. Environmental regulations are among the most important of market factors. The capacity to produce environmental products and services is growing dynamically in many developing countries primarily thanks to collaboration with established companies as well as due to increased demand on the internal market. Nevertheless, little data corroborate the fact that this is also reflected in export.

Present barriers in trade, understood as what are known as "bound tariffs," which are tied to many capital–intensive goods, serve as the base for the rendering of services in the area of waste management. They are low in highly developed countries (below 3% for products found on the list of OECD countries). Many developing countries have their customs rates set a relatively high levels—10% to 20%. In certain cases the tariffs are exceptionally high. (Wysokinska Z., 2005.). In practice, the import of environmental products and services may benefit from many incentives. Technical regulations provide support in adapting environmental products and services to environmental requirements. The dearth of uniform environmental requirements on various national markets is a significant extra–tariff barrier. It is especially standards and certification that have an impact on trade in environmental products and services. On the other hand, trade in niche products searching for new markets may be hindered as a result of a lack of appropriate standards for such products. Thus, imported environmental technologies should be tested and certified by local authorities on individual markets. (Vikhlyaev A ., 2004).

3. Liberalization process within the WTO-the role of Multilateral Environmental Agreements

Supra–national regulations relating to trade that include requirements taking into account aspects of environmental protection are encompassed by the **Multilateral Environmental Agreements** (MEA). This particularly pertains to non–discrimination in trade and transparency in exchanges. The gradual removal of tariff and extra–tariff barriers restricting trade in light of WTO regulations occurs simultaneously with the support and promotion of environmental protection within the strategy of sustainable development. WTO regulations relating to transparency in exchange create conditions for complementarities of trade policy and environmental protection policy. They provide a basis for analysis of product labeling and packing processes in line with environmental requirements as well as assessments by WTO experts as to whether they play a part in establishing new restrictions in international trade. Similar requirements also relate to products tied with merchandise safety and health protection as well as with respect to those WTO regulations that guard against the development of barriers restricting international trade. The integration of trade and the environment with respect to developing countries is one of the priority areas within the framework of sustainable development strategies. Intensive ongoing debates as well as pilot projects on regional and national levels are leading to evolution in actions as well as to initial visible results in this area. It is becoming clear that the integration of trade and the environment necessitates a concrete linking mechanism coupling various aspects on a national and international activity level.

In connection with the Report from the 5th Session of the WTO Ministerial Conference in Cancun, which continued work launched within the framework of the regular sessions of the Committee on Trade and Development (CTE) in the period between the 4th WTO Ministerial Conference in Doha and the 5th in Cancun, it is stated that improved market access for developing countries is a key objective in implementation of sustainable development. Attention is called to the fact that in light of the Principles of Rio de Janeiro (Rio Principle 11 4th), environmental standards and priorities should in particular mirror the environmental and developmental context to which they refer, where standards as applied by certain countries may result in improper and unjustified economic and social costs for others, especially developing countries. Small and medium businesses are particularly "sensitive" to their application.

Many WTO member states call attention to the fact that environmental and health protection legitimize the integration of environmental and trade policy and that countries have the right to introduce their own appropriate level of environmental protection in line with such objectives. However, it is noted that environmental standards should also influence exports. Thus, the aim of any action should not be the lowering of these standards, but rather facilitating adapting to them by exporters. (In this case, technical assistance, support of competitive capacity, and the transfer of technology serve a key role in helping exporters from developing countries in adapting to standards and implementing appropriate production methods.) Many WTO members put particular weight on identifying trade potential for sustainable growth during discussions on future directions of development. The Committee on Trade and Development (CTE) should point to incentives and instruments supporting developing countries in the process of identifying products and developing export markets for environmentally friendly products in areas where many of these countries achieve a comparative advantage. (as above, p. 944).

4. Environmental market in Poland in comparison to other European countries

Products fostering environmental protection[1] have gradually increased their share in total trade turnover in Poland from approximately 3% to 4.5% on the side of exports and from 5% to approximately 7% on the side of imports. These changes were particularly noticeable in the European direction (as above, p. 944).

In its turn, import growth in Poland was even greater. Over the examined period it increased from USD 2.630 million in the year 2000 to USD 6.058 million in the year 2005. In the direction of imports from the European Union, growth went from USD 2.001 billion to USD 4.766 billion. The increase in share of products fostering environmental protection in Polish imports was even greater and amounted to an increase from 5.4% in the year 2000 to 6.0% in 2005 in overall imports, and growth from 6.7% to 8.2% in imports from the European Union. This indicates growing interest in Poland in international trade of products fostering environmental protection, which is a very positive phenomenon in this time of implementation of the Sustainable Development Strategy and the gradual lowering of barriers so as to improve access to developing markets of environmental products and services in both highly developed and developing countries.

A sales volume at a level of **USD 169–179 billion** characterized the **world environmental services market** over the years 1999–2003. World product over this period amounted to approximately USD 169–178 billion, while trade in environmental services was at a level of approximately 0.3–0.4 of the share in world service production. This put its value at a level of from USD 495 million to 654 million on the side of exports and from USD 519 million to 7159 million on the side of imports.

The world environmental services market was dominated by the economically highly developed countries, including mainly the countries of Western Europe that have a total share of approximately 40% over the examined period, with a growing tendency up to the year 2000. From among this group of countries, the share of the European Union was at a level of 38.8% in 2002, while the respective share of EFTA was 2%. From among the countries of the European Union, of greatest importance in terms of share in the world environmental services market, main positions were occupied by countries such as Germany (approximately 9%), Great Britain (approximately 8%), France (approximately 6%)

[1]Products fostering environmental protection were classified into three basic groups: 1) Products and services related to waste management, 2) Cleaning technologies and products, and 3) Products relating to managing processes preventing the creation of pollution. More on this topic may be found in Wysokińska Z., "The International Environmental Goods and Services Market …," (Wysokinska Z., 2005., p. 943).

Italy and the Netherlands (approximately 4%, each), and Denmark (approximately 3%). Important positions in the world environmental services market from among the non–European countries of the OECD were occupied by such countries as the United States (approximately 28%) and Japan (approximately 13% with a slightly downwards tendency over the whole of the examined period). Central and Eastern Europe as well as the European countries of the CIS held a total approximately 2% share in the volume of the examined market, where the share of the countries of Central and Eastern Europe was at a level of approximately 1.4% in the year 2002 and had a strongly growing tendency over the whole of the examined period (1999–2002). The lowest position from among the countries of Central and Eastern Europe was occupied by Poland (approximately 0.43% in the year 2002), followed by the Czech Republic (approximately 0.37%) and Hungary (approximately 0.30%)), where all three had a growth tendency in their shares over the analyzed years.

As can be seen from the conducted analysis, the share of trade in environmental services in the production of environmental services is relatively small and does not exceed 0.4% of world trade. Total world exports in environmental services amounted to USD 654 million in the year 2002, with a systematic growth tendency over recent years (from a level of USD 495 million in the year 2000). Western Europe held an 84% share in world exports and an 86% share in world imports in these services. The share of the United States barely exceeded 3% while for Japan the figure was approximately 1.3% on the side of exports (with a downward tendency in the case of both countries) and approximately 2.5% and approximately 2%, respectively, on the side of imports (with a downward tendency for Japan and growth in share for the United States). Among the countries of the European Union, which holds a 70% share in world exports of environmental services, France was dominant (a 25% share in world exports), followed by the Netherlands (a 16% share) and Belgium (a 12% share). The EFTA countries (with a dominant position held by Switzerland) held a 14% share in world exports of environmental services. The specified countries of Western Europe were also significant importers of environmental services, which bears witness to the high level of advancement of intra–industry trade in environmental services in this area. Central and Eastern Europe as well as the European countries of the CIS held an approximately 3% share in world exports and an approximately 2% and 1% share, respectively, in world imports of environmental services, with a simultaneous significant growth tendency on the side of exports. A strongly growing share in the export of these services was also noted in Estonia, which achieved 0.72%. Among the countries of Central and Eastern Europe, the greatest share in exports was demonstrated by the Czech Republic (0.98%), followed by Poland (0.6%) and Hungary (0.5%).

Two major groups may be identified on the environmental services market in Poland—basic services for the environmental sectors and environmental cluster sector services. The former group includes sewage management and water protection, where this sector includes water distribution services by pipelines, excluding hot water (PKWiU Polish Classification of Products and Services, Section 41) and sewage management (PKWiU, Category 90.00.1), waste management, including the disposal of garbage and wastes (PKWiU, Category 90.00.2), contract–based metal waste and scrap processing (PKWiU, Section 37), wholesale and retail trade in wastes, scrap metal, and other materials for recycling (51.57.10, ex51.18.12, ex52.48.12), snow removal, etc. services (PKWiU, Category 90.00.3), and storage services (PKWiU, Sub–category 63.12.12). The latter group includes environmental research and development services, advisory services, contracts and environmental engineering, analysis services, data collection, estimates, construction, transportation, and other services (including spatial planning services).

Poland's share in the world services market oscillates in the area of 0.4% to 0.5%. The share of environmental services exports measured on the basis of the balance of payments is at a similar level. Imports are at a level in the area of 0.15% to 0.20%, however, the positive trade balance calculated only in the area of basic sectors provides USD 1 to 2 billion annually. If environmental cluster sectors are added to this as well as those for which there is no detailed data in this area, then the balance of turnover in environmental services may reach a level of 30% (approximately) more, although for research and development, design, and engineering services the balance will be negative.

Analysis of the Polish market for environmental services was conducted in line with European Union propositions for modifications of the GATS/WTO classification system because it contains the entire classification and is its expansion modernized by almost a decade. It provides for the subdivision of services into basic sectors like the W/120 GATS/WTO classification system, but it allows for a more accurate disaggregation of environmental cluster sectors, accounting for a single aspect of the activities of those sectors in the area of environmental designations.

The export of environmental services by companies in Poland has been rising, where growth in the year 2001 as compared to 2000 amounted to 36.3 percentage points, while in 2003 as compared with 2002 is almost doubled and amounted to 66.9 percentage points. The volume of environmental services exports was very small over the whole of the analyzed period, however. Growth in exports in the environmental sectors is about one–third greater than growth in their sales on the domestic market in terms of average percentages. The rate of growth of exports is, in general, satisfactory, with an average of over one dozen percentage points per annum. However, this applies to too small an amount and at this time does not have any significant impact on economic results.

Analysis of the collective economic results of business entities rendering environmental services in Poland demonstrates that among all the entities providing environmental services, profit–making companies were dominant during the examined period (from approximately 73% in the year 2000 to 72% in the year 2003). The share of companies achieving good financial results was high among large– and medium–sized companies as well as small ones. However, it was among the ones considered large in terms of numbers of employees that is was significantly higher. Both in public sector entities and private ones those that achieved a positive financial result were dominated by companies providing environmental services, but the share of private companies in this group was greater. A less positive phenomenon was that in both analyzed groups (though to a lesser extent in the private sector), the share of entities making a profit over the analyzed 2000–2003 period decreased.

As can be seen from the analysis presented in the report, both the environmental market and in particular the environmental services market are a part of markets having the greatest development potential in today's world economy. This is borne out by the high rate of its development, especially in the countries of systemic transformation and developing countries. Although presently still holding a relatively small share in this dynamically developing market, the rate of change in this area found in those countries over recent years allows their placement among its potentially growing participants.

Environmental market analysts expect the expansion of industries working for environmental protection as well as the environmental services sector to a size of more than USD 600 billion by the year 2010. This is when the share in growth potential of the systemic transformation countries of Central and Eastern Europe as well as the countries of the CIS, mainly Russia, may gradually become more important in the long term. It is expected that this growth will be particularly characteristic of environmental cluster developing countries as well as systemic transformation ones and that the growth rate of these countries will amount to approximately 8%–12%.

Although the countries of Western Europe and other highly developed countries hold dominant shares in the world environmental services market, they have been facing a steady decline in the development of exports of these services over recent years. Due to growing operating costs in the environmental services sector in those countries, which is mainly the result of their high salary levels, it may be expected that in the upcoming years there will be greater expansion and investments by Western European companies (mainly from the countries of the European Union such as France, the Netherlands, and Belgium as well as Switzerland) as well as from other highly industrialized economies in both developing countries and in countries that have recently undergone systemic transformation. These particularly include countries from the Central and Eastern Europe region, including mainly the three greatest producers of environmental services in this area, which includes Poland, the Czech Republic, and Estonia, as well as Russia.

The better and continuously improving access to the world environmental market is witnessed by the previously carried out liberalization of trade within the framework of OECD countries in line with WTO requirements as well as in the significantly slower, but nevertheless present, rate of liberalization taking place in trade in developing countries.

The market volume of developing countries in the area of environmental services may be estimated as being an approximately 8.5% share of the world market, with a steady growth tendency over recent years. Their share in world exports and imports of these services oscillated around the 6%–7% mark in world trade while in world environmental services production in exceeds an 8% share. This shows the growing involvement of both domestic environmental service providers in these countries and the even greater degree of growth in foreign investments (from the highly developed countries) in this sector, potentially one of the most dynamically developing sectors of the world economy.[2]

5. Conclusions

As can be seen from the presented analysis, both the environmental products market and the environmental services market are among markets with the greatest development potential in today's world economy.

This is borne out by the high rate of their development, especially in the systemic transformation and developing countries that, albeit still holding a relatively small share in

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[2]These conclusions are derived from an expert report entitled "Ocena szans Polski na międzynarodowym rynku wyrobów i usług środowiskowych" [An assessment of Poland's chances on the international environmental product and services market] developed by the author for the Ministry of the Economy in 2007.

this dynamically developing market, demonstrate a rate of change in this area allowing these countries to be placed among its potentially growing participants.

CEE countries in their process of accession to the EU and adaptation to European environmental standards undertook significant steps in the 1990s to improve their natural environments, increasing their imports of goods designed to aid in environmental protection and technologies to implement "clean production" of export goods. These steps should improve the competitiveness of Polish, Czech, and Hungarian goods and products in the future on both the European and global markets.

As a member state of the European Union, Poland should make an active entry with its production and sales in these dynamically developing segments of the market and take advantage of available benefits, simultaneously playing a role in improving the state of the natural environment in countries of the world most in need of such products and technologies.

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10

Impacts of Climate Change on Animal Production and Quality of Animal Food Products

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1. Introduction

Nowadays, almost all inhabitants of the Earth are affected by different health problems associated with nutrition, although their causes are in striking contrast with each other. In the developed societies certain chronic, non-infectious diseases are caused not only by overfeeding but also by an unhealthy ratio of the ingested nutrients. According to the statistics, 50% of deaths can be attributed to diseases of the cardiovascular system, and 30% to tumor diseases. Diet is one of the major risk factors in the development of these illnesses. That is why through changing undesirable dietary habits and consuming food more satisfactory to human nutrition requirements we may have every right to hope that an ever-increasing percentage of the population can live up to their genetically determined lifespan.

In addition to numerous other factors, the quality of foods of animal origin (e.g. meat) is probably influenced by the quality of feed most of all, therefore a very important area of food science research is focused on improving meat quality by feeding so that it can better meet the requirements of human nutrition.

Animal nutrition in the 21st century aims to provide safe and good quality foodstuffs of animal origin besides a high efficiency of production and a low level of environmental pollution. These criteria, however, contribute to the complexity and rapid expansion of nutrition science. The continuously increasing demand of the human population needs to be supplied from a diminishing agricultural area, while maintaining the sustainability of production. According to the global trends, the challenges facing animal nutrition in the 21st century can be summarized as follows: more awareness and activity of participation is needed in animal production to supply quality and safe food in sufficient quantities, in accordance with the requirements of the society.

Considering the limited nature of available agricultural area, the efficiency of animal production needs to be improved. This can be achieved by (i) increasing biological efficiency, ii) technological efficiency and iii) economic efficiency. The science of animal nutrition deals with the first two factors by using advanced knowledge. One of the practical solutions for saving grains for human consumption is to increase the amount of feedstuffs available for animal nutrition by using by-products. This concept is also in agreement with the principles of sustainability (Babinszky & Halas, 2009).

Further growing global populations, land degradation, loss of arable land due to urbanization anticipated climate change involves many challenges for agriculture. Food production on a global scale is able to keep pace with population growth as well as serious regional deficits only, and poverty related nutritional deficiencies affect nearly one billion people.

It is very well known that agriculture is very sensitive to climate variability and extreme weather events, such as droughts, floods and storms etc. The forces that shape our climate are also critical to farm productivity. Human and industrial activities have already changed plenty of atmospheric properties, such as temperature, precipitation, concentration of carbon dioxide in the air and ozone at ground-level. The experts forecast that these trends will continue. While food production may benefit from a warmer climate, the increased risk of droughts, floods and heat waves will pose challenges for agriculture. Moreover, the long-term changes in climate, water supply and soil moisture could make it less feasible to continue crop production in some regions (http://www.epa.gov/ climatechange /effects/agriculture.html).

The research on climate change and its implications is at present in the focus of much scientific interest. In addition to comprehensive research efforts there is an increasing need for incorporating the fact and impacts of climate change both in the area of regular education and of agricultural extension services. Since neither the present status of climate change nor its expected future development are unequivocal facts – particularly in consequence of the expected influence of the international treaties on climate protection– the continuous monitoring of the process, of changes and their influence are necessary both from the meteorological and from the user side.

The question most frequently raised in connection with climate change is concerning its impact on agriculture (crop and livestock production), and from a broader perspective on our food supply. In other words, how animal production and thus the production of foodstuffs of animal origin and their quality are influenced by climate change through feed crop production?

The question can be asked at various levels – local, regional, continental and global – but no unequivocal reply is possible, just as there is none for the question of climate change. The global weather forecasting models used for long-term climate forecasts are undergoing continuous development. Downscaling is an area where particularly rapid progress is expected. Climate scenarios prepared by climatologists should be downscaled and evaluated in the most sophisticated manner possible and should be linked to the local regional production situation. Any action program, elements of response, prevention, adaptation, remedy and remediation steps can essentially be based on the climate changes predicted for the given region.

Interactions existing among the available biological, biometrical (yields) and meteorological data can be explored by using various statistical methods. The expected changes are entered into the equation as independent parameters and these can provide a basis for drawing conclusions for the future. By the practical application of the results of plant and animal growth simulation models (relying on a background of advanced computer technology), and of open-field small plot trials (open top chambers, in which for example the effects of atmospheric carbon dioxide can be studied) and climate chamber animal trials the stability of food production and sustainable agricultural production can be ensured even beside changing environmental conditions (Babinszky et al., 2011)

It should be noted moreover, that food supply predictions based on climate change scenarios also imply a broad margin of error, since in addition to climate other factors (genetics, agrotechnology, adaptive abilities) have a major influence on agricultural production as well. The study of these factors is expected to become a focal point of future research work. The effect of climatic change on crop production and animal nutrition should be studied in the near future, together with the investigation and evaluation of different climate scenarios, in the interest of maintaining sustainability of production

The aim of this chapter is to present the impact of changing meteorological factors on crop production, on the metabolism of farm animals and in consequence on the volume and quality of animal products from the aspect of human nutrition. The chapter also investigates how the adverse effects of climate change can be alleviated.

2. The impact of climate change on feed crop production

Agriculture – and thus the stability of food supply – is an activity, which besides natural vegetation is the most sensitive to the changing climate and weather. Unfavourable climatic factors may lead to a significant decline, and sometimes to the complete elimination of crops. Efforts to research the adaptive potential of crops are urgently needed to prevent this turn of events. Production technologies adapted to the cropping site conditions and to the requirements of the crops, the increased use of varieties / hybrids that better tolerate drought and the extreme conditions, and the selective breeding aimed at these objectives are of key importance.

A possible consequence of climate change may be the necessity of switching from natural precipitation based production to irrigation-based production wherever it is possible. The development pattern of soil humidity as expressed in percentage of the maximum useful water content of the soil provides immediate information about how the water supply conditions of the soil meet the requirements of different crop species. Several studies conducted in temperate zone countries agree in their finding that a 10 % decline in precipitation raises the irrigation water requirement by at least 7-8 %, but this is also subject to the crop species and the environmental conditions.

Much of the relevant data in literature suggests the necessity of distinguishing between the *potential* and the *actual* vegetation periods. A consequence of the higher daily mean temperatures is that the *potential* vegetation period will be longer. At the same time the higher temperature leads to accelerated growth and this in turn shortens the crop lifecycle, and thus the duration of the *actual* vegetation period is also shortened. Under such circumstances it is reasonable to either grow varieties having a longer growth season (these usually produce higher yields than varieties with a shorter growth season, and can also be stored better), or to grow after crops. In this latter case the same area can be harvested twice within the same year (Babinszky et al., 2011).

There are three distinct types of photosynthesis: C3, C4, and CAM (Crassulacean Acid Metabolism). C3 photosynthesis is the typical photosynthesis used by most plants. C4 and CAM photosynthesis are both the outcome of adaptation to arid conditions because they result in better water use efficiency. In addition, CAM plants can save precious energy and water during harsh times, while C4 plants, in contrast to C3 plants, can photosynthesize faster under the high heat and light conditions of the desert, because they use an extra biochemical pathway and special anatomy to reduce photorespiration.

The three different types of photosynthesis can be characterized as follows (http://wc.pima.edu/Bfiero/tucsonecology/plants/plants_photosynthesis.htm):
C3 Photosynthesis: C3-plants – with stomata open during the day – get their name from CO_2 being first incorporated into a 3-carbon compound. The enzyme involved in photosynthesis is called Rubisco, and it is also involved in the uptake of CO_2. Photosynthesis takes place throughout the leaf. Their adaptive value is more efficient under cool and moist conditions and under normal light than that of the C4 and CAM plants because it requires less machinery (fewer enzymes and no specialized anatomy). Most plants are C3.
C4 Photosynthesis: C4 plants are called so because the CO_2 is first incorporated into a 4-carbon compound. Their stomata are open during the day. They use PEP (phosphoenolpyruvate)-carboxylase as the enzyme involved in and enabling a very fast uptake of CO_2, which is then "delivered" to Rubisco for photosynthesis taking place in the inner cells. In contrast to C3 plants this photosynthesis occurring under high light intensity and high temperatures is faster because CO_2 is delivered directly to Rubisco, not allowing it to grab oxygen and undergo photorespiration. Water use efficiency is better too, because PEP Carboxylaze brings in CO_2 faster and so the stomata do not need to be kept open that much (less water lost by transpiration) for the same amount of CO_2 gain for photosynthesis. C4 plants include several thousand species in at least 19 plant families.
CAM Photosynthesis: CAM plants are named after the plant family in which it was first discovered (Crassulaceae) and because the CO_2 is stored in the form of an acid before being used in photosynthesis. The stomata are open at night (when evaporation rates are usually lower) and are usually closed during the day. The CO_2 is converted to an acid and stored during the night. During the day, the acid is broken down and the CO_2 is released to Rubisco for photosynthesis. In contrast to C3 plants the water use efficiency of this group is better under arid conditions due to their stomata being open at night when transpiration rates are lower (no sunlight, lower temperatures, lower wind speeds, etc.). CAM plants include many succulents such as cacti and agaves, and also some orchids and bromeliads (http://wc.pima.edu/Bfiero/tucsonecology/plants/plants_photosynthesis.htm).
The increase in temperature usually favors species with C4 type photosynthesis, which are better from several aspects than the C3 type species. Worth highlighting of these are the high net productivity of photosynthesis and the fact that they use significantly less water per unit of dry matter production. In addition, for C4 plants the CO_2 absorbing capacity of PEP-carboxylaze – the primary enzyme of CO_2 fixation – is more than 30 times higher than that of RuDP (ribulose 1,5 diphosphate)-carboxylase, and consequently they are also able to absorb more efficiently any CO_2 released during photorespiration. This is particularly advantageous for C4 plants under stress conditions (high temperature, aridity, high photo intensity), as they are not forced to rely on CO_2 replenishment through the stomata. Under such circumstances the stomata remain closed, which substantially reduces the loss of water caused by transpiration.
Peer reviewed studies also report that besides the increase in temperature and aridity, the third dominant environmental element of climate change, i.e. the increase of atmospheric CO_2 concentration is more favorable for the C3 photosynthesis species. Due to the simultaneous change of these three factors in the future, it is difficult to make predictions either at the level of the biosphere or of the natural and artificial biocoenoses. In case of the most prevalent weed in Hungary, i.e. the common ragweed, the simultaneous increase of the two abiotic factors (temperature, carbon-dioxide concentration) equally favored the

production of biomass and of pollen, and also the initial phenophase of the flowering period shifted to an earlier time.

Of the 18 weed species considered to be the most dangerous worldwide, 14 belong to the C4 group, while of the 15 crops most important for global food supply only 3 species are C4. In consequence, the result of any increase in the carbon-dioxide concentration is that in the competition between weeds and crops the competitive ability of crops in the agroecosystems is enhanced, and thus their weed suppressing potential is strengthened (Babinszky et al., 2011).

The impact of climate change on feed crop production also influences the feed base of farm animals because it affects the yield, quality and price of forage and concentrate crops, since – as mentioned before – the photosynthesis of C4 feed crops (corn, sorghum, millet) is more efficient, their heat and drought tolerance is better than those of the C3 crops (wheat, barley, rye, oat, sunflower, alfalfa, soy).

In summary it can be concluded, that climate change has a major impact on feed crop production. Thus for instance C3 plants will face more stress in consequence of higher temperatures and of any eventual decline in the annual amount and/or change in the annual distribution of precipitation. For this reason the selective breeding of plants will have to focus on selecting for drought resistant varieties of C3 plants for example in order to avoid loss of yields.

Nutritionists are also going to face a serious challenge. Using the latest results of animal nutrition and its related disciplines (microbiology, immunology, physiology, molecular biology, precision nutrition, information technology, etc.) they are to develop feeding technologies and feed formulas in which the latest feed crop varieties of improved drought resistance are used more extensively. All this should be used in the everyday practice of producing foodstuffs of animal origin besides avoiding any decline in the quality and safety of the product (foodstuffs of animal origin) and alleviating the environmental load of livestock production.

3. The impact of climate change on the performance of farm animals and the quality of animal food products

As mentioned in the above sections, recent research data and model predictions suggest that the average temperature of the Earth is increasing, which will have a significant impact on agricultural production (Bernstein et al., 2007). However, it is also forecasted that climate changes will result in more extreme weather in different parts of the world, leading to storms and frequent changes of hot and cold temperatures. It appears reasonable to expect not only the feed crop sector but also the livestock sector to come up with solutions and new strategies for maintaining and even increasing the production potential under the altered climatic conditions. The development of an action plan is crucial considering the increasing food demand of the human population.

3.1 Thermoneutral zone and thermoregulation of farm animals

In order to better understand how climate change affects livestock performance it is necessary to become acquainted with the bases of livestock production, and particularly with the processes pertaining to the utilization of dietary energy, since the ambient temperature has a major impact on the energy metabolism of food producing farm animals.

The concept and importance of the thermoneutral zone and the thermoregulation of the animals are briefly reviewed below for this purpose.

Physiological processes are associated with heat production, which is the sum total of non-productive energy utilized by the animal and of the energy "lost" in the course of converting the dietary nutrients. The non-productive energy is used for maintenance, i.e. it satisfies the energy requirement of such essential physiological processes as the maintenance of the body temperature, the nervous system, organ functions, ion pumping, energy requirement for minimal activity, etc. The total of heat produced in the course of digestion, excretion and metabolism of nutrients is called heat increment. Within a certain range of ambient temperature and besides unvarying feed and nutrient intake the total heat production of the animal remains constant (Figure 1). This temperature range is called the thermoneutral zone. In a thermoneutral environment the heat production of the animal is at the minimum, and thus the dietary energy can be used for production (growth, egg and milk production) efficiently. Unfavorable temperatures (too cold or too hot environments) lead to an increased heat production by the animal, i.e. there is more loss of energy, and in consequence less energy remains for production at the same level of energy intake, and the efficiency of energy utilization deteriorates. The upper and lower critical temperatures for different animal species and age groups are shown in Table 1. The species, age and body condition of the animals all have a significant influence on the critical temperature, but other environmental factors affecting their thermal sensation and heat dissipation, such as air velocity and air humidity, are also crucial. Increasing the airflow improves the efficiency of evaporative cooling, but higher humidity has the opposite effect. In cold, humid conditions the heat conductivity of wet hair increases, thus the animal becomes more sensitive to the lower ambient temperature. Based on these examples it can be seen that in case of high humidity levels the comfort zone of the animals becomes narrower, the lower critical temperature increases while the upper critical temperature decreases.

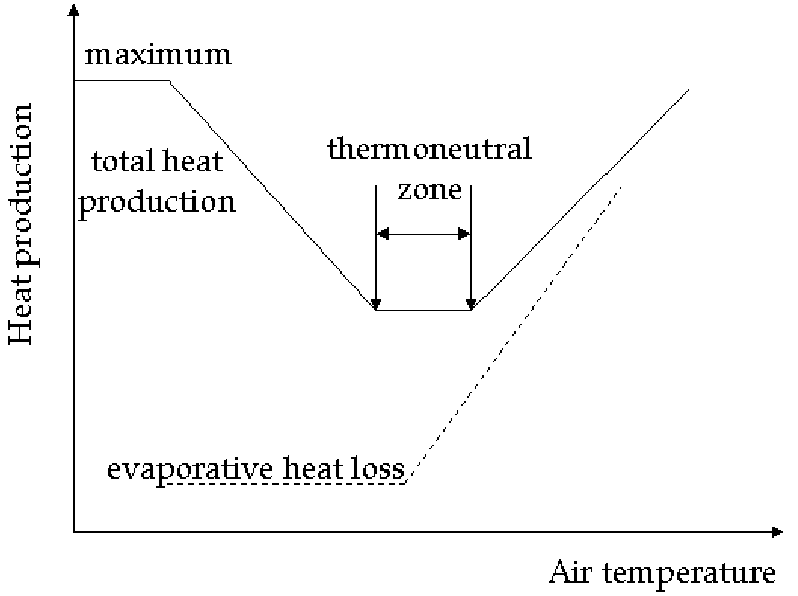

Fig. 1. Relationship between ambient temperature and heat production of farm animals.

	Lower	Upper
	critical temperature (°C)	
Lactating sow with piglets	15°C for sow 32°C for piglets	26°C for sow No practical upper limit for piglets
Prenursery, 3-15 kg	26	32
Nursery, 15-35 kg	18	26
Growing pigs, 35-75 kg	15	25
Finishing pigs, 70-100 kg	10	25
Sow, boar >100 kg	10	25
Dairy cow	-12/-1*	24
Newborn dairy calf	8-10	35
1-day-old chicken	32	35
Finishing broiler	16	26
1-day-old turkey	35	38
Finishing turkey	16	26
Laying hen	16	27-29

*Lower critical temperature: -12 °C for Holstein and Brown Swiss, -1°C for Jersey

Table 1. Lower and upper critical temperature of farm animals at different age or body weight (FASS, 2010).

Thermoregulation is the ability of the animals to maintain their body temperature in cold or hot environments, consisting of behavioral, physiological and anatomical responses that affect energy metabolism. In a cold environment the rate of oxidation increases, in other words, the body "burns" more nutrients, thus boosting its heat production, in order to compensate for the higher heat loss caused by the lower ambient temperature. Shivering is a tool aiding this process; since the energetic efficiency of muscle work is low, the resulting heat production is quite significant. If heat loss exceeds heat production, the result will be hypothermia and death. As the thermoregulatory mechanisms of newborn and young animals – particularly in swine and poultry species – are poorly developed, the cold environment increases the number of mortalities. According to predictions a characteristic feature of climate change will be the rising average temperatures, and this may become an advantage for the survival rate of young animals.

As seen in the above, the maintenance energy requirement of animals increases in a cold environment, which reduces the amount of energy available for production. However, the higher use of non-productive energy is not the only factor reducing the amount of energy available for production. Another contributing factor is the poorer digestibility of nutrients caused by the low ambient temperature. This means that in cold temperatures the higher energy consumption is associated with a relatively lower energy supply. Higher feed or energy intakes can help the animals to compensate for this lower energy supply to a certain extent.

From a practical perspective higher temperatures are much more hazardous for growing/finishing and breeding animals than a cold environment. Temperatures exceeding the higher critical level compromise animal performance not only by changing the energy and nutrient metabolism, but also by upsetting the body homeostasis, with detrimental consequences both for immunocompetence and for product quality. In general, livestock with high production potential are at greatest risk of heat stress, thereby requiring the most attention (Niaber & Hahn, 2007). Therefore, in the present chapter the high temperature induced metabolic changes and its consequences will be discussed in detail.

3.2 Effect of global warming on the metabolism of farm animals – biological background

At thermal equilibrium the difference between heat production and heat loss of the animal is zero. If heat production exceeds heat loss from radiation, convection, evaporation, and conduction, heat is stored and hyperthermia results in an increased body temperature. In farm animals with only a few sweat glands or none at all (poultry, swine), evaporation through rapid air exchange (panting) is one of the most important mechanisms for cooling the body. It is well known, that rectal temperature is a good indicator of internal body temperature. For this reason rectal temperature and respiratory rate are the usual indicators of heat stress even in cattle (Brown-Brandl et al., 2001; Kadzere et al., 2002). Animals respond to an unfavourable ambient temperature in a very complex manner. Figure 2 shows the most important influences of the climatic environment on the physiological processes of the animals, together with the consequences of these changes in their production potential and product quality. In a hot environment, when the air temperature is above the upper critical temperature, the ability to lose heat is limited; therefore, farm animals reduce their feed intake and thus the heat increment in order to keep the thermal equilibrium. Studies have reported a strong negative correlation between rectal temperature and feed intake in pigs, poultry, and dairy cows at the time of heat stress. High ambient temperature causes hyperthermia in the body, which reduces the activity of the appetite center in the medulla oblongata. Thus it is the higher temperature that triggers the reduction of feed intake, in proportion to the increase of the ambient temperature. In order to lower the heat production, farm animals reduce their physical activity as well (Collin et al., 2001) and spend less time with eating (Brown-Brandl et al., 2001).

The lower feed intake results in a poorer nutrient supply, which obviously compromises the production performance and parameters. This loss of performance, however, is usually more than what would be justified by the reduced feed intake. The cause of the lower efficiency of nutrient and energy utilization is partly the higher energy use of animals due to heat stress, and partly the altered electrolyte balance of body fluids that may impair the protein metabolism (Patience, 1990). The changes in the protein metabolism are then clearly affecting the milk production, egg production and growth of the animals. As discussed earlier, above the upper critical value the respiratory rate linearly increases with the ambient temperature. The enhanced respiration results in a higher CO_2 emission, which may cause respiratory alkalosis. The CO_2 concentration in the body fluids is a metabolite with significant acidic properties playing a significant role in the acid/base balance. The shift in the acid/base balance can be compensated for by the electrolytes fed in the diet. The results of a large number of studies with birds, dairy cattle and lactating sows show the benefit of changing the dietary electrolyte balance (DEB) during heat stress in order to avoid any loss of performance when compared to animals kept in a thermoneutral environment (West et al., 1991; Dove & Haydon, 1994; Sayer & Scott, 2008). The optimal temperature for fast growing, lean genotypes is lower than that for the unimproved animals or conventional hybrids (Brown-Brandl et al., 2001), since heat production related to the maintenance processes is linearly related to muscle mass. The underlying problem is that the genetic selection for rapid growth rate, high egg or high milk production results in a high metabolic heat production by the animals without a significant increase in their ability to lose heat (Renaudeau et al., 2010). It follows from the foregoing that intensive genotypes tolerate global warming much less than the extensive or semi-intensive breeds.

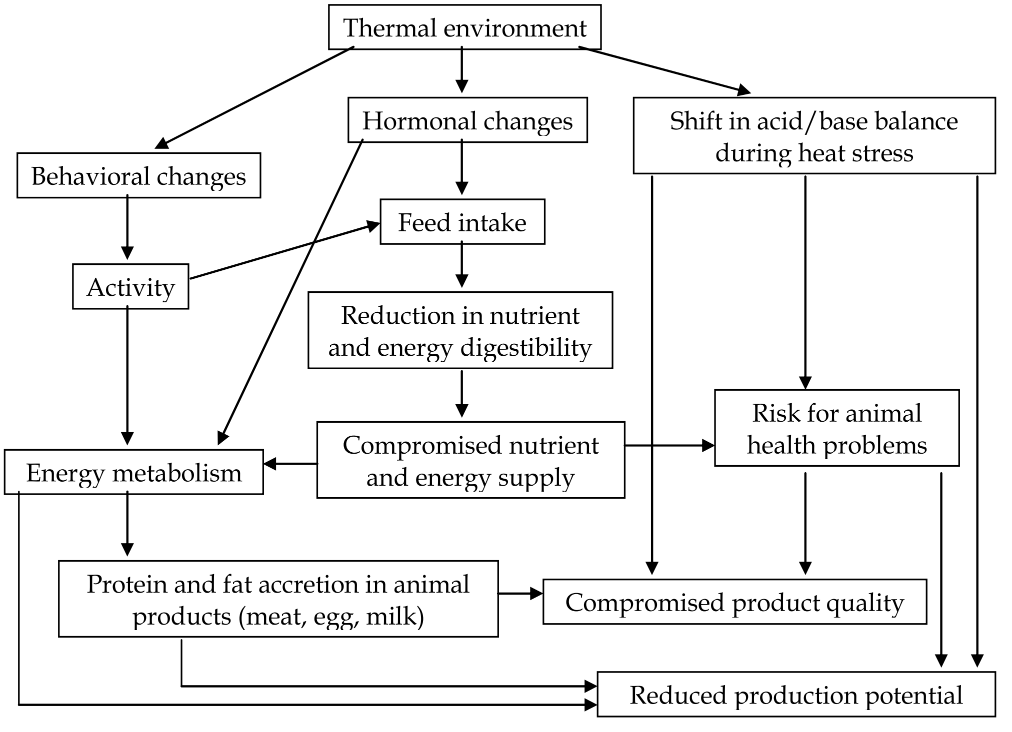

Fig. 2. Schematic representation of the potential mode of action of inconvenient thermal environment on the production potential and product quality of livestock.

Several studies have demonstrated that heat stress may reduce disease resistance or immune responsiveness of domestic animals; however, it depends on several variables, such as species and breed, duration of the exposure, severity of stress, and the type of immune response considered. A moderate heat stress would probably not modify immunological parameters (Lacetera et al., 2002); severe heat stress however may cause immune suppression, such as lower number of circulating white blood cells (Heller et al., 1979) and a reduction in antibody production (Zulkifi et al., 2000). Due to the production potential oriented selection, intensive genotypes are usually more susceptible to any disease; and it should also be noted that the increasing temperature provides better conditions for microorganisms and viruses. At the same time the use of pharmaceuticals, such as antibiotics or other drugs in food-producing animals may impair product quality and/or may constitute a food safety hazard, and can finally lead to a loss of consumer confidence in the product. Consumers are increasingly aware in their selection of foodstuffs, and as a consequence of their traceability animal food products originating from animals fed with medication lose their competitive edge compared to products from non-medicated animals.

3.3 The effect of heat stress on the production of farm animals and product quality
3.3.1 Meat and egg production in poultry

There is a large number of reports on the effects of high ambient temperature and humidity on poultry production, since the poultry industry is concentrated in hot climate areas of the world, mainly in Asia and South America (Daghir, 2009). However, their higher production performance and feed conversion efficiency make today's chickens more susceptible to heat stress than ever before (Lin et al., 2006). The thermoregulation characteristics of poultry differ to some extent from those of mammals due to their high rate of metabolism associated with more intensive heat production and low heat dissipation capacity caused by their feathers and lack of sweat glands. Evaporative cooling is achieved exclusively by panting. In the first days of their life poults need hot climate (32-38°C, Table 1), but the optimal temperature decreases rapidly with age by 2.5-3.0°C per week (FASS, 2010). After feathering birds prefer mean ambient temperatures between 18-22°C for their growth performance and egg production although the optimal temperature for feed efficiency is higher. The crucial temperature for poultry is 30°C, because up to this point birds, through a better feed conversion rate and lower basal metabolic rate, are able to compensate for the energy loss caused by the lower feed intake (Daghir, 2009). Above 30°C the feed and energy intake declines to such an extent that birds are no more able to compensate for it, production declines rapidly and the rate of mortality increases.

The reduction of feed consumption in response to high temperatures is closely associated with the severity and duration of exposure. In broilers the rate of feed refusal during heat stress increases with age (Gonzalez-Esquerra & Leeson, 2005) and can be as high as 50%. Accordingly, layers reduce their feed intake by approximately 30-50% in severe heat stress (34-35°C). In addition, several studies reported that high ambient temperatures decrease the digestibility of nutrients in poultry likely due to a reduced activity of trypsin, chymotrypsin, and amylase (Hai et al., 2000). Consequently, the lower and by most probability insufficient nutrient supply limits egg production and egg mass in layers, and the growth rate in broilers. During heat stress birds lose a large amount of carbon dioxide by panting; CO_2 however, is essential for Ca-carbonate in eggshell formation. Therefore, in addition to an insufficient nutrient supply, the compromised egg shell formation limits the egg production further (egg/day or egg production/number of birds), which can be very substantial as the egg production percentage might decline from 80-90% to 50-60%, with a 10 g lower egg weight on average (Mashaly et al., 2004; Table 2). Furthermore, the lack of carbon dioxide results in decreasing eggshell thickness and an increasing number of broken eggs that further aggravates the profit losses in hens kept in a hot environment.

As mentioned before, hyperventilation during heat stress results in respiratory alkalosis due to the high rate of CO_2 excretion. This means that there will be an excess of alkaline metabolites in the body, as the formation of HCO_3^- is insufficient due to the high loss of CO_2. In order for the body to be able to maintain the homeostasis of electrolytes in body fluids it increases the level of K^+ and Na^+ excreted in the faeces and urine, while the Cl^- concentration of the blood rises. Due to the anyway considerable surplus of Cl ion it is recommended to discontinue chlorination – where chlorinated water is used – on extremely hot days (Daghir, 2009). The high rate of monovalent ion discharge also impairs the water balance of the birds. Despite the fact that at high temperatures the birds have a higher water intake, the water retention capacity of the body decreases significantly due to the altered electrolyte balance; accordingly, the reduction in intracellular water alters the osmotic pressure and electrical potential of cell membranes as well as the intracellular-extracellular

	Weeks of treatment					
	1	2	3	4	5	Mean
Daily feed consumption (g/bird per day)						
Control	76.3[a]	96.1[a]	93.7[a]	84.1[a]	83.2[a]	86.7[A]
Cyclic	50.9[b]	74.5[b]	62.8[b]	70.5[b]	70.8[b]	65.9[B]
Heat stress	23.2[c]	38.4[c]	54.4[c]	48.2[c]	43.8[c]	41.6[C]
Egg production (%)						
Control	81.2[a]	88.3[a]	89.0[a]	91.0[a]	87.4[a]	87.4[A]
Cyclic	78.4[a]	81.9[a]	85.7[a]	83.3[a]	83.1[a]	82.5[A]
Heat stress	48.0[b]	52.9[b]	63.1[b]	61.1[b]	55.8[b]	56.2[B]
Egg weight (g)						
Control	56.4[a]	56.3[c]	56.2[a]	56.2[a]	57.1[a]	56.4[A]
Cyclic	53.2[b]	53.3[b]	53.5[b]	53.5[b]	54.0[b]	53.5[B]
Heat stress	51.1[c]	46.8[c]	46.0[c]	45.4[c]	45.0[c]	46.9[C]
Egg shell weight (g)						
Control	5.03[a]	5.13[a]	5.09[a]	5.10[a]	4.96[a]	5.06[A]
Cyclic	4.45[b]	4.77[b]	4.90[b]	4.87[b]	4.82[a]	4.76[B]
Heat stress	3.44[c]	3.62[c]	3.60[c]	3.51[c]	3.31[b]	3.50[C]
Egg shell thickness (x 0.01 mm)						
Control	35.2[a]	36.2[a]	35.8[a]	33.9[a]	33.1[a]	34.8[A]
Cyclic	32.2[b]	35.0[b]	35.8[a]	33.6[a]	33.0[a]	33.9[A]
Heat stress	26.8[c]	29.3[c]	28.3[b]	28.4[b]	28.7[b]	28.3[B]

[1] Control: 23.9°C and 50% relative humidity; Cyclic: ranging from 23.9 to 35°C and from 50 to 15% relative humidity, representing natural cyclic temperatures during hot summer months; heat stress: 35°C and 50% relative humidity.

[a, b, c] and [A, B, C] means in the same column with no common superscript differ significantly at P≤ 0.05 level

Table 2. Effect of heat stress on different production parameters in commercial laying hens kept different thermal conditions[1] (Mashaly et al., 2003).

homeostasis (Borges et al., 2003). The lack of homeostasis and the heat stress per se accelerate the production of free radicals in the body and lead to a higher risk for oxidation, which is detrimental for the hatchability of eggs, as well as for the growth performance and meat quality of poultry.

Broilers were observed to respond to high ambient temperatures by a decreased protein synthesis and increased protein breakdown (reviewed by Lin et al., 2006). This appears to be supported by trial findings that report lower body protein and muscle tissue protein plus higher fat levels in heat stress (Gonzalez-Esquerra & Leeson, 2005; Aksit et al., 2006). The deterioration of meat quality is not limited to the altered protein/fat ratio, as the mobilization of minerals and vitamins from tissues due to heat stress (Sahin et al., 2009) further compromises the nutritive value of eggs and meat (Sahin et al., 2002). The prevalence of other deficiencies of meat quality, such as high drip loss, too pale color (Aksit et al, 2006; Table 3), and PSE (pale, soft and exudative) meat also increase (McKee & Sams, 1997) and these contribute to a significant decline in consumer confidence.

	Yield		Meat nutrient composition		Meat quality[2]			
	Carcass (%)	Breast (%)	Moisture (%)	Protein (%)	pH	L*	a*	b*
Control	73.8[a]	29.9[a]	74.7[a]	23.5[a]	6.00[a]	48.94[a]	2.99[a]	4.19[a]
28-22°C	72.9[b]	29.5[a]	74.4[a]	22.1[ab]	5.95[ab]	53.04[b]	4.49[b]	5.71[b]
34°C	71.5[c]	28.4[b]	72.4[b]	21.6[b]	5.89[b]	53.94[c]	5.21[b]	4.44[a]
SEM	0.2	0.2	0.2	0.3	0.02	0.30	0.28	0.31
P-values	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003

[1] Control: temperature was maintained at 22°C; 28-22°C: temperature was 28°C from 1000 h to 1700 h and at 22°C from 1700h to 1000 h; 34°C: temperature was kept at 34°C from 3 to 7 weeks of age
[2] L*: lightness; a*: redness, b*: yellowness
[a, b, c] means in the same column with no common superscript differ significantly at P≤ 0.05 level
SEM: Standard Error of the Mean

Table 3. Effect of rearing temperature[1] on carcass and breast meat percentage, meat composition and some meat quality traits (Aksit et al., 2006).

In summary, high ambient temperatures impair egg production by decreasing the number and weight of eggs as well as by reducing the eggshell quality, whereas in meat-type chickens lower growth rates and higher feed per gain ratios are predominant. The deterioration of meat quality traits due to heat stress occurs mainly in consequence of the associated higher rate of lipid peroxidation and the altered electrolyte balance.

3.3.2 Pig performance and pork quality

The climate change with rising mean temperatures may cause a permanent stress load for pigs, especially in continental summer or warmer climate areas. As shown in Table 1, the upper critical temperature for pigs from nursery to adult ages is 25-26ºC; however, some research data suggest that the optimal temperature decreases with the increase in body weight. The heavier an animal, the less ability it has to lose heat due to the relative small surface area compared to its body weight. In consequence feed refusal increases with body weight at high ambient temperatures (Close, 1989; Quiniou et al., 2000).

In case of sows kept at high ambient temperatures (29ºC vs 18ºC) the feed intake over the entire lactation period may fall back by more than 50%, resulting in a loss of body condition far exceeding the optimum and also leads to poorer growth of the piglets (Table 4).

	Ambient temperature (ºC)				
	18	22	25	27	29
Daily feed intake (g/d)					
Day 1 to 21	5666	5419	4947	4520	3079
Day 7 to 19	7161	6401	6084	5321	3483
Body weight loss (kg)	23	22	25	30	35
Backfat thickness loss (mm)	2.1	1.9	2.7	3.5	3.5
Pig growth rate (d 1-21; g/d)	244	245	233	212	189

Table 4. Effect of ambient temperature on performance of multiparous lactating sows (Quiniou & Noblet, 1999).

The condition of the sows is also in close correlation with the number of days to oestrus and the reproductive performance. Studies with pair fed sows showed that the energy metabolism and hormonal status of the animals changed during heat stress and the lower milk production is not exclusively explained by the reduced feed intake (Prunier et al., 1997; Messias de Bragan et al., 1998). Renaudeau et al. (2003) suggest, that the apparent inefficiency of the sow mammary gland in hot conditions could be attributed to an increased rate of blood flow irrigating the skin capillaries in order to dissipate body heat and this in turn results in a lower blood flow to the mammary gland cells. Feeding high fat diets (125 g fat per kg of dry matter) to the sows during lactation in order to alleviate hyperthermia leads to decreased heat production, which may reduce the feed refusal of the sows kept at high ambient temperatures (Babinszky, 1998). Feeding high fat diets also improves the energetic efficiency of milk production when compared to sows fed high starch diets (with low dietary fat levels, Table 5). From the aspect of energetic efficiency milk fat production is more efficient from dietary fat than from dietary carbohydrates because it is converted more directly (Babinszky, 1998).

	Exp. 1*			Exp. 2*		
	LF	MF	RMSE	LF	HF	RMSE
ME intake ($MJ/kg^{0.75}/d$)	1605	1626	160	1445	1404	112
Heat production ($MJ/kg^{0.75}/d$)	795	779	20	771^{a}	719^{b}	18
Energetic efficiency of milk production (%)	71	72	1	70	73	1

* In exp. 1 LF: low fat diets (43g/kg dry matter); MF: medium fat diets (75 g/kg dry matter); in exp. 2 LF: low fat diets (37 g/kg dry matter); HF: high fat diets (125 g/kg dry matter)
RMSE: Root Mean Square Error
$^{a, b}$ means in the same row with no common superscript differ significantly at P≤ 0.05 level

Table 5. Effect of dietary energy source on the heat production of lactating sows and on the energetic efficiency of milk production (Babinszky, 1998).

Since the milk production of the lactating sow determines the performance of the suckling pigs in terms of their growth rate, mortality and morbidity, any reduction in the milk yield will have a negative impact on the profitability of pig production. Moreover, heat may also compromise the parameters of fertility: the quality of eggs and sperm deteriorates; embryo mortality between days 1 to 15 increases and maturity is delayed. In consequence, the number of piglets per sow may be less when sows are exposed to high ambient temperatures for longer periods of time.

High temperatures cause loss of appetite in pigs; however, both the upper critical temperature and the rate of feed refusal are influenced by the relative humidity of the air (Collin et al., 2001; Huynh et al., 2005). With the increase of humidity a 60 – 70 kg pig may lower its feed intake by up to 80-150 g/day (Huynh et al., 2005). The lower feed intake compromises the daily gain, however, after exposure to hot periods of 30-33ºC pigs display compensatory growth, they overcome their heat stress and grow further, but they can't compensate for temperatures as high as 36ºC (Babinszky et al., 2011). There is a curvilinear relationship between the increase of temperature and the average daily gain and feed conversion rate of pigs fed *ad libitum* (reviewed by Noblet et al., 2001). The average daily gain reaches its maximum between temperatures of 15 to 25ºC in young pigs (up to 30-34 kg) and between 10-20ºC in growing and finishing pigs. Both cold and severe heat stress compromise feed conversion; however, during moderate heat stress (2-3ºC above the upper critical temperature) pigs have the ability to compensate for the lower feed intake by decreasing their maintenance related heat production. Besides constant heat stress, diurnal high temperatures can also be detrimental to pig performance. The average daily feed intake and the average daily gain decreased by 10 and 20%, respectively, and the feed conversion (feed/gain) increased by approximately 8% when pigs were kept in a daily range of 22.5 to 35ºC in contrast to the thermoneutral (20ºC) temperature (Lopez et al., 1991). In the interest of performance and immune response it is recommended to avoid any higher fluctuations (±12ºC) of the mean of 20ºC (Noblet et al., 2001).

Recent publications highlight the fact that high temperatures not only impair growth but also change body composition and thus can impair the nutritive value and quality of pork. Prolonged heat stress (30-33ºC) reduces the rate of protein deposition in growing and finishing pigs (Kerr et al., 2003; Le Bellego et al., 2002). As seen in the above, the lower protein deposition is probably not just in consequence of the lower nutrient supply. Halas et al. (2004) demonstrated in their model simulation that the rate of protein deposition is sensitive to any changes occurring in the maintenance energy requirement of the body. Heat stress triggers hormonal changes that influence the metabolism of nutrients. Reduced levels of thyroid hormones were consistently observed in swine kept in a hot environment in contrast to a thermoneutral milieu (Messias de Bragan et al., 1998; Renaudeau et al., 2003**)**. Thyroid hormones are responsible for the metabolic rate and thermogenesis besides influencing the protein turnover within the body. Although carcass fatness decreases as a result of lower feed intake during heat stress, the shift of fat distribution from external sites towards internal sites was found to be attributable to a reduced activity of the lipogenic enzyme in backfat and a higher activity of lipoprotein lipase in lean fat (Noblet et al., 2001).

In conclusion, heat stress impairs feed intake and swine performance in the lactating sow and in growing and fattening pigs. The extent of this detrimental effect depends mainly on body weight and the actual temperature and relative humidity of the air. Recent studies show that growing and fattening pigs kept in hot environments deposit less protein, which compromises pork quality with regard to the protein to fat ratio in the meat. Any means of reducing heat production or increasing heat loss of the animals are beneficial in the efforts to avoid the weakening of the production potential of swine when facing with global warming.

3.3.3 Cattle production: milk production, milk quality and beef production

In dairy cows, similarly to other species the various factors of the environment, such as the average temperature, humidity and air velocity all play an important role in the fertility, reproductive performance and milk yield of the animals, and this is particularly true in animals with high genetic potential. The optimal ambient temperature for dairy cows is between 5 to 15ºC. Over 15ºC the animals start to sweat, although they are still able to maintain the equilibrium between heat production and heat dissipation. Heat dissipation by sweating gradually increases and although it becomes quite intense above the upper critical temperature (25ºC) the cow is no more able to maintain the heat balance at such high temperatures. Kadzere et al. (2002) found that on days of heat stress the amount of water lost through evaporation may be up to or even exceed the amount of water excreted in the milk. The high rate of water loss stresses the importance of water supply for dairy cows at high temperatures. The efficiency of body cooling by evaporative water loss, however, decreases with the increase of humidity. The use of the Temperature-Humidity Index (THI) is suggested as an indicator of the thermal climatic conditions (THI = 0.72(W + D) + 40.6, where W is wet bulb and D is dry bulb temperature in ^{o}C). When the THI is in the range of 72-80, 80-90 or 90-98, the corresponding heat stress is mild, medium or severe. Both the increasing ambient temperature (from 25 to 32^{o}C), and the increasing THI (from 73 to 82) have a negative impact on the dry matter intake and milk production of cows (West et al., 2003). The relevant data show, that the shorter the animal is exposed to heat stress, the better they can tolerate it, although even a moderate heat stress will impair their production performance. As mentioned earlier, there are other environmental factors besides temperature and humidity that affect thermal sensation. According to the results of a model simulation the critical ambient temperature that can compromise the respiratory response of a 600 kg live-weight Holstein cow is largely dependent on the daily milk yield, coat depth, exposed surface area, air velocity and water vapor pressure (Berman, 2005; Table 6) and in varying environmental conditions the upper critical temperature of the animals can fluctuate in a wide range (8 to 42°C).

Item		Terms in model				
Milk yield (kg/d)		35	35	45	35	35
Coat depth (mm)		3	6	3	3	3
Exposed surface area (%)		100	100	100	75	50
Air velocity (m/s)	PW[a]	Predicted threshold air temperatures, °C				
0.2	1	37	36	32	29	16
0.2	3.4	30	27.5	25	24	8
1.5	1	41	42	36	34	22
1.5	3.4	40	39	34	33	14
0.85	1	39	37	36	34	20
0.85	3.4	36	31	31	31	11

[a] water vapor pressure (kPa)

Table 6. Simulation values for air temperature (°C) at which threshold respiratory response (53% of maximal respiratory heat loss) is attained by a 600-kg body weight Holstein cow (Berman, 2005).

The heat stress caused feed refusal predisposes the animal to certain metabolic disorders, first of all to ketosis. The occurrence of ketosis at herd level not only leads to a temporary decline in milk production, but in consequence of the mortalities may also cause a drop in the number of dairy cows. The adaptive mechanisms that serve survival, for instance in the case of harsh ambient temperatures, weaken the production performance. One element of the long-term adaptation to high temperatures is slowing the heart rate, which leads to a lower level of heat production associated with maintenance. At the same time circulation in the mammary glands is impaired, resulting in poorer milk yield. The ability of dairy cows to adapt to the changes of their environment depends on their genetic potential. The present-day selection for production weakens heat tolerance, thus combined selection for heat tolerance and production is recommended when facing the challenge of climate change (Ravagnolo & Misztal, 2000).

The lower feed intake and higher water consumption during heat stress result in a modified fermentation and volatile fatty acid production in the rumen since the high temperature may affect the functioning of rumen bacteria. Of the volatile fatty acids produced in the rumen and transported to the bloodstream acetic acid is primarily used for lipid synthesis, while the level of propionic acid influences the protein content of milk. In a study with Jersey cows the proportion of acetic acid in the rumen contents as well as the ruminal pH significantly decreased when the cows were kept at 30°C instead of 20°C (Bandaranayaka & Holmes, 1976). In consequence the protein and fat content of the milk, and also the proportion of middle-chain fatty acids (C_6 –C_{14}) in milk fat decreased at high temperature.

The lower feed intake caused by high ambient temperatures compromises the protein supply of the cows in an indirect manner as well, in so far as the lower rations mean less sulphur supply, which may limit the protein synthesis by rumen bacteria, and which certainly affects the level of the essential amino acid, methionine. The lower level of microbial protein, which has a crucial role in the protein supply of ruminants, and/or the lower methionine content in the rumen flora clearly lead to a decrease of milk protein. Consequently the sulphur supply of rumen flora should receive particular attention at high ambient temperatures in order to avoid the fall of milk protein. Several studies have confirmed that adequate sulphur supply yields further benefits. Adding potassium, sodium, or magnesium sulfate to diets of dairy cows may enhance the digestibility of dry matter; therefore, it is recommended to increase dietary sulfur during heat stress in order to improve the digestibility of nutrients and to maintain the protein content of milk (Kadzere et al., 2002).

Heat stress increases loss of body fluids due to sweating and panting and results in an altered water balance of the body and the osmolarity of cells. Enhanced respiration associated with a higher rate of CO_2 loss leads to an altered blood pH and respiratory alkalosis. An increased urinary pH can help to overcome alkalosis caused by the high excretion of bicarbonate (HCO_3^-) (Kadzere et al., 2002); however, these processes have energetic and thermoregulatory consequences. Excretion of sodium in the sweat and urine increases during heat stress, at the same time the level of Na available in the body determines, even if indirectly, the milk fat content. $NaHCO_3$ acts as a key buffering agent in the rumen, alleviating the low-fat milk syndrome. Several studies have shown significant increases in the milk production of heat-stressed dairy cows when fed higher than recommended (NRC, 1989) concentrations of sodium ($NaHCO_3$) and potassium (i.e. KCl) (reviewed by Silanikove et al. (1997).

In beef cattle the unfavorable meteorological conditions directly affect the animals and their physiology as discussed in the above section for dairy cows. Extreme weather conditions diminish the growth performance (weight gain, feed intake and feed conversion potential) of beef calves, particularly of those kept outdoors. Slower growth and smaller slaughter weight however are reflected in the quality of meat as well, since animals of the same age but smaller body weight have less muscle fat and also the taste panel traits of juiciness and tenderness are poorer (Keane & Allen, 1998). The predicted climate changes not only weaken the performance of livestock per se, but also compromise the conditions for production by reducing the quality of feedstuffs, as earlier discussed in this chapter. Increasing mean temperatures and declining precipitation reduce the dietary crude protein and digestible organic matter content of grass; it is unlikely, however, that any future increases in precipitation would compensate for the declines in forage quality following from the projected temperature increases (Craine et al., 2010). Aridity, water deficiency may lead to a drop in groundwater levels, alteration and thinning of pasture flora, and in consequence to a decline in feed supply, besides aggravating the problems of water supply (Babinszky et al., 2011). As a result, cattle are likely to experience greater nutritional stress in the future with the two options of either accepting the loss of performance or being prepared to provide supplemental nutrition to the extensive beef sector as well. Feeding concentrate to beef cattle increases the costs of beef production, and it may also affect the nutritive and health value of meat. In respect of fatty acid composition, numerous publications suggest that the meat of grass fed cattle contains more n-3 fatty acids and conjugated linoleic acid than meat from their concentrate fed peers (Scollan et al., 2006; Nuernberg et al., 2005). These fatty acids play an important role in maintaining health and preventing diseases (i.e. cardio vascular diseases, cancer) and consumers are increasingly aware of these functional components of foods. In addition to the above-mentioned problems, extreme weather may result in respiratory disease, immune suppression and thus higher mortality of the animals, which further reduces the profitability of beef production.

Summarizing the relevant data it can be stated that sever heat stress results in an average production loss of 1.5-2 liters/cow/day (5-10 % of the daily milk yield). Moreover, the altered rumen fermentation influences not only milk yield but also milk composition by reducing its protein and fat content. In case the predicted climate change occurs, the present beef production potential can only be maintained if supplemental feeds are offered, but this would significantly reduce the economic efficiency of cattle production and may have an impact on beef quality as well.

It is clear from the previous section that the efficiency of nutrient metabolism in farm animals suffers if the climatic conditions fall outside the thermoneutral environment. It should also be emphasized that poorer nutrient digestibility and efficiency of utilization both lead to a higher rate of nutrient excretion (i.e. N and P), with a consequent negative impact on the environment. The higher rate of nutrient excretion damages the actual production potential as well as the product quality, and it also compromises the health status of feed producing animals with possible feed safety consequences.

4. Feeding strategies in response to climate change

Climatic conditions determine the energy and nutrient metabolism of farm animals. According to relevant data climate change leads to a higher mean ambient temperature, and it may even result in extreme weather in certain parts of the World. This calls for a discussion of feeding strategies in response to climate change, including nutritional manipulation and feeding during cold and heat stress.

4.1 Feeding strategies during cold stress

As earlier mentioned, animals consume more feed at low ambient temperatures in order to compensate for the increased energy requirement used in thermoregulation. From the aspect of energy requirements a cold environment is essentially the equivalent of reduced energy supply, and thus higher feed intakes and higher energy intakes can meet the extra demand of thermogenesis. When the increased feed intake is prevented by the limitations of the animal's gastro-intestinal system, any means of boosting the dietary energy of the feed may be suitable for maintaining growth, and egg and milk production. Although increasing the dietary energy in a thermoneutral environment is associated with the improvement of feed conversion (the amount of feed required to produce 1 kg of product), in cold ambient temperatures, however, feed conversion may become worse or in the best case does not change with the feeding of high energy density diets due to the higher use of maintenance – i.e. non-productive – energy.

The body attempts to compensate for the excessive heat loss suffered in cold temperatures by a higher rate of heat production, and one component of this is to increase the use of maintenance energy. Heat, however, is also generated in the course of digesting and converting the dietary nutrients (the thermic effect of diet), which helps to maintain body temperature in conditions below the lower critical temperature; accordingly the feeding of diets with a high thermic effect will help the animals cope with the too cold environment. Thus for example, when high fiber diets are fermented by the colon bacteria a relatively high portion of energy is lost as heat; and the oxidation of proteins / amino acids as a form of energy producing process also produces lot of heat. Therefore, feeds containing a high percentage of fermentable fibers or excess protein increase the heat production of the animals. In practical feeding, however, protein overfeeding is not recommended either from the economical or the environmental point of view.

4.2 Feeding strategies during heat stress

Since heat production after ingestion of the diet is high, farm animals reduce their feeding activity at high ambient temperatures, which bears significant consequences on their nutrient intake. The practice of feeding the daily ration in several smaller portions or during the cooler parts of the day follows from the above. Based on the previous sections other potential feeding strategies can be applied at the time of heat stress, which (i) reduce the heat production by the animals; (ii) compensate for the lower nutrient supply; and (iii) alleviate heat stress induced metabolic changes. It should be noted, however, that during severe heat stress these methods should be used in combination in order to maintain the production performance of the farm animals and the quality of their products.

4.2.1 Methods to reduce the total heat production of livestock

Methods to reduce total heat production of farm animals consist of (i) fat supplementation, (ii) feeding low protein diets with synthetic amino acids according to the ideal protein concept, and (iii) adding dietary betaine.

(i) In comparison to other nutrients, fat generates the least heat, either when deposited as body fat or when used for energy, thus high fat diets reduce the total heat production of the animals. Accordingly, fat supplementation moderates feed refusal, which is critical for the production potential. At the same time, fat supplementation boosts the energy density of the diet, as the energy content of fat sources (both of plant and of animal origin) is far the highest compared to the other nutrients and to compound feeds. By adding fat to the diet the energy requirement of the animals can be met accurately even if the feed intake decreases to some extent above the upper critical temperature.

(ii) The so-called ideal protein refers to a well-defined amino acid pattern, which expresses the requirement of essential amino acids in percentage of lysine. The amino acid pattern of the ideal protein changes to some extent during the life of the animals in accordance with their level of production (Table 7). Amino acid conversion and N excretion are the lowest when diets are formulated according to ideal protein concept. Excess amino acids that cannot be used in protein synthesis due to a limiting factor (such as a limiting amino acid, energy supply or genetic potential) are metabolized in the body. Compared to other nutrients, the oxidation of amino acids yields the most heat contributing to the total heat production. Consequently, the heat increment is higher when excess amino acids are present in the diet. The heat increment from protein metabolism is at the minimum if the dietary protein level meets the requirements of the animal, and if the amino acid content or even the ileal digestible amino acid content corresponds to the ideal protein concept.

	Body weight range		
Amino acids, % of Lys	5-20 kg	20-50 kg	50-100 kg
LYS	100	100	100
THR	65	67	70
TRP	18	19	20
MET + CYS	60	65	70
ILE	60	60	60
LEU	100	100	100
VAL	68	68	68
HYS	32	32	32
PHE + TYR	95	95	95

Table 7. Amino acid composition of ideal protein as a percentage of lysine for growing and finishing pigs (Baker & Chung, 1992).

(iii) Betaine (trimethylglycine) is an intermediate metabolite in the catabolism of choline, which can modify the osmolarity, acts as a methyl donor, and has potential lipotropic effects. Schrama et al. (2003) showed that under thermoneutral conditions dietary betaine supplementation (1.23 g/kg) reduced the total heat production of pigs. Moreover, recent studies repeatedly recommend using betaine in pig and poultry feeds during heat stress (Metzler-Zebeli et al., 2008), as being a methyl donor it can be used in the antioxidant defense (for glutathione-peroxidase) system, and it also efficiently inhibits the reduction in cell water retention.

As previously mentioned, dietary fiber increases the heat production of the animals, and this raises the question as to how feed should be formulated for animals that require high levels of dietary fiber, such as gestating sows and ruminants. In gestating sows the diluted (low energy content) feed with high fiber content prevents the sows becoming overweight, which could otherwise lead to health problems and insufficient milk production during lactation. According to data reported by de Lange et al. (2006), the overall energy cost of ingesting and excreting indigestible material in growing pigs is very small, thus the use of poorly digestible fiber sources in gestating sow diets may be beneficial at high temperatures. In ruminants high dietary fiber content supplied in the daily ration is indispensable for adequate rumen fermentation. Bearing in mind the positive correlation between the metabolizability of the diet and the efficiency of energy utilization, it can well be recommended to feed high quality forages and other highly digestible fiber sources to ruminants during heat stress. This will result in a somewhat lower heat production by the animals, in contrast to cows fed with poor quality forages. At the same time it is probable, that due to the extreme weather conditions high quality forages can only be produced using special agro techniques, which will increase their price. The role of drought resistant grasses (e.g. brome grass, tall fescue, crested wheatgrass, etc.) and leguminous species becomes more important in the flora of pastures for grazing animals (Babinszky et al., 2011); however, new varieties of grasses would likely be used requiring joint research projects of plant breeders with animal nutritionists.

The above sections discussed the extent of feed refusal during heat stress and its effect on livestock performance. If the decrease in feed intake can be alleviated or prevented, the nutrient supply will meet the requirements of the animals for high production potential and good quality food production.

4.2.2 Compensating for reduced nutrient supply

Since heat stress impairs feed intake and the digestibility of nutrients too, it is recommended to feed more concentrated diets with high levels of easily digestible nutrients in hot environments. This should be implemented with the use of various options offered by the feed manufacturing technologies (hydrothermic treatments, micronization), and also by increasing the level of dietary vitamins and minerals, and perhaps by improving their bioavailability. The bioavailability of nutrients can be achieved in part by enhancing the digestibility of nutrients in the small intestine (ileal digestibility) and also by boosting the utilization of absorbed nutrients (e.g. use of organic trace elements). Adding different enzyme supplementation to the diet can improve the ileal digestibility of nutrients, such as amino acids, carbohydrates and Ca and P. It is suggested, however, to use substrate specific dietary enzymes (phytase, xylanase, β-glucanase, etc.) in accordance with the composition of feed.

The use of methods that improve the digestibility and bioavailability of nutrients is also desirable from the aspect of environmental protection. Improving the digestibility and conversion of nutrients, and meeting the requirements of the animals accurately can serve to curb the environmental load from animal husbandry. At the same time it should be stated that enhancing the nutritive value of animal diets becomes particularly important in hot climates.

4.2.3 Alleviating heat stress induced metabolic changes

The third group of nutritional strategies aims to alleviate the heat stress induced metabolic changes within the body. These are means to enhance the oxidative defense or alleviate the shift in electrolyte balance within the body. Several micronutrients possess direct or indirect anti-oxidative properties; those most extensively examined in farm animals are vitamin C, E and A, zinc and selenium as well as methionine. According to the findings of relevant studies the nutrients listed in the above improve the defense of farm animals against lipid peroxidation; also the body requires more of these antioxidants during heat stress. This is why it should be stressed, that vitamin and mineral supplementation not always leads to the improvement of production performance or product quality of animals kept in hot environments, even though they are essential to maintaining their health status. The excretion of Na and K and the amount of water lost from the body increase during heat stress, which together may lead to a shift in the acid / base balance. Supplementing monovalent ions in the diet can lessen the decrease of water retention by the body. Salts suitable for the purpose are ammonium chloride, sodium and potassium bicarbonate, sodium and potassium hydro carbonate, potassium sulphate, etc., which can be equally used in poultry, swine and ruminant nutrition.

With respect to alleviating the non-desirable consequences of climate change, the combined application of the options discussed in the above can counteract the negative impact of conditions outside the comfort zone of farm animals. Knowing the altered nutrient requirements and adjusting the nutrient supply to them can help to prevent the deterioration of production performance and product quality. However, in addition to precision feeding, housing should be adjusted to the climatic conditions as well, i.e. animals should be kept in well insulated, heated or cooled buildings, in accordance with the ambient temperatures. The most important action for alleviating the impact of heat stress is to open up enclosed buildings, in order to increase their cubic capacity. Outdoor pens become more important for breeding animals and further solutions can be to establish sprinkler systems, wallows, and to cool the buildings with adiabatic systems or heat exchangers (Babinszky et al., 2011). There is a consensus that genetic selection should aim to improve the heat tolerance of high producing farm animals without impairing their genetic potential. The continuously expanding poultry production in the tropical and subtropical regions of the Earth already necessitates the revision of selection strategies of breeding programs (Lin et al., 2006). There are promising results from efforts aimed at developing technologies to improve the adaptation of meat and egg type poultry to hot environments. The improvement of adaptive abilities to the changes of the ambient temperature besides maintaining the existing production potential will become one of the selection objectives and technical solutions in response to the climate change, and not only for poultry but for other farm animal species as well. Based on all this it can be concluded that the combined application of animal feeding and housing developments plus of genetic programs is required in order to maintain or even improve the production efficiency and product quality of farm animals despite the climate change.

5. Conclusion

In summary it can be concluded that we should expect climate change to cause long-term changes in the environment, which in turn affect feed crop production and the production of farm animals.

An important task facing feed crop breeders is to create C3 feed crop varieties that as a result of the selective breeding efforts become more drought tolerant besides maintaining their average yields and nutrient contents. It will be our task as nutritionists to use these improved feed crop varieties in a highly focused and professional manner when formulating diets.

When developing professional animal nutrition however, we should not only rely on traditional nutritional science but should also use the results of its related disciplines (microbiology, immunology, molecular biology, molecular genetics, digestive physiology, etc.) besides having a thorough knowledge of the energy metabolism of farm animals. As discussed earlier, there is a very close relationship between the energy metabolism of the animals and the ambient temperature, and the animal performance and the quality of their products. The knowledge of these factors enables us to alleviate by means of nutrition the stress caused by climate change and in consequence to produce high quality and safe foodstuffs meeting the requirement of human nutrition without increasing the environmental load of production.

This also means that the different disciplines can only provide an adequate response to the challenges of climate change in cooperation. Therefore, climate researchers, meteorologists, plant breeders, crop producers, animal nutritionists, biologists, geneticists, livestock producers, animal housing technicians, nutrition biologists, doctors, etc. should all work together in the frames of a carefully structured and coordinated project to achieve this objective.

The task is given, and its accomplishment depends on us only.

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11

Climate Change Impacts: An Assessment for Water Resources Planning and Management in the Pacific Northwest of the U.S

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1. Introduction

Assessing the hydrological impacts of climate change in the Pacific Northwest (PNW) region of the United States is important. Many global circulation models (GCMs) have a wide range of temperature and precipitation predictions for the PNW region (Bureau of Reclamation, 2011). Numerous studies have reported that decreasing snow pack, increasing temperatures and decreasing streamflow for many basins. For instance, Mote (2003) indicates that annual average temperatures in the Northwest rose faster than the global average during the 20th century. This warming occurred mostly during the winter and spring. The predominance of winter and spring warming, especially in regard to extreme minimum temperatures, was confirmed more recently in a smaller study at two locations: one in Western Montana and the other in British Columbia (Caprio et al., 2009). The warming climate has resulted in a lengthened growing season (Kunkel et al., 2004), decline of snowpack (Mote, 2006), and earlier timing of the spring runoff (Stewart et al., 2005; Hamlet and Lettenmaier, 1999). Water supply in the West is vulnerable to climatic change, mainly because it relies heavily upon the capture of the spring runoff. Precipitation typically accumulates in the mountains as snowpack and is released during the spring melt, which may continue at high elevations into July. Warmer temperatures are likely to lead to more rain and less snow in the winter, causing an increase in the wintertime streamflow and decrease in spring runoff. Warmer weather is also likely to cause snowpack to retreat to higher elevations and experience earlier melt (Hamlet and Lettenmaier, 1999).

2. Expected future climate

In our study, we chose the following five models based on the discussion above, which includes all three scenarios, A1B, A2 and B1 for five global circulation models. The models are: MIROC and CCSM3 (wet and warmer winter), HadCM3 (warmer and drier summer) and PCM (cooler and summer). The outputs, primarily precipitation and temperature, from the GCMs are coarser and they needed to be first downscaled to a specific area if we were to get meaningful interpretation of the impacts of climate change at the local scale. The original climate projections are from the World Climate Research Programme's (WCRP's) Coupled

Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, which was referenced in the Intergovernmental Panel on Climate Change Fourth Assessment Report. We downloaded bias-corrected and spatially downscaled climate projections for the models mentioned above which were derived from CMIP3 data and served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/, described by Maurer et al (2007).While there are many methods for downscaling the climate data that can be useful, we preferred this method of bias-corrected and spatially downscaled climate projections as we are using this dataset currently for our Snake River Basin modeling project. The resolution of these datasets is monthly, 1/8th degree gridded products for the study sites. Since we required daily precipitation and temperature data for hydrological modeling, we temporally disaggregated monthly data to a daily time step by delta (change factor) method. There is a six-step procedure we performed to temporally disaggregate the GCM climate model data downloaded from the link above and is shown in Figure 5. This included a random picking of a historical year to compute mean of the daily precipitation and temperature of the gridded observed record for the same month as the future year. By calculating the difference between future monthly mean temperature and historical mean of monthly mean temperature, 'Δt' and by calculating the ratio between future monthly mean precipitation and historical mean of monthly mean precipitation, 'r', we have addition and multiplication factors. Finally, by adding "Δt" to daily temperature of the month of the randomly selected year and multiplying daily precipitation by "r" for the month of randomly selected year for the given month. We repeated this process for other months of the year for future years and for the remaining grid cells.

For the Boise River basin region between 2010 and 2060, changes in precipitation ranged between -3.8 % to 36% (A2), -9% to 35% (A1B) and B1 (-6.7% to 30.5%). However, changes in temperature are expected to be between 0.02-3.6 °C (A2), 0.8-3.9 °C (A1B) and 0.5-3.1 °C (B1). In the Spokane River region, changes in precipitation are expected to be between -3.8 % to14% (A2), -6.7% to 17.9 % (A1B) and -7.4 % to 14.3 % (B1). Changes in temperature will likely be 0.1-3.2 °C (A2), 0.8-3.5 °C (A1B) and 0.3-2.7 °C (B1). Overall, the chosen climate models showed a rise in temperature (0.31 °C to 0.42 °C/decade for Rathdrum Prairie and 0.34 °C to 0.46 °C/decade) and an increase in annual precipitation (4.7% to 5.8% for Rathdrum Prairie and 5.3% to 8.5% for Treasure Valley) over a period of next five decades between 2010-2060 (Figure 6 and Figure 7). Precipitation forecast is less certain than temperature trends as there is less agreement among the models. This is generally the case even at the global scale. However, temperature increase is found to be consistent among the models considered in this study. In general, both the regions are expected to see increased annual precipitation (4-8%) and temperature (0.31-0.45 ºC/decade) when averaged over all the GCMs.

Our objective in this study is to understand and quantify the impacts of climate change in these basins by analyzing the high flows and low flows for the period between 2010 and 2060. These flows have direct implications on how the water resources have to be managed in the basin under future climate conditions. Also, we investigate the importance of bias-correcting (conditioning) the streamflows that are critical for drawing meaningful conclusions for a given basin.

3. Study area

3.1 Boise River basin

The Boise River is a tributary of the Snake River in southwestern Idaho with a drainage area of 10,619 km2 (Figure 1(a)). The Boise River originates from the three forks of the Sawtooth

Range that subsequently join together at the Arrowrock Reservoir to form the mainstream flowing west through the Snake River Plain that finally merges with the Snake River at Parma. Topography has west to east gradient, exceeding 3000 m at the Sawtooth Range and low elevation of 640 m in the western part near Parma. The basin receives precipitation in the wintertime and the spring snowmelt-induced runoff, which begins in the lower elevations around March, typically continues to contribute a significant amount of streamflow from the high mountains into July. The peak flow period is followed by a relatively dry warm summer. During the fall season, due to reduced transpiration and autumn rainfall as well as the groundwater contribution to baseflow, the streamflow increases slightly. The average annual precipitation in the basin is 661mm and average annual mean temperature is 5.9°C. The land cover in this area is highly diverse, including alpine canyons, forest, rangeland, agriculture land and urban area (Figure 2(a)). The eastern part of the basin (upstream of Lucky Peak Dam) is mainly covered by forests. The lower part of the river basin is covered by grassland, cultivated crops and developed urban areas.

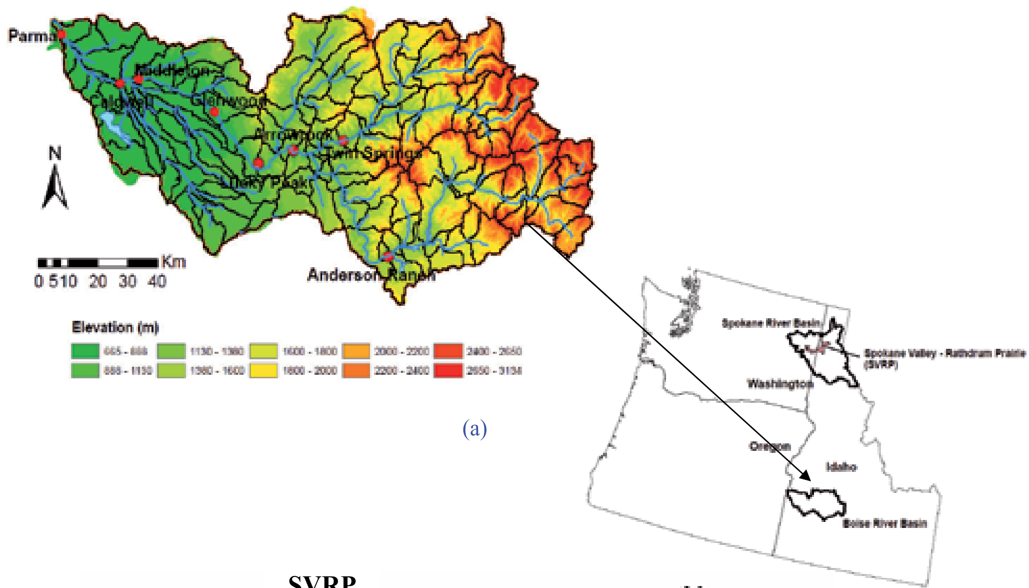
3.2 Spokane River basin

The Spokane River is located in the northern Idaho and eastern Washington with a drainage area of 17,200 km^2 (Figure 1 (b)). It rises from Lake Coeur d'Alene, Idaho and flow west through the Spokane Valley until reaching Spokane, WA. The elevation of the basin increases from west to east and the upper forested catchments receive higher precipitation. The general climate in this area is warm and dry summer (mean temperature 16°C, total precipitation in winter is 130mm), while cold and moist winter (mean temperature -3.4°C, total precipitation during winter is 328mm). The average annual total precipitation is 878 mm and average annual mean temperature is 6.2°C. More than 2/3 of the precipitation (319 mm) is received in the winter as snow. The average annual evaporation is 420 mm that is approximately 49% of the average annual precipitation. The aquifer, known as the Spokane Valley Rathdrum Prairie aquifer (SVRP), is extending from Lake Pend Oreille, Idaho to Spokane, Washington. It is the "sole water aquifer" for its 500,000 population and the aquifer is heavily extracted due to rapid growth in the region and its area is 830 km^2 covering the two states. There are a number of lakes surrounding this aquifer that serves as the sources for recharge in addition to precipitation. A series of flooding occurred during the last Glacial Age and made the soil in SVRP primarily unconsolidated coarse-grained sands, gravels, cobbles and boulders with relatively high hydraulic conductivity (Barber et al, 2009). As a result, there is a strong surface water and groundwater interaction between this aquifer and the Spokane River. Reach gains and losses are interlacing from Post Falls, Idaho to Spokane, WA. Land cover in this watershed is dominated by forests and other land cover types include urban or suburban area in the SVRP area and agriculture in the western part of the watershed (Figure 2(b)).

4. Modeling procedure

4.1 Calibration and Validation for the Boise River basin

The Soil Water Assessment Tool (SWAT) was implemented for our study. SWAT is a continuous simulation model and is widely used with readily available inputs in Geographic Information System (GIS). For data-limited, complex terrain such as ours, this model provides the firsthand information on the hydrological processes relatively easily. Furthermore, we have customized this model for other Idaho watersheds earlier (Stratton et



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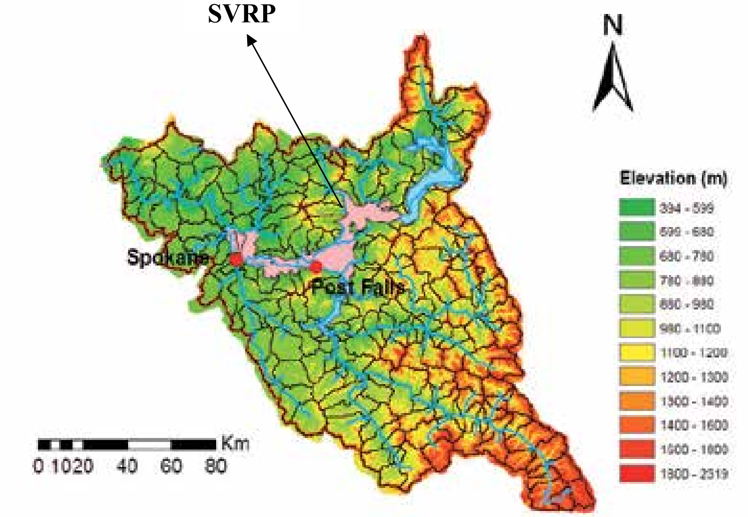
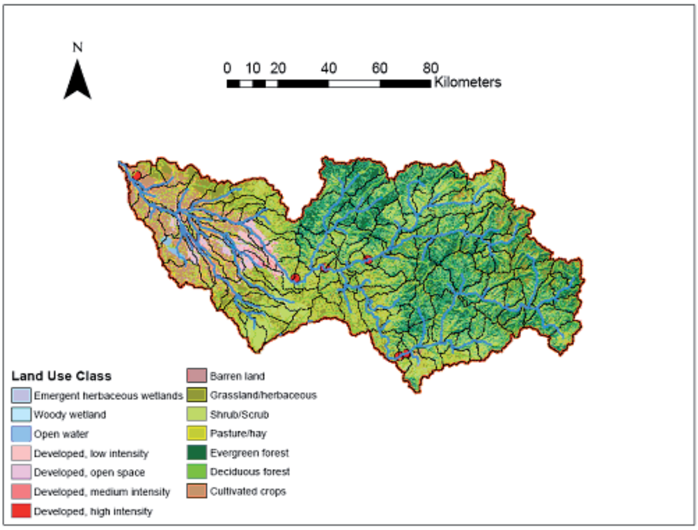


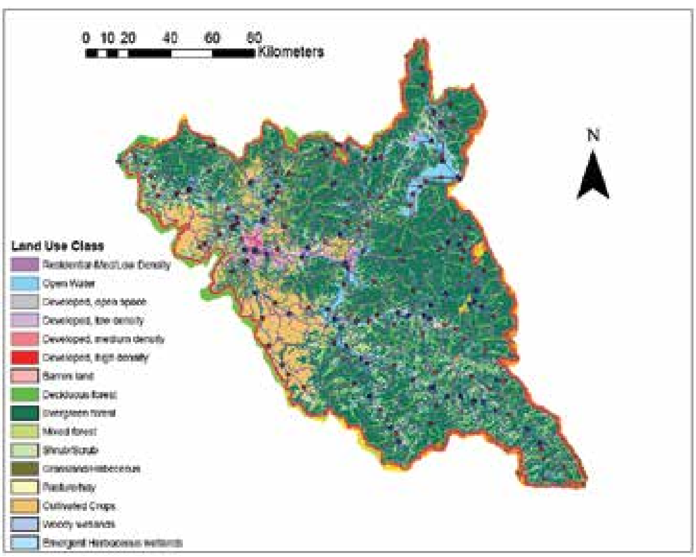
(b)

Fig. 1. Location map showing the Boise River Basin (top) and the Spokane River Basin (bottom).

al., 2009, Sridhar and Nayak, 2010). The basic drivers for this model are USGS-derived Digital Elevation Model, STATSGO soil layer, National Land Cover Data 2001 for vegetation and weather data. We divided the entire basin into 140 sub-basins to represent the spatial heterogeneity of the basin in the model. We also used 74 grids at the 1/8th degree resolution to drive the hydrology model with GCM-produced precipitation and temperature after downscaling them as explained above. The calibration analysis is briefly included here and Jin and Sridhar (2010) provides a detailed description on calibration.



(a)



(b)

Fig. 2. Land use map used in the SWAT model from the National Land Cover Data set for (a) the Boise River Basin (b) the Spokane River Basin.

Based on the sensitivity analysis and manual verification, we identified 16 parameters of interest for this basin. We started with all 27 hydrological flow-related parameters and ranked by their order of sensitivity in simulating the basin hydrology. It resulted in about 10 parameters as the most sensitive ones for this basin. We then manually added additional parameters that were considered to be important for capturing the basin scale hydrological processes. For instance, even if the model sensitivity analysis did not consider melt factor as an important one to be calibrated, we included it manually. Followed by the sensitivity analysis and manual evaluation, we included 16 parameters for our next calibration procedure.

The identified parameters were SCS curve number, deep aquifer percolation fraction, maximum canopy storage, soil depth, threshold water depth in the shallow aquifer, available soil water capacity, saturated hydraulic conductivity, channel effective hydraulic conductivity, soil evaporation compensation factor, plant uptake compensation factor, ground water delay, deep aquifer percolation fraction, surface runoff lag time, snow pack temperature lag factor and snow melt base temperature. These parameters with their optimal values are shown in Table 1(a&b). These were considered optimal based on the objective functions, correlation coefficient (R^2) and Nash-Sutcliff Efficiency (NSE) index. For monthly calibration, as performed in this study, Stratton et al. (2009) suggested that an R2 of greater than or equal to 0.6 is desirable. We additionally considered an NSE factor as another metric for calibration. It can be inferred from our statistical analysis that these metrics rely on the quality of the observed streamflow data as well as spatial and temporal distribution of streamflow gages. Therefore, after identifying the sensitive parameters for both the basins, we generated the optimum parameters based on the autocalibration function, Sequential Uncertainty Fitting Version 2 (SUFI2) calibration algorithm which is explained below. The lower bound and upper bound columns indicate the range a given parameter can move in space while calibrating it. Also, there are options for the parameter estimation within this algorithm, known as IMET options, for replacement, multiplication and addition/subtraction and here we used replacement or multiplication options.

SUFI2 (Sequential Uncertainty Fitting Version2) is a program that is linked with SWAT for calibration. This optimization method calibrates the parameter to achieve best fitness and to the maximum degree to account for the uncertainty between the simulated and measured data. The metric used in this calibration procedure is R-factor and P-factor (Abbaspour, 2008). The calibration process is to adjust the parameter values to make R-factor close to 1 and P-factor close to 0. This program includes several steps: 1. Define the objective function; 2. Define the initial range of the parameters; 3. Perform the sensitivity analysis (optional, but highly recommended); 4. Employ the Latin Hypercube Sampling (LHS) approach of the parameters. The common number of combinations of parameters is n=500-1000; 5. Run the simulation n times and save the simulated output variables of interest, corresponding to the measurement; 6. Calculate the objective function; 7. Calculate the metrics for fitness and uncertainty; 8. Adjust the range of parameters and repeat "1". By this way, the optimal set of parameters is obtained for the subsequent simulation. SWAT is a HRU-based model that makes the parameters distributed for each HRU. This may be tedious to collect or estimate a large number of parameters for a simulation of even a small watershed. In order to facilitate the calibration of such distributed parameters, SUFI2 has been improved to accommodate the aggregate of parameters. This is implemented by encoding the extended parameters to include the information on what locations to apply a parameter value and hence to aggregate the parameters and this format is adopted in our research.

Historic period was divided into calibration (1958-1963) and validation (1964-2004) windows for this analysis. This splitting of calibration and validation is essential in order to

Parameter name	Parameter definition:Parma	low bound	up bound	imet	Calibration Sites Lucky Peak	Arrowrock	Twin Springs	Anderson Ranch	scale level
Canmx	Maximum canopy storage (mm)	0.816	9.802	v	4.344	3.109	2.508	8.351	hru
Cn2	Initial SCS CN II value	-34.77	37.44	r	-32.5	-21	-32.9	-21.68	hru
Alpha_Bf	baseflow alpha factor (days)	0	1	v					hru
Epco	Plant uptake compensation factor	-50	50	r					hru
Esco	Soil evaporation compensation factor	0.95	1	v					hru
Gw_Delay	Groundwater delay (days)	0	192.3	v					hru
Gw_Revap	Groundwater revap coefficient	0.02	0.2	v					hru
Revapmn	Threshold water depth in the shallow aquifer for "revap" (mm)	0.01	500	v					hru
Gwqmn	Threshold water depth in the shallow aquifer for flow (mm)	0	673	v	572.2	422.3	535.5	75.5	hru
Rchrg_Dp	Deep aquifer percolation fraction	0	1	v	0.488	0.89	0.364	0.272	hru
Ch_K2	channel effective hydraulic conductivity (mm/hr)	3.8	80.8	v	19.8	72.3	51.01	34.2	subbasin
Sol_Awc	Available water capacity (mm H2O/mm soil)	-50	50	r	8.9	16.9	12.38	13.9	hru
Sol_K	Saturated hydraulic conductivity (mm/hr)	12.5	37.5	r					hru
Surlag	surface runoff lag time (days)	0	10	v	1.446				basin
Timp	Snow pack temperature lag factor	0.001	1	v	0.0063				basin
Smtmp	snow melt base temperature (C)	1.8	5.5	v	4.1				basin
	note: for imet, v - replacement, r - multiplying initial value by value (in percentage)								

Table 1 (a). Calibration of the SWAT model using Sequential Uncertainty Fitting algorithm to obtain the optimum parameters representing the basin characteristics for four calibration sites (Lucky Peak, Arrowrock, Anderson Ranch, Twin Springs) in the Boise River Basin.

Parameter name	Parameter definition	low bound	up bound	imet	Parma Calibration values	scale level
Canmx	Maximum canopy storage (mm)	0.816	9.802	v	1.705	hru
Cn2	Initial SCS CN II value	-34.77	37.44	r	23.6	hru
Alpha_Bf	baseflow alpha factor (days)	0	1	v	0.0601	hru
Epco	Plant uptake compensation factor	-50	50	r	9.46	hru
Esco	Soil evaporation compensation factor	0.95	1	v	0.962	hru
Gw_Delay	Groundwater delay (days)	0	192.3	v	173.2	hru
Gw_Revap	Groundwater revap coefficient	0.02	0.2	v	0.191	hru
Revapmn	Threshold water depth in the shallow aquifer for "revap" (mm)	0.01	500	v	3.66	hru
Gwqmn	Threshold water depth in the shallow aquifer for flow (mm)	0	673	v	643.9	hru
Rchrg_Dp	Deep aquifer percolation fraction	0	1	v	0.252	hru
Ch_K2	channel effective hydraulic conductivity (mm/hr)	3.8	80.8	v	13.36	subbasin
Sol_Awc	Available water capacity (mm H2O/mm soil)	-50	50	r	-28.88	hru
Sol_K	Saturated hydraulic conductivity (mm/hr)	12.5	37.5	r	36.73	hru
Surlag	surface runoff lag time (days)	0	10	v	1.446	basin
Timp	Snow pack temperature lag factor	0.001	1	v	0.0063	basin
Smtmp	snow melt base temperature (C)	1.8	5.5	v	4.1	basin
	note: for imet, v - replacement, r - multiplying initial value by value (in percentage)					

Table 1 (b). Calibration of the SWAT model using Sequential Uncertainty Fitting algorithm to obtain the optimum parameters representing the basin characteristics for Parma in the Boise River Basin.

evaluate the performance of the model independent of the calibration effects. The SWAT model was calibrated and verified at five locations (Twin Springs, Anderson Ranch Reservoir, Arrowrock Reservoir, Lucky Peak Reservoir and Parma) in the Boise River basin and two locations (Post Falls and Spokane) in the Spokane River basin, thus covering the large areas of both the basins. The locations were chosen based on the availability of data from U.S Geological Survey (USGS) and the outflow points identified after subdividing the basins into subbasins in the model. Also, it was preferred to distribute the locations from upstream to downstream sections in order to study the impacts and variability of the watershed hydrology due to climate change. Note that some parameters are calibrated at finer scales, which is known as, Hydrological Response Unit (HRU). These HRUs were based on the unique combination of soil, vegetation and slope and are derived from the GIS layers by overlaying them and the total number of HRUs exceeded over 5500. Some other parameters were calibrated at the subbasin level while the remaining parameters were at the basin level.

The selected parameters were subsequently employed for historical hydrological simulations. Statistical results (R^2 >0.7 and Nash-Sutcliff Efficiency >0.7) of calibration and historical validation of streamflows are shown in Table 2. Validation of Twin Springs and Anderson Ranch were slightly less when compared with the other sites with NSE of about 0.65. However, both the sites have an R^2 greater than 0.8 for the validation period. It is generally expected the validation period statistics will be similar or slightly inferior to that of the calibration period statistics. Streamflow data used for calibration could be attributed to this decreased NSE in addition to the parameters related to snow-melt induced runoff in these forested upstream locations.

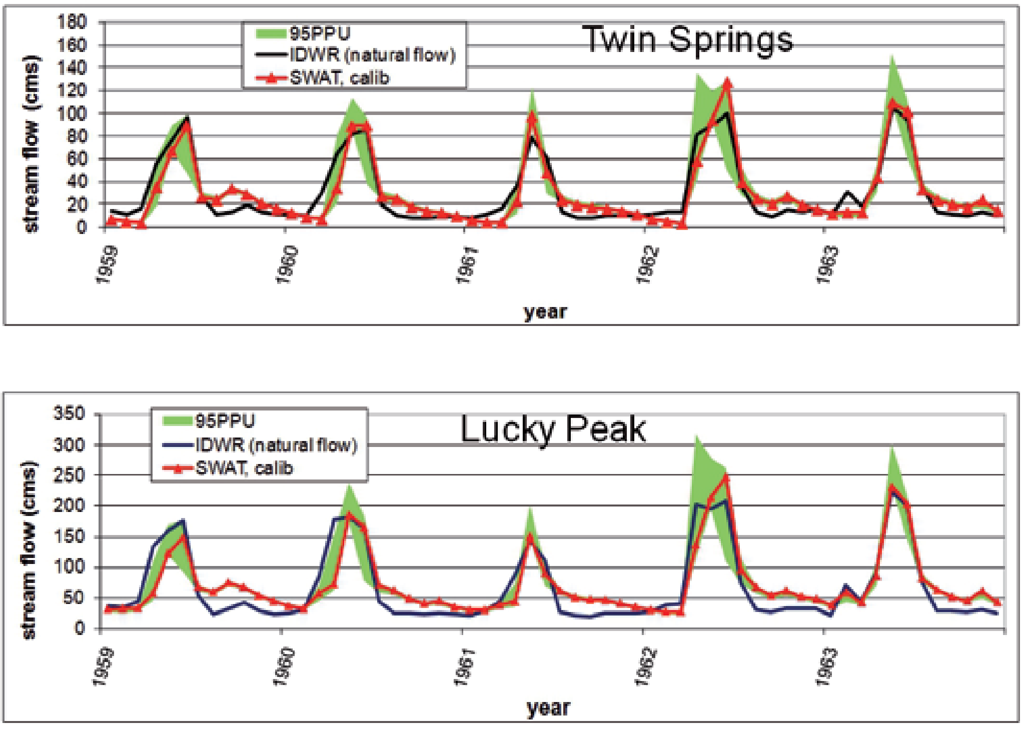
Capturing both low flows and high flows was considered as a prerequisite for our implementation of the model with the calibrated parameters under the climate change scenarios. As changes to the hydrologic conditions are expected to occur rapidly in the future, knowing the historic behavior of flows and hydrology as the baseline reference is critical. Streamflows simulated for historical conditions showed good correlation both in terms of peak flow magnitudes and the timing of snowmelt for the historic climate conditions. Figure 3 shows the correlation between the model-simulated streamflow and observed natural flow for Twin Springs and Lucky Peak. Natural or unmanaged high flows ranged between 113-170 m3/s for the upstream locations and 340-450 m^3/s for the downstream gaging stations and low flows were between 28-57 m3/s in the Boise River basin. Flows at Twin Springs, Anderson Ranch, Arrow Rock, Lucky Peak, Glenwood, Middleton, Caldwell and Parma were verified. Our simulation also showed that interannual variability in streamflows was relatively high for the Boise River basin for the historic climatic conditions. Other water balance components (evapotranspiration, soil moisture, recharge) were analyzed. Evapotranspiration accounted for 50-60% of total precipitation annually. Soil moisture and recharge accounted for about 10-15% of annual precipitation.

4.2 Calibration for the Spokane River basin

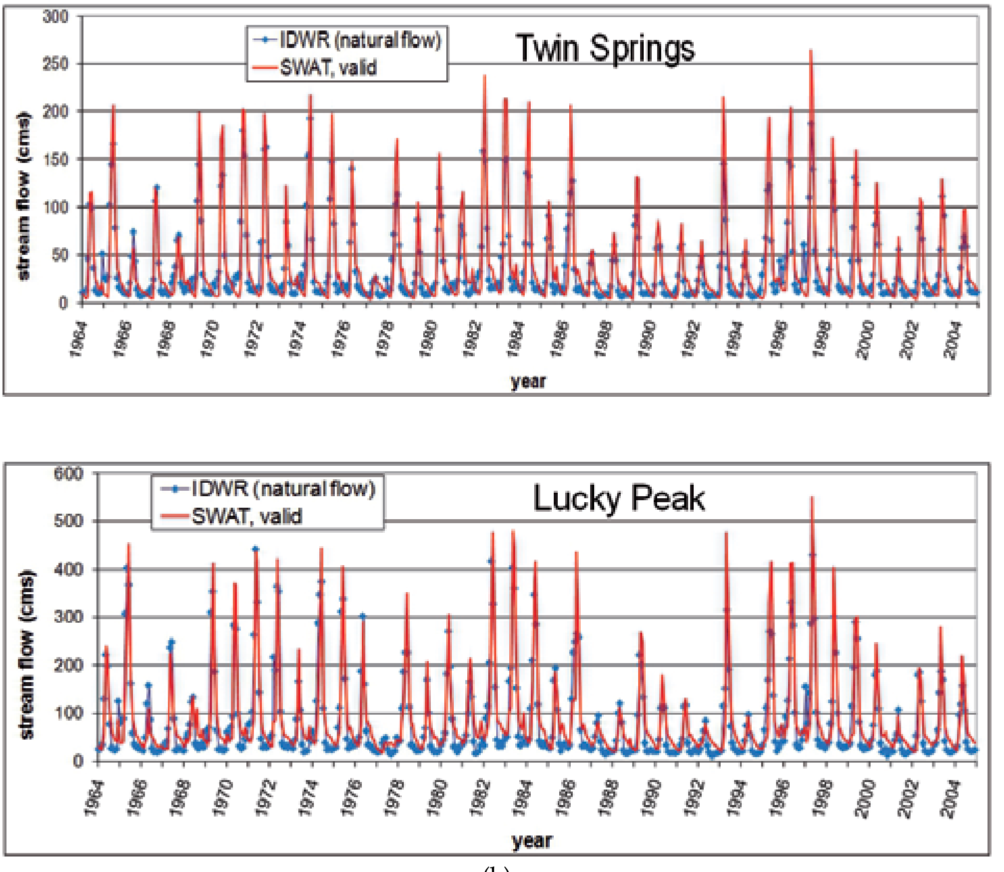
Similar to earlier implementation, the SWAT model was configured to run for the whole of Spokane River basin in order to establish the hydrologic connectivity and the watershed characterization including the aquifer. To understand the flow pattern in the upstream portion of the Spokane River basin which lies in Idaho, it is essential to consider the entire

Subbasin		r^2	NSE	P-factor	R-factor
Parma	calibrated (1959 - 1963)	0.80	0.73	0.50	0.40
	validated (1964 - 2004)	0.82	0.79		
Lucky Peak	calibrated (1959 - 1963)	0.79	0.78	0.32	0.43
	validated (1964 - 2004)	0.78	0.73		
Arrow Rock	calibrated (1959 - 1963)	0.75	0.75	0.32	0.45
	validated (1964 - 2004)	0.77	0.70		
Twin Spring	calibrated (1959 - 1963)	0.87	0.85	0.4	0.5
	validated (1964 - 2004)	0.81	0.65		
Anderson Ranch	calibrated (1959 - 1963)	0.87	0.70	0.4	0.55
	validated (1964 - 2004)	0.83	0.64		

Table 2. Calibration and Validation statistics for various gaging locations in the Boise River Basin.



(a)



(b)

Fig. 3. Streamflows for Twin Springs and Lucky Peak simulated by the SWAT model during (a) calibration (1959-1963) and (b) validation period (1964-2004).

watershed beyond Idaho borders. Therefore, our delineation of the basin includes both the regions in Idaho and Washington. There are 226 sub-basins and over 5700 HRUs derived from a combination of DEMs, slope and soil layers and 144 weather points within this basin to drive the model with the GCM data.

We identified 15 sensitive parameters for this basin and they included surface flow, groundwater, soil and snow parameters similar to that of the Boise River region. Initial calibration was performed by dividing the region above Post Falls and the region below Post Falls. A combination approach of autocalibration using SUFI algorithm followed by manual calibration for the Post Falls and Spokane streamflow stations showed good correlation for the historic period. Optimum values of the parameters are shown in Table 3. The parameters that we calibrated were baseflow factor, maximum canopy storage, SCS curve number, deep aquifer percolation fraction, soil evaporation compensation factor, plant uptake compensation factor, ground water delay, deep aquifer percolation fraction, threshold water depth in the shallow aquifer, available soil water capacity, saturated hydraulic conductivity, channel effective hydraulic conductivity, surface runoff lag time, snow pack temperature lag factor and snow melt base temperature.

Parameter name	Parameter definition:Parma	low bound	up bound	imet	Calibration Sites Post Falls	 Spokane to Post Falls	scale level
Alpha_Bf	baseflow alpha factor (days)	0.05	0.15	v	0.077	0.079	hru
Canmx	Maximum canopy storage (mm)	1.28	3.84	v	2.7	1.8	hru
Ch_K2	channel effective hydraulic conductivity (mm/hr)	10	30	v	31.5	19.9	subbasin
Cn2	Initial SCS CN II value	6.38	19.14	r	7.78	12.9	hru
Epco	Plant uptake compensation factor	-50	50	r	16.1	-37.4	hru
Esco	Soil evaporation compensation factor	0.33	1	v	0.55	0.9	hru
Gw_Delay	Groundwater delay (days)	101	303	v	188.4	146.7	hru
Gw_Revap	Groundwater revap coefficient	0.047	0.141	v	0.093	0.133	hru
Gwqmn	Threshold water depth in the shallow aquifer for flow (mm)	219	656	v	333.8	299.2	hru
Revapmn	Threshold water depth in the shallow aquifer for "revap" (mm)	0.01	500	v	299.1	146.9	hru
Sol_Awc	Available water capacity (mm H20/mm soil)	12.5	37.5	r	18.6	33.3	hru
Sol_K	Saturated hydraulic conductivity (mm/hr)	4.27	12.8	r	5.7	13.2	hru
Surlag	surface runoff lag time (days)	2.27	6.81	v	6.3		basin
Timp	Snow pack temperature lag factor	0.01	1	v	0.0035		basin
Smtmp	snow melt base temperature (C)	1.61	4.83	v	3.39		basin
	note: for imet, v - replacement, r - multiplying initial value by value (in percentage)						

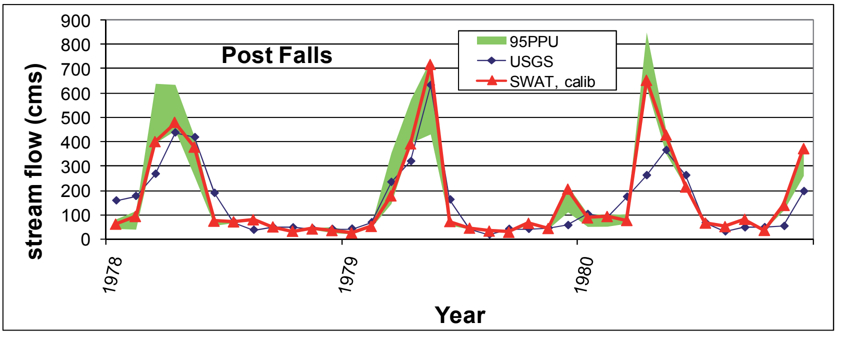
Table 3. Calibration of the SWAT model using Sequential Uncertainty Fitting algorithm to obtain the optimum parameters representing the basin characteristics in the Spokane River Basin.

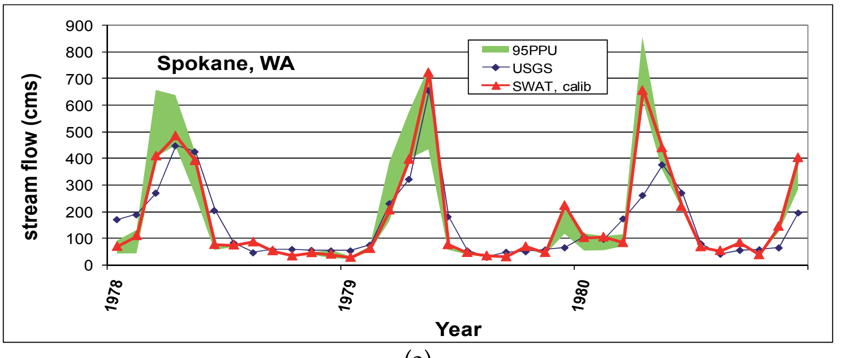
The calibrated SWAT model was verified at two locations (Post Falls and Spokane) in the Spokane River basin, thus covering the large areas of the Spokane River basin (Figure 2). Both seasonality and peakflows were captured by the model under historic climate conditions. Statistical results with R2 >0.65 and Nash-Sutcliff Efficiency >0.55 for the calibration and historical validation with R2 >0.66 for the model performance in predicting streamflows are shown in Table 4. However, for the second validation period, 1981-99, both R2 (0.66) and NSE (0.41) have shown a slightly inferior performance of the model. Normally, the validation period statistics is somewhat lower when compared against the calibration period and we found it to be the case in this study also. However, the correlation coefficient of 0.6 was considered reliable in order for us to use this as a predictive tool in our hydrological impact analysis.

Subbasin	Gage station		r^2	NSE	P-factor	R-factor
Post Falls	Post Falls, ID, 12419000	calibrated (1978 - 1980)	0.76	0.58	0.39	0.45
		validated (1953 -1977)	0.72	0.65		
		validated (1981 -1999)	0.66	0.48		
Spokane	Spokane, WA, 12422500	calibrated (1978 - 1980)	0.75	0.55	0.33	0.46
		validated (1953 -1977)	0.71	0.62		
		validated (1981 -1999)	0.66	0.41		

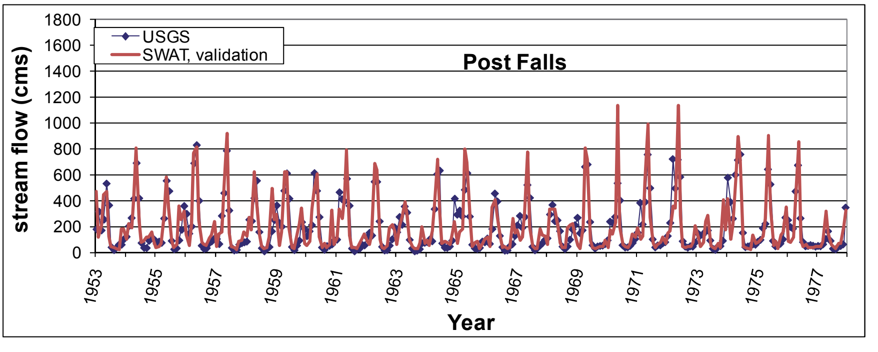
Table 4. Calibration and Validation statistics for various gaging locations in the the Spokane River Basin.

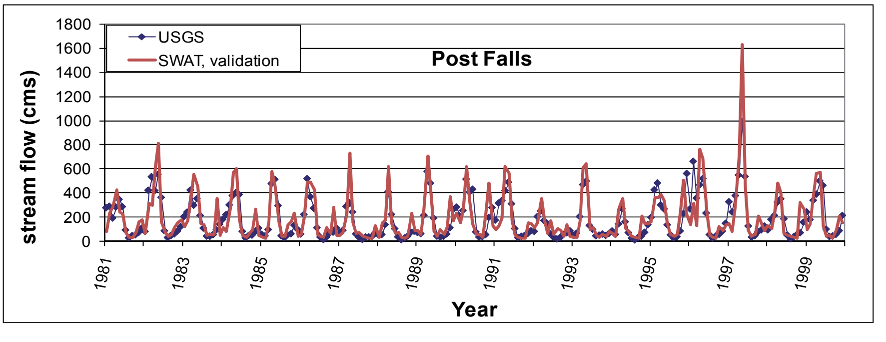
For the Spokane River basin, high flows ranged between 560-850 m3/s. Historic climate analysis showed that interannual variability in streamflow was relatively high for the Bois River basin. However, this was slightly less in the Spokane River basin which can be attributed to precipitation variability in the historic climatic conditions. There was an earlier snowmelt for both the regions as a result of increasing temperature trends, especially at lower elevations. Streamflows simulated by the model was verified against the observations. Figure 4 shows the time series of streamflows captured by the model for Post Falls and Spokane gaging stations.

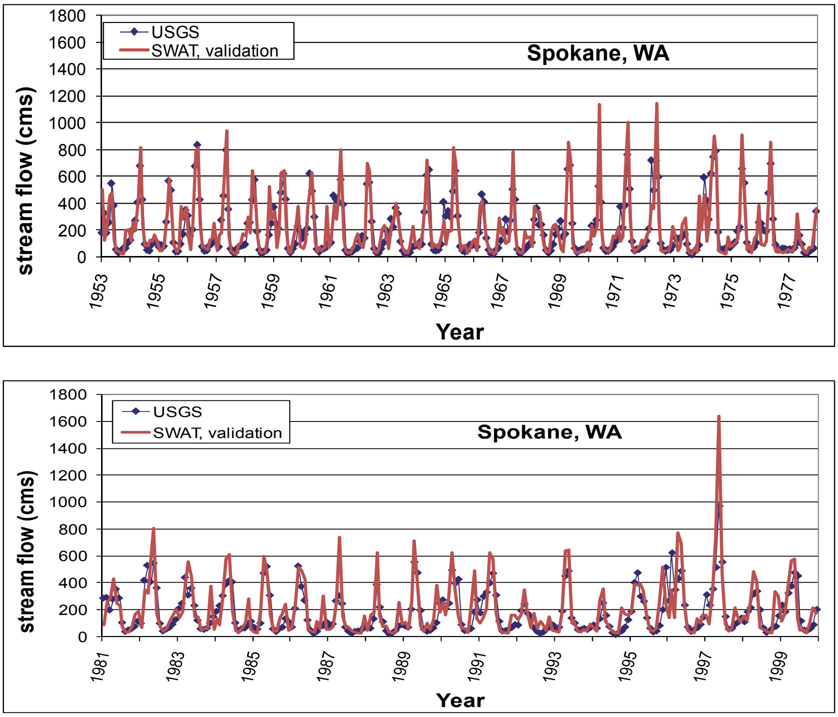

Post Falls
95PPU
USGS
SWAT, calib
stream flow (cms)
900
800
700
600
500
400
300
200
100
0
1978
1979
1980
Year


Spokane, WA
95PPU
USGS
SWAT, calib
stream flow (cms)
900
800
700
600
500
400
300
200
100
0
1978
1979
1980
Year

(a)


USGS
SWAT, validation
Post Falls
stream flow (cms)
1800
1600
1400
1200
1000
800
600
400
200
0
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
Year


USGS
SWAT, validation
Post Falls
stream flow (cms)
1800
1600
1400
1200
1000
800
600
400
200
0
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
Year



(b)

Fig. 4. Streamflows for Post Falls and Spokane simulated by the SWAT model during (a) calibration (1978-1980) and (b) validation period (1953-1977; 1981-2000).

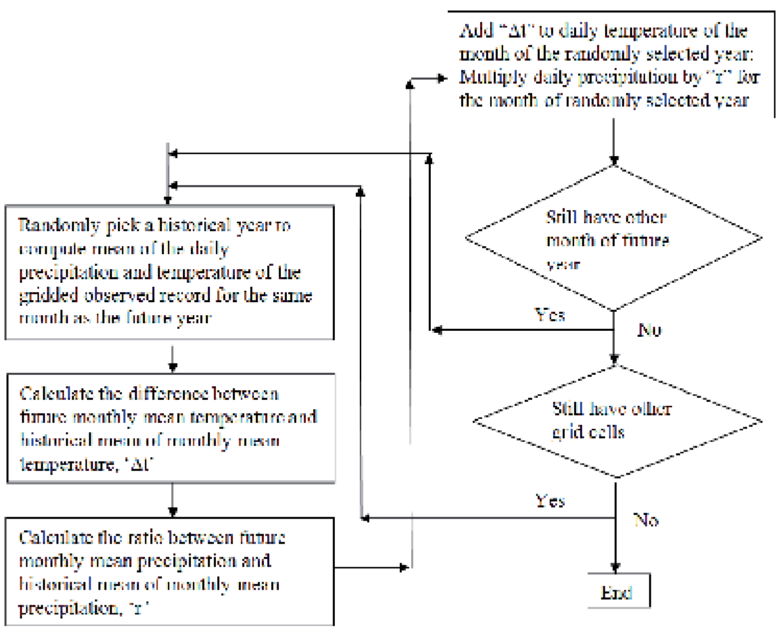


Fig. 5. Flowchart of downscaling method for precipitation and temperature.

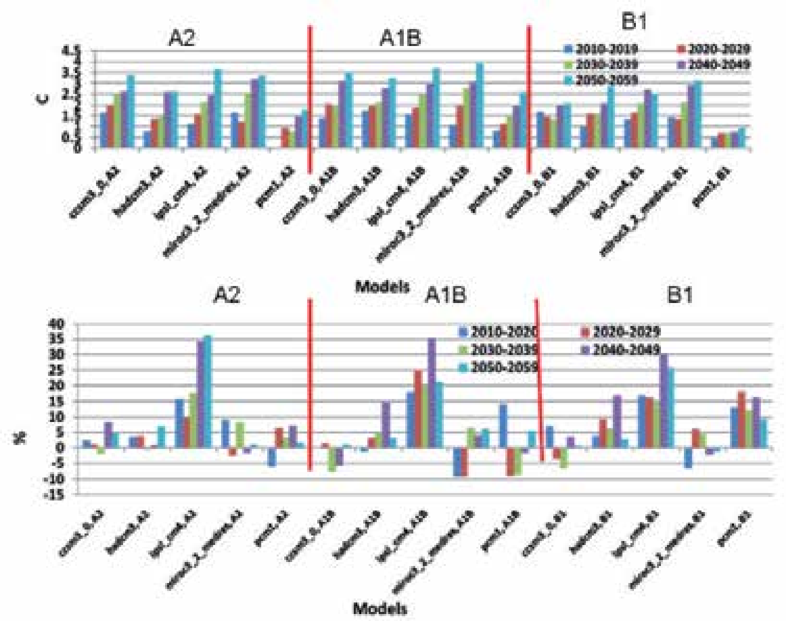


Fig. 6. Temperature (top) and Precipitation (bottom) trends under climate change conditions for the Boise River basin between 2010 and 2060. The models used are CCSM3, HADCM3, IPSL CM4, MIROC 3.2 and PCM.

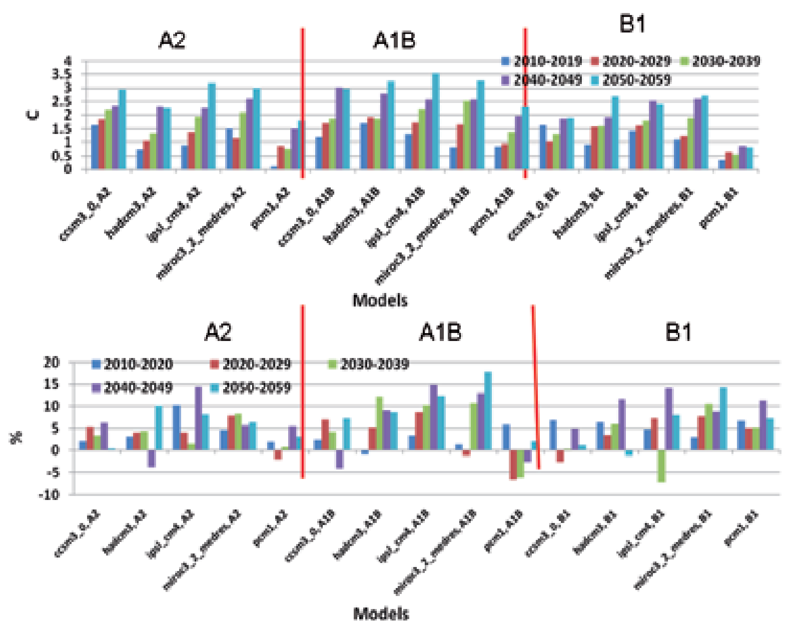


Fig. 7. Temperature (top) and Precipitation trends under climate change conditions for the Spokane River basin between 2010 and 2060. The models used are CCSM3, HADCM3, IPSL CM4, MIROC 3.2 and PCM.

5. Results and discussion

5.1 Bias correction of streamflow

While the calibration exercise resulted in reasonable correlation (r=0.8) between the simulated and observed streamflow, we recognized a positive bias from the model estimates were to be corrected. This is especially the case when the peak flows and low flows are overestimated. These are the times when future climate model-based predictions are sensitive to earlier melt and altered low flow regions. By correcting the bias, applications of future streamflow projections can be made useful for water resources planning and management purposes.

In order to perform the bias correction, we first averaged the monthly streamflows for the historic periods for each month. For instance, historical January flows were averaged for each gaging locations and subtracted from modeled flows of future projections for the same month. This is repeated for each month in a year and for each location. This bias correction exercise reduced model-simulated peak flows and low flows that were comparable to historic trends.

5.2 High flows

The seasonal flows can be divided into high flows and low flows. The high flows are defined in our study as the flows that occur between March and June. We computed high flows for various locations within the basin. This high flow analysis is critical especially in the context of climate change as we expect increased flows in the region due to increased precipitation according to the choice of the models in this study.

As a result of the increased precipitation and temperature, generally both the regions are expected to have increased streamflows during the peak flow season (Figure 8) and decreased flows in the summer. In order to make sure that flows are realistic, we bias-corrected the predicted flows by comparing with the long-term flow data. With all the climate scenarios that have been analyzed in the study, a wide range of predictions is probable for the entire 50 year period between 2010 and 2060. The choice of the model in understanding the flow pattern becomes critical. This was observed for all the emission scenarios, A1B, A2 and B1 where we have projected mostly increased precipitation possibilities and the range of peak flows (March through June) is expected to increase by 116.6 cms (A2), 93.0 cms (A1B) and 110.9 cms (B1). This is based on the average of the eight sites in the Boise River basin where flows are predicted by the model. However, there are uncertainties in these predictions as evidenced from decreases in peak flows predicted in some scenarios. An eight site average of decrease in peak flows for the Boise River basin revealed the flows as 34.6 cms (A2), 47.9 cms (A1B) and 38.7 cms (B1). These are due to some scenarios where precipitation is predicted to be decreasing. In general, the peak flow averages expected to increase by 17.6 cms (A2), 11.0 cms (A1B) and 22.4 cms (B1). Thus, the high flows in the future will probably be higher than historic high flows. Table 5(a) shows the flows based on the averages from eight sites.

As in Figure 9, in the Rathdrum Prairie basin the peak flow increases are expected to be about 71.5 cms (A2), 17.3 cms (A1B) and 53.8 cms (B1) based on the two site average flows predicted by the model. However, the decreases in peakflows are also greater than that of the decreases in the Boise River Basin. For instance, a decrease in peak flows by 206.8 cms (A2), 215.0 cms (A1B) and 170.7 cms (B1) are also simulated by some scenarios that predict a decrease in precipitation. Precipitation uncertainty causing flow variations appears to be magnified in the higher latitudes such as the Rathdrum Prairie basin. However, nearly all scenarios agree that there will be a slight advancement in the timing of snow melt in the Treasure Valley and the Rathdrum Prairie basins. The peak flow averages are expected to decrease by about 74.4 cms (A2), 93.9 cms (A1B) and 65.2 cms (B1). Table 5(b) shows the flows based on the averages from eight sites.

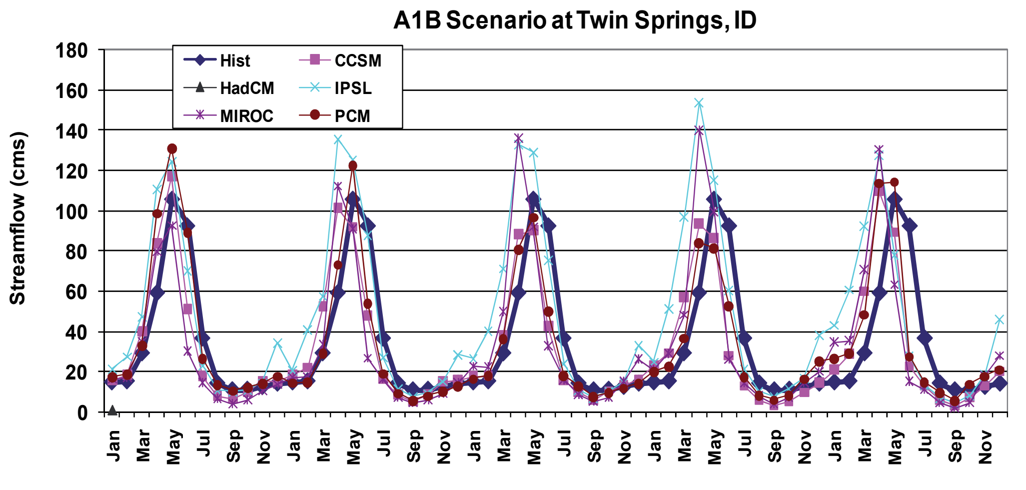
	A2	A1B	B1
Peak flow maximum decrease (cms)	34.6	47.9	38.7
Peak flow maximum increase (cms)	116.6	93.0	110.9
Peak flow mean increase (cms)	17.6	11.0	22.4

(a)

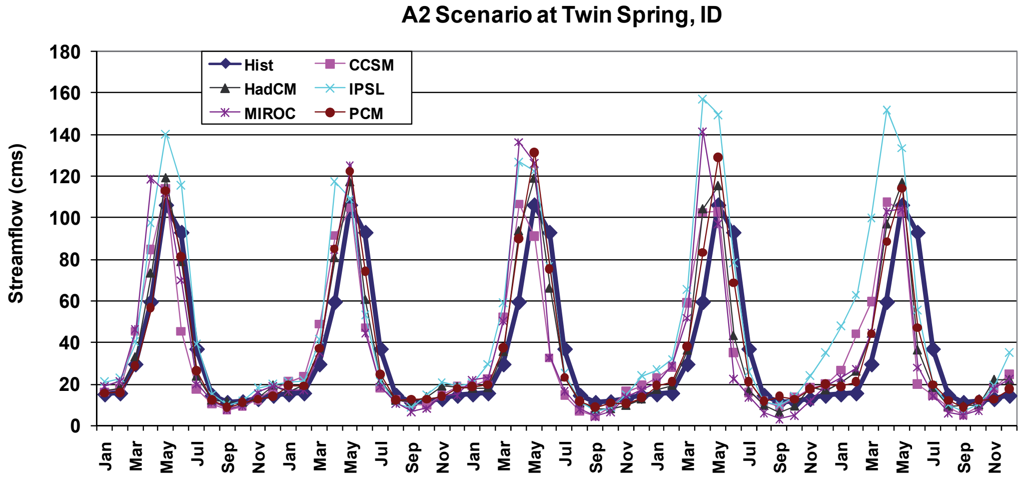
	A2	A1B	B1
Peak flow maximum decrease (cms)	206.8	215.0	170.7
Peak flow maximum increase (cms)	71.5	17.3	53.8
Peak flow mean decrease (cms)	74.4	93.9	65.2

(b)

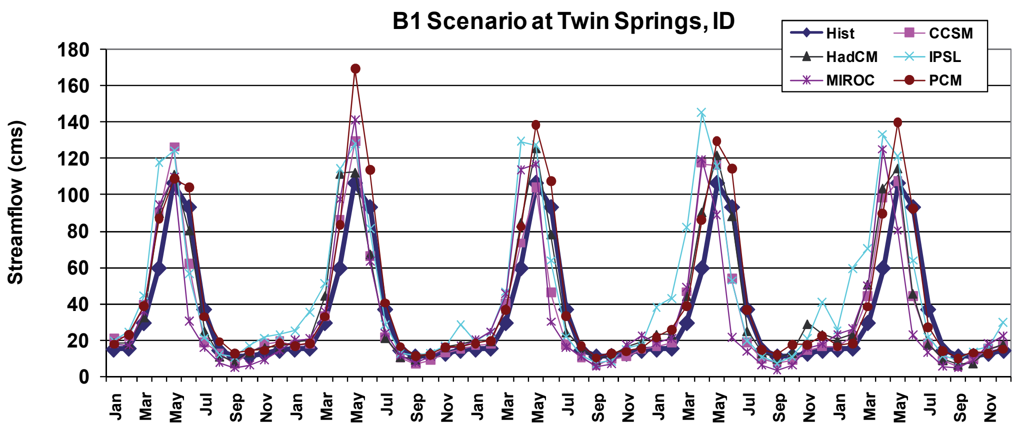
Table 5. (a) The Boise River Basin future peak flow change range (8-site average) between 2010-2060 for each scenario (A2, A1B and B1) ; (b) The Rathdrum Prairie Basin future peak flow change range (2-site average) between 2010-2060 for each scenario (A2, A1B and B1).



(A1B)



(A2)

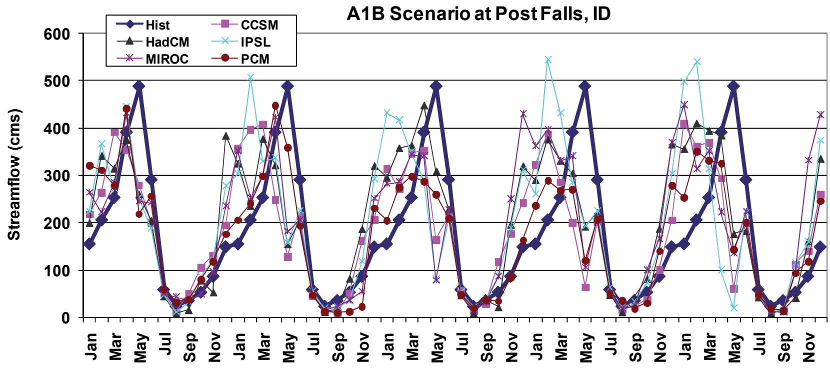


(B1)

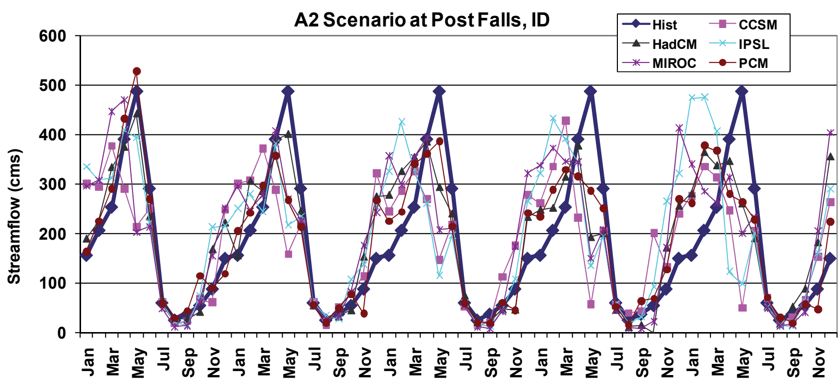
Fig. 8. Seasonal streamflows for each decade between 2010 and 2060 at Twin Springs in the Upper Boise River basin for each scenario for A1B (top), A2 (middle) and B1 (bottom). Higher peak flows are expected to occur in May and low flows are about the same or slightly above when compared against the historic flows.

5.3 Low flows

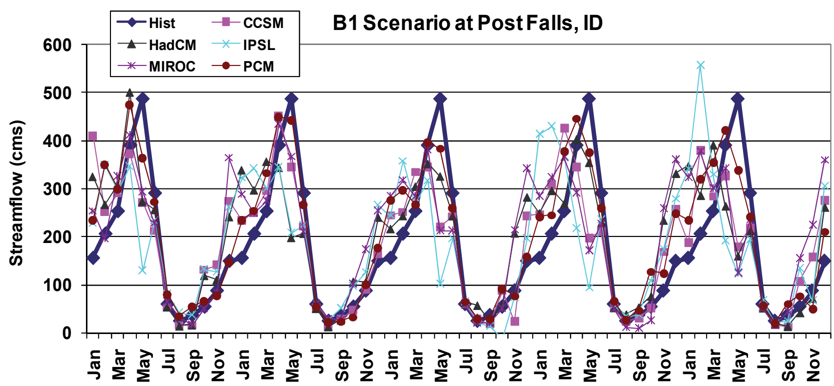
Streamflows in the low flow period (July through Oct) are decreasing in the Boise River basin. More specifically, the average maximum increase in the summertime flows are 5.5 cms (A2), 2.2 cms (A1B) and 9.5 cms (B1) scenarios. Minimum low flows predicted by the model have projected decreasing flows by 17.6 cms (A2), 18.7 cms (A1B) and 17.2 cms (B1). In general, the low flow averages declined in the future by 8.0 cms (A2), 10.7 cms (A1B) and 6.2 cms (B1). Notably, the low flows are expected to be lower than historic low flows



(A1B)



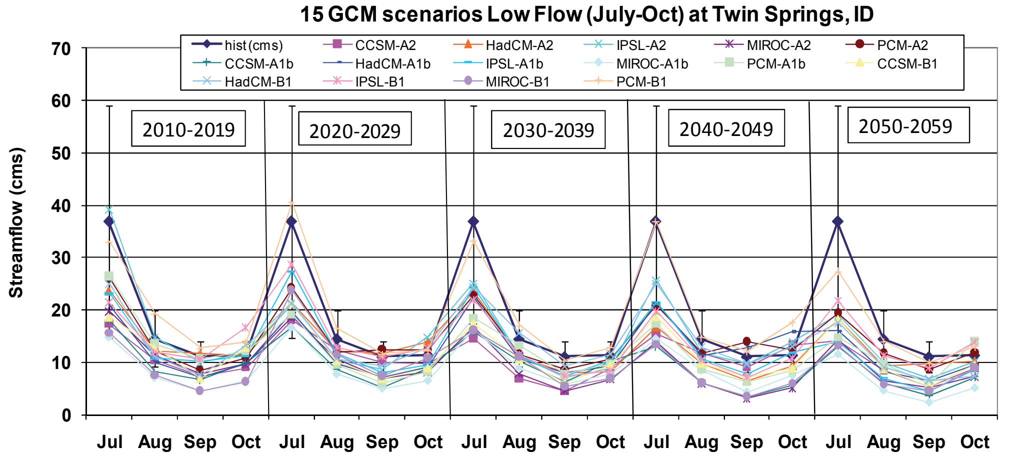
(A2)



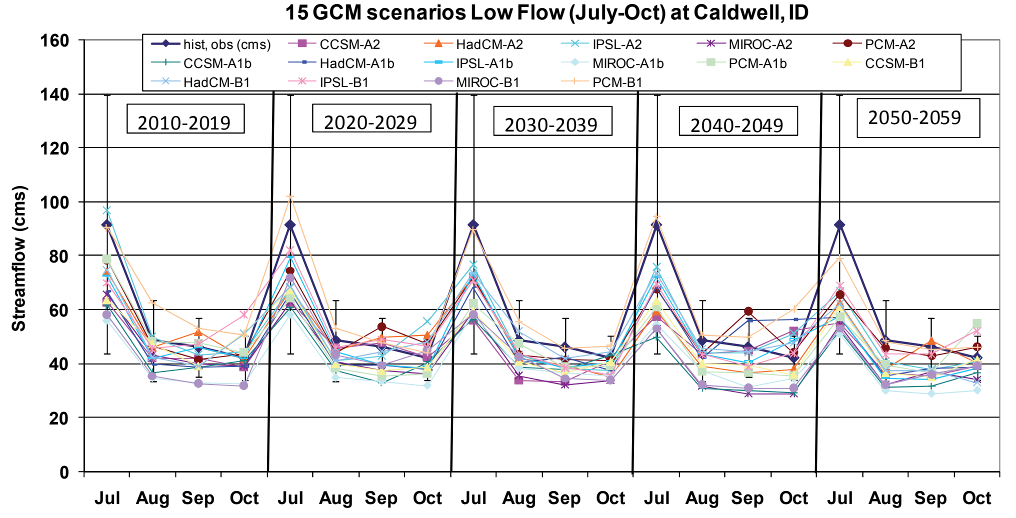
(B1)

Fig. 9. Seasonal streamflows for each decade between 2010 698 and 2060 at Post Falls in the Spokane River Basin for each scenario for A1B (top), A2 (middle) and B1 (bottom). Higher peak flows are expected to occur in May and low flows are about the same or slightly above when compared against the historic flows. Low flows are about the same or slightly below when compared against the historic flows.

(Figure 10). The summertime minimum low flows in the Rathdrum Prairie appear to have decreased when compared against the historic conditions (Figure 11). For instance, a decrease in flow by 29.4 cms (A2), 25.6 cms (A1B) and 29.7 cms (B1) is predicted. The maximum low flows are increasing by 52.3 cms (A2), 27.0 cms (A1B) and 46.3 cms (B1). A minimal increase in the average low flows, rather than a decrease as in the Treasure Valley region, by about 5.4 cms (B1) is simulated by these models. The results are shown in Table 6 (a&b). While most of the increase could be attributed to climate change, as can be noticed from our historic model validation approximately some 20% of the flows were unexplained by mode (r^2=0.8) and therefore uncertainty in the hydrological model predictions should be included when planning the water availability forecasts.



Twin Springs



Caldwell

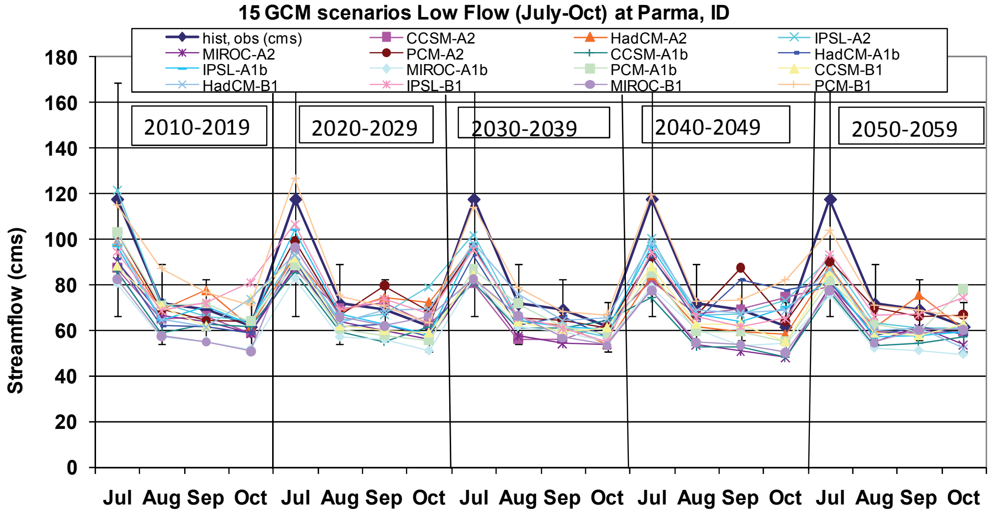


Fig. 10. Low flows for each decade between 2010 and 2060 at Twin Springs, Caldwell and Parma in the Boise River Basin.

	A2	A1B	B1
Peak flow maximum decrease (cms)	17.6	18.7	17.2
Peak flow maximum increase (cms)	5.5	2.2	9.5
Peak flow mean decrease (cms)	8.0	10.7	6.2

(a)

	A2	A1B	B1
Peak flow maximum decrease (cms)	29.4	25.6	29.7
Peak flow maximum increase (cms)	52.3	27	46.3
Peak flow mean decrease (cms)	-0.028	-2.2	5.4

(b)

Table 6. (a) The Boise River Basin future low flow change range (8-site average) between 2010-2060 for each scenario (A2, A1B and B1); (b) The Rathdrum Prairie Basin low future low change range (2-site average) between 2010-2060 for each scenario (A2, A1B and B1).

The volume of flow changes in the Boise River basin at Lucky Peak was also computed. This was done by computing the area under the hydrograph (by adding the ordinates through the trapezoidal method) with the historic volumes. Table 7 shows the decadal averages of increase in flow volumes in acre-ft for A2, A1B and B1 scenarios. The increase in flow volumes are 249 ac-ft (A2), 149 ac-ft (A1B) and 327 ac-ft (B1). The overall average when combining all of these flow volumes results in increasing flow volume by 242 ac-ft.(convert ac-ft to square kilometer-meter).

	A2	A1B	B1
2010-2019	248	120	228
2020-2029	89	97	472
2030-2039	236	125	215
2040-2049	340	270	442
2050-2059	332	132	279
Average	249	149	327

Table 7. Decadal changes in flow volumes (square kilometer-meter) between 2010-2060 for each scenario (A2, A1B and B1).

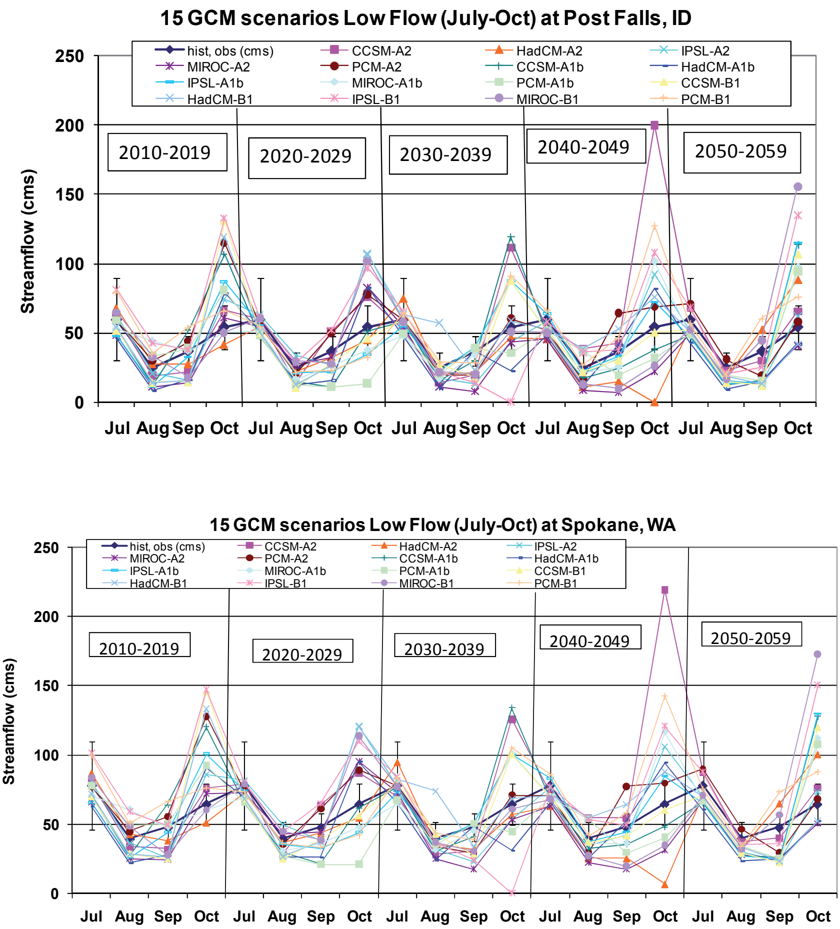
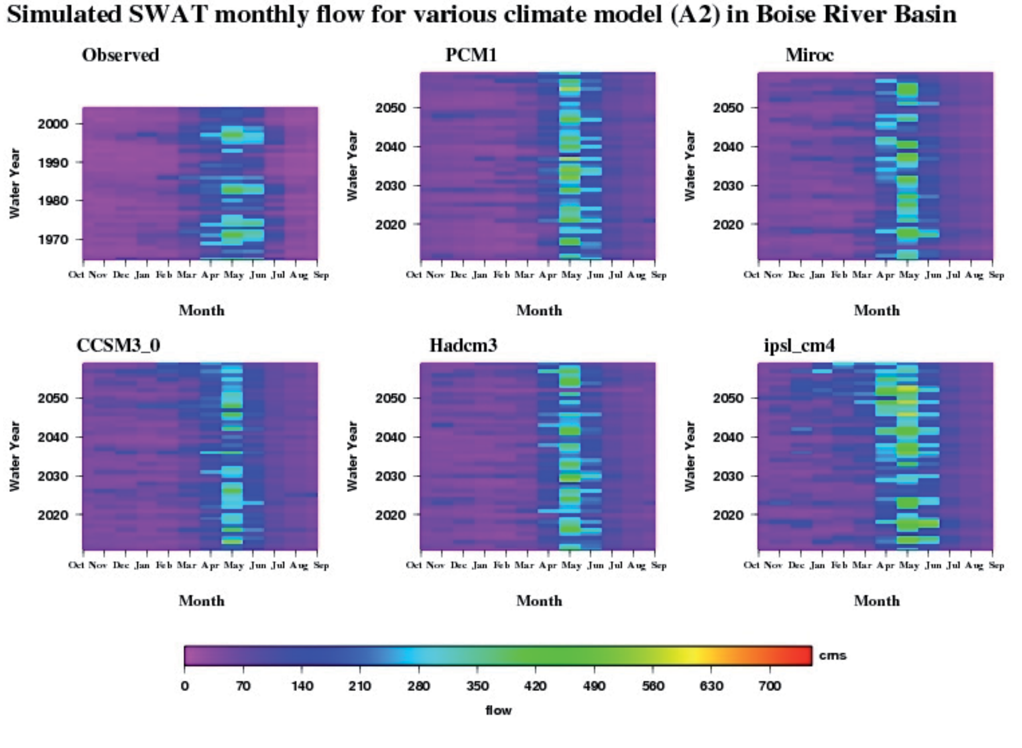


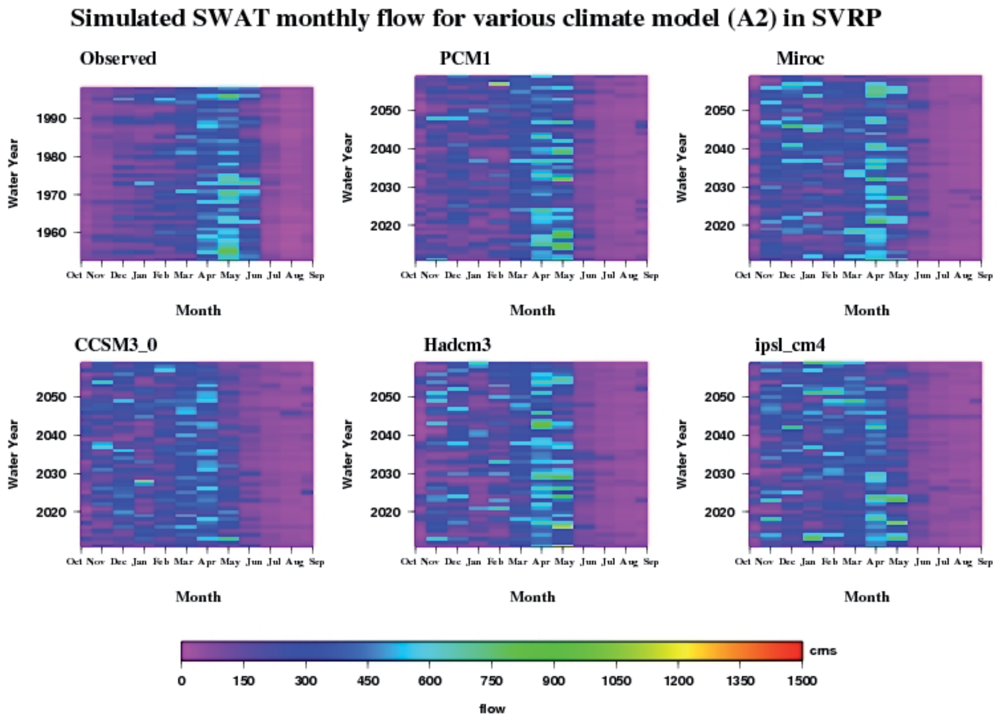
Fig. 11. Low flows for each decade between 2010 and 2060 at Post Falls in the Spokane River Basin.

5.4 Time maps

When simulating the flows under the climate change scenarios, one of the main things is to verify the timing of peak flow and its shift in the future. Using the time maps, we show that there is a shift in timing for all the three emission scenarios at least by 3-4 weeks in the Rathdrum Prairie aquifer region whereas Boise River basin showed 2-3 weeks of shift in the timing of peak flow. This shift is significant when the runoff needs to be stored or released from the system for flood control or irrigation. If we have to let the inflows released due to earlier melting, potentially there will be less water available for the crop growing season water demand. If we consider storing them, an additional analysis is critical to see if we have adequate storage capacity and room for flood control in both the basins. Figure 12 shows Lucky Peak in the Boise River basin and Post Falls in the Rathdrum Prairie region for A2 scenario streamflow generation in the future. Recall that A2 scenario considers increased emission leading to higher temperatures than any other scenarios and therefore melt timing analysis it is appropriate to consider A2 as a worst case scenario where maximum shift to be expected.



a. Lucky Peak, ID



b. Post Falls, ID

Fig. 12. Time maps at (a) Lucky Peak, ID in Boise River Basin and (b) Post Falls, ID in the Spokane River Basin.

6. Conclusion

In conclusion, we expect that on a regional basis an increase of 5-7 °F in temperature as well as an increase in precipitation over the northwestern and north-central portions. Many global climate models also agree with a decrease in the April 1st snowpack resulting in a decrease in streamflow of about 8 to 20%. In general, the major river basins in PNW region such as the Columbia and Snake Rivers are expected to see an increase in December-March runoff and a decrease/increase in April-July (peakflow) and a decrease in July-October (low flow). While precipitation increases can result in increased runoff, a consistent pattern in temperature increase among all climate models can result in net decrease in annual runoff due to enhanced evapotranspiration under warming conditions. The PNW region is also expected to see more cool-season rainfall and runoff. In addition to precipitation and temperature changes, warming could lead to more intense and heavy rainfall interspersed with longer, relatively dry periods.

In this study, we identified five climate models that are relevant to capturing the future trends in precipitation and temperature. The models include CCSM3 (warmer and dry summer through 2020), HADCM3 (warmer and dry summer through 2040), IPSL CM4 (wetter winter), MIROC 3.2 (warmer and wetter winter) and PCM (cooler and dry summer). They represented a wide range of conditions and also change by time. After identifying the models, we downloaded the spatially downscaled climate model data from CMIP3 source developed by Bureau of Reclamation and other collaborators and subsequently temporally disaggregated them from monthly to daily to run the hydrology model. The precipitation forecast is less certain. In other words, some models predicted increased precipitation between 2010 and 2060 while other models predicted a decrease in precipitation. However, temperature increase is found to be consistent. For the Treasure Valley region, changes in precipitation ranged between -3.8 % and 36%. Changes in temperature are expected to be between 0.02 and 3.9 °C. In the Rathdrum Prairie region, changes in precipitation are expected to be between -6.7% and 17.9 %. Changes in temperature will likely be ranging between 0.1 and 3.5 °C. Overall, the chosen climate models showed a rise in temperature (0.31 °C to 0.42 °C/decade for Rathdrum Prairie and 0.34 °C to 0.46 °C/decade) and an increase in annual precipitation (4.7% to 5.8% for Rathdrum Prairie and 5.3% to 8.5% for Treasure Valley) over a period of next five decades between 2010-2060

In order to study the response of the hydrology model due to changes in precipitation, we implemented the SWAT hydrology model to simulate the basin scale hydrologic response to changing climate. However, it is critical to calibrate the model based on the observed flow for multiple sub-basins in each basin. Therefore, we first calibrated the SWAT model for the Spokane River basin using the flows from Post Falls and Spokane. Similarly, we calibrated the model for the Boise River basin using the flows from Parma, Lucky Peak, Arrowrock, Twin Springs and Anderson Ranch. This calibration exercise resulted in 16 parameters adjusted for various processes within the basin including snowmelt, vegetation, groundwater and surface runoff. In both basins the model performance was evaluated using the R^2 values and we obtained a value of 0.6 or higher and that is considered to be good in the modeling environment for extending the simulation framework with selected parameters to another period.

The SWAT hydrology model was implemented under future climate conditions using the newly calibrated parameters. Considering a wide range of precipitation and temperature outlook, we expected predictions about the basin hydrology to express a broad range in streamflows, evapotranspiration and recharge during the simulation period of the entire 50 year period between 2010 and 2060. This was observed for all emission scenarios, A1B, A2 and B1 and based on the average of eight sites (Twin Springs, Anderson Ranch, Arrowrock, Lucky Peak, Glenwood, Middleton, Caldwell and Parma) in the Boise River basin the peak flows (March through June) appear to increase by 116.6 cms (A2), 93.0 cms (A1B) and 110.9 cms (B1). Also, decreased peak flows of 34.6 cms (A2), 47.9 cms (A1B) and 38.7 cms (B1) are expected. These are due to some scenarios where precipitation is predicted to be decreasing. In general, the peak flow averages expected to increase by 17.6 cms (A2), 11.0 cms (A1B) and 22.4 cms (B1). We averaged the two site predictions (Post Falls and Spokane) in the Rathdrum Prairie basin to understand the peak flow trends. It was found that increases are expected to be about 71.5 cms (A2), 17.3 cms (A1B) and 53.8 cms (B1) based on the two site average flows predicted by the model. However, the decreases in peakflows are also greater than that of the Boise River Basin. For instance, a decrease in peak flows by 206.8 cms (A2), 215.0 cms (A1B) and 170.7 cms (B1) were simulated by some scenarios.

The low flows (July-Oct) predicted by the model have projected decreasing flows by 17.6 cms (A2), 18.7 cms (A1B) and 17.2 cms (B1) in the Boise River basin. In the Rathdrum Prairie, a minimal increase in the average low flows, rather than a decrease as in the Treasure Valley region, by 5.4 cms (B2) is simulated by these models. Thus, the low flows are expected to lower than historic low flows and high flows are anticipated to be higher than historic high flows and earlier. The Boise River and the Spokane River are tributaries to the Snake and

Columbia River and as a result of this increased peak flow, we might anticipate that the Columbia River will have increased high flows and potential for flooding in the next decades.

We also anticipate a shift in the timing of snowmelt and this shift is advancing from current peak melt period of May to April. This has been consistent for both the basins. This is pretty typical of many regions in the Western U.S, including Pacific Northwest, which is expected to cause some management problems related to the water resources in the region. An earlier melt, if not stored, might cause some shortages in the system thereby possibly impacting various sectors including irrigated agriculture, hydro power and domestic as well as municipal water supply.

7. Acknowledgement

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12

Human Ecology of Vulnerability, Resilience and Adaptation: Case Studies of Climate Change from High Latitudes and Altitudes

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United States of America

1. Introduction

Human societies in Arctic (high latitude) and mountain (high altitude) regions contributed little to the causes of climate change, yet they are among the first to observe and respond to its impacts (Crate & Nuttall, 2009; Krupnik et al., 2004; Orlove et al., 2008). Many of these communities are indigenous and maintain dynamic relations within their local ecologies through subsistence activities. This means they are keen observers of their habitat, and raises concern that their food and livelihood securities are vulnerable to adverse impacts of climate change (Kassam, 2009a, 2009b). The risk that climate change impacts may overwhelm high latitude and high altitude communities is increased by other chronic stressors, including legacies of colonialism, economic imperialism that constrains local economies, recurring natural disasters, shifting and conflicting political alliances, and war. Put tersely, climate change is an additional layer of complexity on already existing inequities.

Social scientists are compelled to address issues of justice, so it is appropriate that significant research efforts be devoted to the regions of the world most affected by climate change. This paper examines the concepts of vulnerability and adaptation through a human ecological lens that was developed in the contexts of Arctic and sub-Arctic communities (Kassam, 2009a), and has been applied in the Afghan and Tajik Pamirs (Kassam , 2009b)[1]. Two case studies will focus on the human ecology of vulnerability and adaptation in those regions. Emphasis is placed on possibilities to integrate diverse indigenous and scientific knowledge systems towards the reduction of specific vulnerabilities to climate change impacts.

2. A human ecological perspective

Human ecology developed out of the science of ecology, but did not gain a foothold within the discipline (Bruhn, 1974). In the 1950s, Amos Hawley proposed human ecology as a field of sociology, and consequently, human ecology developed in the social rather

[1] The concepts and case studies presented in this paper draw freely from Kassam and The Wainwright Traditional Council, 2001, Kassam 2009a, b and Kassam 2010.

than the biological sciences. Nevertheless, human ecology has retained its roots in the concepts and principles of ecological science. In the inaugural issue of *Human Ecology* published in 1972, the editors defined human ecology as "the complex and varied systems of interaction between man and his living and non-living environment" (Editors, 1972). In the twenty-first century, human ecology has the potential to develop into what Odum has called the "third culture", or the bridge between biophysical and social sciences (Odum & Rapport, 1997). Therefore, human ecology clearly requires collaboration between social, physical, and biological scientists. It also requires substantive involvement of communities that are its focus.

Scientists with diverse intellectual and methodological approaches have participated in shaping the identity of human ecology as an academic discipline. Human ecologists have long debated the relationship between culture and nature, with some tending towards cultural materialism and/or environmental determinism (Kormondy & Brown, 1998) while others have proposed that nature is predominately a social construct (Gunderson & Holling, 2001). This tension is by no means resolved within the field. Informed by the worldviews of indigenous communities in the Arctic, the authors understand culture as an aspect of nature, but emphasize the potential for human communities to assert agency within a certain range of social and ecological possibilities. We view human communities as full participants in ecosystems, and therefore hold any dichotomy between culture and nature to be false.

This paper employs a human ecological lens developed through participatory research with indigenous communities in the Arctic and sub-Arctic. The lens consists of four distinct, but interrelated elements: diversity and perception; human ecological relations; context; and practical wisdom or *phronesis* (Kassam, 2009a).

Humans and other organisms perceive the world around them by recognizing difference. Since differentiation enables perception, and without perception there is no knowledge, diversity is the source of knowledge. The loss of diversity threatens the essence of our humanity. Multiple ways of perceiving and knowing the world, based on differentiated experiences of diversity, are therefore the indispensible assets of human communities at all scales.

Ecology is the science of connectivity; humans engage the diversity around them through ecological relations. Human ecological relations are informed and sustained through active engagement with one's ecology. Hunting, gathering, agro-pastoralism, and other subsistence livelihoods require direct interactions with humans, other animals, plants, inanimate and spiritual entities. Human ecological relationships can also be indirect, reflecting the complex connectivity inherent in sociocultural-ecological systems. For instance (as will be illustrated below), the relationship between the bowhead whale and the Iñupiat is indirectly affected by anthropogenically-induced impacts of climate change on sea ice caused by greenhouse gas emissions.

Context is the particular space in which human-ecological relations are possible: it is the *oikos* (household or habitat) that is at the root of the disciplines of *economics* and *ecology*. While some may view the abiotic as "background", indigenous communities often recognize the physical environment as actively participating in sociocultural-ecological processes. Ecologists confirm the significance of feedbacks between so-called living and non-living elements of ecosystems. Nothing can be relegated to the "background" if we appreciate the complexity of human experience within ecosystems. Therefore, context is not simply a physical or geographical space, but a multi-dimensional reality described by the ecological relations that are possible within it. As a dramatic contextual shift, climate change impacts human ecological relations and requires adaptations of people in their habitat. Although climate change is a global phenomenon, its impacts differentiate at local scales and adaptations must be context-specific. Nonetheless, the particular experiences of indigenous communities can speak to general trends and contribute to theoretical perspectives in order to guide broader-scale initiatives.

As they draw on ecological relations to sustain themselves, all human communities rely on practical wisdom, or *phronesis*. Aristotle wrote that in order to understand *phronesis,* we must observe those who are adept at securing the wellbeing of households, and their habitats (*oikos*). Indigenous communities that engage in subsistence lifestyles rely on their immediate ecology to survive. These communities develop context-specific ecological knowledge and paradigms of the broader world. *Phronesis* therefore includes knowing *that* some things are generally the case and knowing *how* to act in a specific context (see Figure 1). The interaction between context-specific and context-independent knowledge is critical to adaptation. As communities anticipate and respond to climate change, they combine previous context-specific experiences along with context-independent knowledge gained from other sources. In essence, they are learning *how* to respond to new conditions.

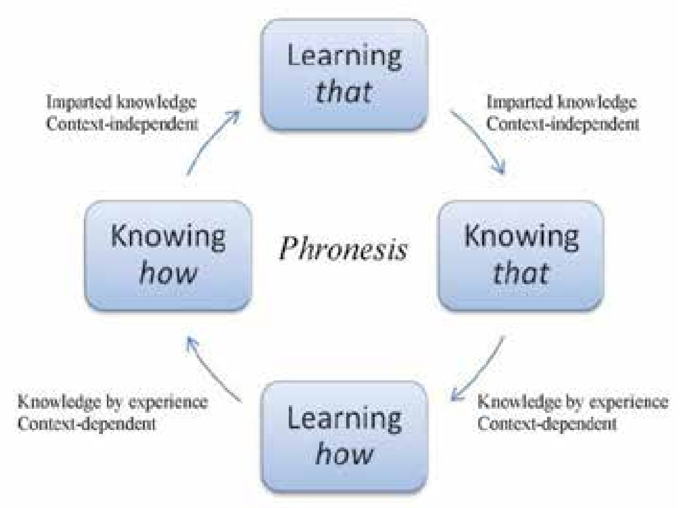

Fig. 1. The Cycle of Practical Wisdom

2.1 Viewing vulnerability, resilience, and adaptation through the human ecological lens

Analysis of the vulnerability, resilience, and adaptation of indigenous peoples are vital to understanding the implications of climate change. Recent scholarship on climate change has drawn on theories of vulnerability (Adger & Kelly, 1999; Agrawal, 2008; Ribot, 1995). Although there are many definitions of vulnerability in use in the social science literature, we accept the consensus reached by the Intergovernmental Panel on Climate Change (IPCC). In its Fourth Assessment Report, the IPCC defines vulnerability as the "degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (Baede et al., 2007: 89). The propensity to focus on vulnerability alone can give the impression that indigenous peoples are merely passive victims of climate change. Human communities also have agency. Hence, our analysis would not be complete without accounting for the ways these communities are highly resilient to change. The IPCC defines resilience as the "ability of a social or ecological system[2] to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change" (Baede et al., 2007: 86). Therefore, vulnerability and resilience co-exist and must be taken into consideration simultaneously.

Viewed through the human ecological lens, vulnerability is directly related to perceptions of diversity, context, human ecological relations, and *phronesis.* A greater number and quality of ecological relations (i.e. complex connectivity) can reduce the vulnerabilities of a community to many impacts. For example, a community that plants a diversity of crops is generally less likely to experience food shortages if certain crops are affected by disease or pest outbreaks. The cycle of practical wisdom (Fig. 1) within human ecological relations allows communities to transform context-specific knowledge and reduce their vulnerabilities to adverse climate change impacts. A community that knows *how* to build homes to withstand rare flood events, for instance, is less vulnerable to increases in the frequency and intensity of flooding resulting from climate change. Communities' that engage in subsistence activities such as hunting, fishing, gathering or agriculture are able to perceive nuanced changes in their environment, and this increases the likelihood that they will respond. For example, a community that can perceive a slight change in water quality has more time to respond to the degradation before it reaches crisis levels (Alessa et al., 2008).

Climate change strategies are often classified as either mitigation or adaptation. The IPCC defines mitigation as "Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to *Climate Change*, mitigation means implementing policies to reduce *greenhouse gas* emissions and enhance *sinks.*" (Baede et al., 2007: 84), whereas adaptation includes "Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected *climate change* effects." (Baede et al., 2007: 76). In short, mitigation addresses the causes of climate change, while adaptation deals with its effects. Industrial countries that are responsible for climate change need to develop both kinds of strategies. Many indigenous communities can do little to mitigate the causes of climate change and therefore must adapt to its local effects. However, adaptation is not limited to responses to change, because communities may adapt by preparing for future possibilities (Hassan, 2009).

It should be recognized that when considering adaptation strategies, vulnerability and resilience can only be defined in relation to a specific threat. The same qualities that make a

[2] While we accept the IPCC definition of resilience, we note that it separates ecological from social systems. This conceptual dichotomy, as we noted previously, is not useful in addressing the issue of climate change. In fact, such a bifurcated perspective may have contributed to anthropogenically-induced climate change.

community resilient to one threat may make it vulnerable to another. For example, a high degree of social-connectivity would hasten a community-level response to a natural disaster, but the same connectivity may also accelerate the spread of infectious disease. Therefore, any conversation about adaptation to vulnerability must refer to specific contextual changes. The most effective adaptations respond to existing hazards while at the same time anticipating new risks or opportunities. In fact, if adaptations were only responsive, they would rarely contribute to resilience, because actions to reduce vulnerability to one set of threats often increase vulnerability to others.

While the focus of our analysis of vulnerability, resilience, and adaptation is in relation to climate change, we also acknowledge that non-climate-based drivers of change contribute to the vulnerability of human communities. In short, climate change is taking place under pre-existing conditions of inequity (Okereke, 2006; Paavola & Adger, 2005,). These additional stressors have a cumulative negative effect when combined with the adverse effects of climate change.

Given the vulnerability of indigenous societies, which are highly dependent on their ecological habitat (such as those in the circumpolar arctic and mountainous regions of the Pamir), and the chronic, long term impact of climate change, the issues of distributive, intergenerational, and environmental 'justice' to fund and support responsive action becomes highly relevant. Furthermore, as the impacts of climate change are unevenly distributed across the globe, thus affecting areas where existing socio-economic inequities persist, the issue of ethical 'responsibility' becomes equally pertinent (Adger, 2001; Füssel, 2010; Grasso, 2010a, 2010b; Harris, 2010; Ikeme, 2003; Jamieson, 2009; Johnston, 2011; Kasperson & Kasperson, 2001; Lahsen *et al*. 2010; O'Hara, 2009; Okereke 2006; Okereke and Dooley 2010; Paavola and Adger 2006; Page, 2006; Pelletier, 2010; Posner & Weisbach, 2010; Shukla, 1999; Thomas & Twyman, 2005). While there is much being written and debated in international forums about these issues, we maintain that scholars can take 'responsibility' and commit to act 'justly' by contributing as a *community of inquirers* to build anticipatory capacity with *communities of social practice* where the impacts of climate change are immediate and local in scale.

3. Case studies

Climate change is a global phenomenon, even if human communities are contributing unequally to its causes. Many of the direct impacts of climate change are context-specific to a local scale. The case study approach is productive for appreciating concrete impacts, and can produce more general knowledge for scientists interested in larger-scale phenomena. It is important to remember that Galileo in his physical experimentation as well as Darwin in his zoological research relied on context-specific studies that resulted in reconfigurations of scientific knowledge (Kassam, 2009a). In this spirit of valuing local knowledge without diminishing the importance of globalized studies, we present two case studies of vulnerability and adaptation to climate change from the high-latitude Arctic, and the high-altitude Pamir Mountains. Both study locations are areas of high biocultural diversity, and are currently being affected by climate change. Both case studies are fundamentally dependent on local knowledge. The sections that follow employ the human ecological lens to understand human vulnerability and adaptation to social and ecological change.

3.1 High-latitude case study: Wainwright, Alaska

Research with the Iñupiat of Wainwright, Alaska, conducted in 2001 demonstrates the human ecological implications of climate change that are useful in understanding vulnerability and adaptation. Wainwright (70.59° N, 160.07° W), is located 480 km north of the Arctic Circle and 136 km southwest of Barrow on the Chukchi Sea (Figure 2). The community is comprised of mix of *Kuugmiut*, 'people of the Kuk River,' and *Utuqqagmiut*, 'people of the Utuqqaq River.' Both groups are Iñupiat (Braund, 1993). Known as *Ulguniq* by the Iñupiat, Wainwright is one of seven communities belonging to the North Slope Borough, the political subdivision or municipal government for northern Alaska. The population of Wainwright in 2001 was approximately 550 residents with 91 families (Kassam & The Wainwright Traditional Council 2001; Kassam, 2009a).

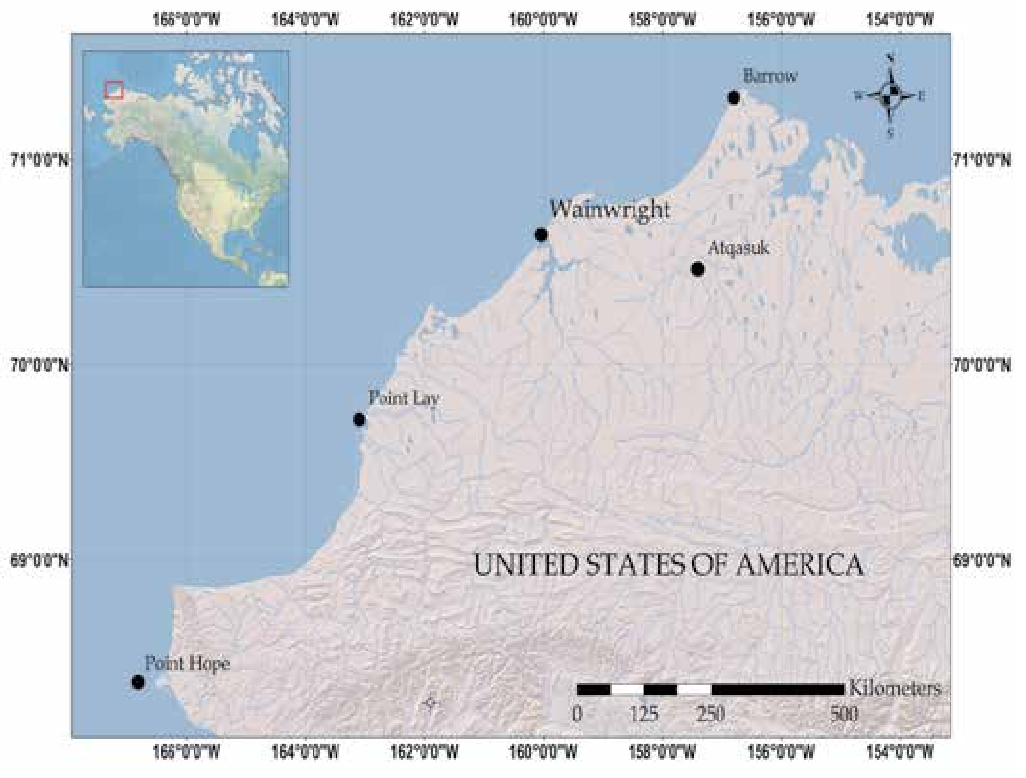

Fig. 2. Location of Wainwright, Alaska

Subsistence activities of the Iñupiat connect them to a diversity of life and require them to observe contextual changes. Iñupiat knowledge of sea-ice, which is required for subsistence activities, has enriched our collective understanding of climate change in the Arctic (Kassam, 2009a; Krupnik & Jolly, 2002).

Iñupiat knowledge of sea-ice is well documented (Kassam, 2009a; Nelson, 1969). Knowing *how* to survive with and on sea-ice plays a fundamental role in subsistence hunting activities around Wainwright. The residents maintain relations with many sea mammals to meet their nutritional needs despite risks associated with travel on open water and sea ice (Fuller & George, 1999; Ivie & Schneider, 1988; Kassam & The Wainwright Traditional Council, 2001;

Luton, 1986; Nelson, 1969, 1982). The Iñupiat have therefore developed significant context-dependent knowledge of sea-ice and methods for interacting with it.

3.1.1 Perception and diversity

Knowledge of sea-ice derives from perception and enables hunters to discern changes in sea-ice conditions. In 1999, hunters and gatherers who participated in research focused on the impact of chemical pollutants on subsistence foods also made several observations about sea-ice that demonstrated the need for further research on climate change in the community. These observations included a 25-year warming trend. Hunters also observed that warmer fall and winter months also appeared to have delayed the freeze-up of sea-ice around Wainwright, from the beginning of October until December. Hunters also reported that when sea-ice does form, it is less robust in some areas than in the past. Furthermore, climate change impacts make subsistence activities potentially dangerous, because the harvests of marine mammals require calm winds and strong ice for safe travel. Changes in sea-ice have direct consequences for the safety of hunters. For example, hunting crews must know if the ice will support the weight of marine mammals, such as a bowhead whale (Kassam, 2009a).

3.1.2 Relations

The seasonal round of subsistence harvesting of the Iñupiat of Wainwright illustrates complex relations with twenty-nine species of animals and plants (see Figure 3). The seasonal round also shows that many of these relations depend on ice conditions, a foundational element of their ecological context.

Social relations within the community of Wainwright are also closely tied to subsistence activities. Gender roles are linked to the relations between Iñupiat and the bowhead whale. When a whale is successfully hunted, it is understood to have given itself to the wife of the whaling captain (Bodenhorn, 1990). The whaling captain's wife, with the support of other women in the community, assumes specific roles to ensure a successful hunt, including directing the butchering, sharing the harvest, and storage of the whale for later distribution to the entire community for several subsequent festivals. Additionally, rules regarding cleanliness of the home and behaviour between husband and wife guide domestic interactions. The whaling captain and his crew are responsible for cleaning out the ice cellar to prepare for the whale's arrival. In this way, gender roles are tied to relations with the bowhead whale.

The human ecological relations of Iñupiat hunters to the bowhead whale are also demonstrated during the *Nalukataq* celebration held after a successful hunt, the community gathers to feast and thank the whale and the whaling crew. Social relations between community members and the bowhead whale are both honoured and strengthened during the *Nalukataq*, demonstrating that relations between Iñupiat and bowhead whales are central to both the cultural values and social structure of the community of Wainwright (Kassam, 2009a)

The above examples demonstrate the complex connectivity between Iñupiat communities, animals such as the bowhead whale, and sea-ice. These diverse relations doubly reinforce the sociocultural with the ecological. Both nutritional needs and social ties mutually support each other through understanding of sea-ice and relations with the bowhead whale. Climate change impacts would likely affect these relations and increase the vulnerability of these communities to complex feedbacks of ecological and sociocultural change.

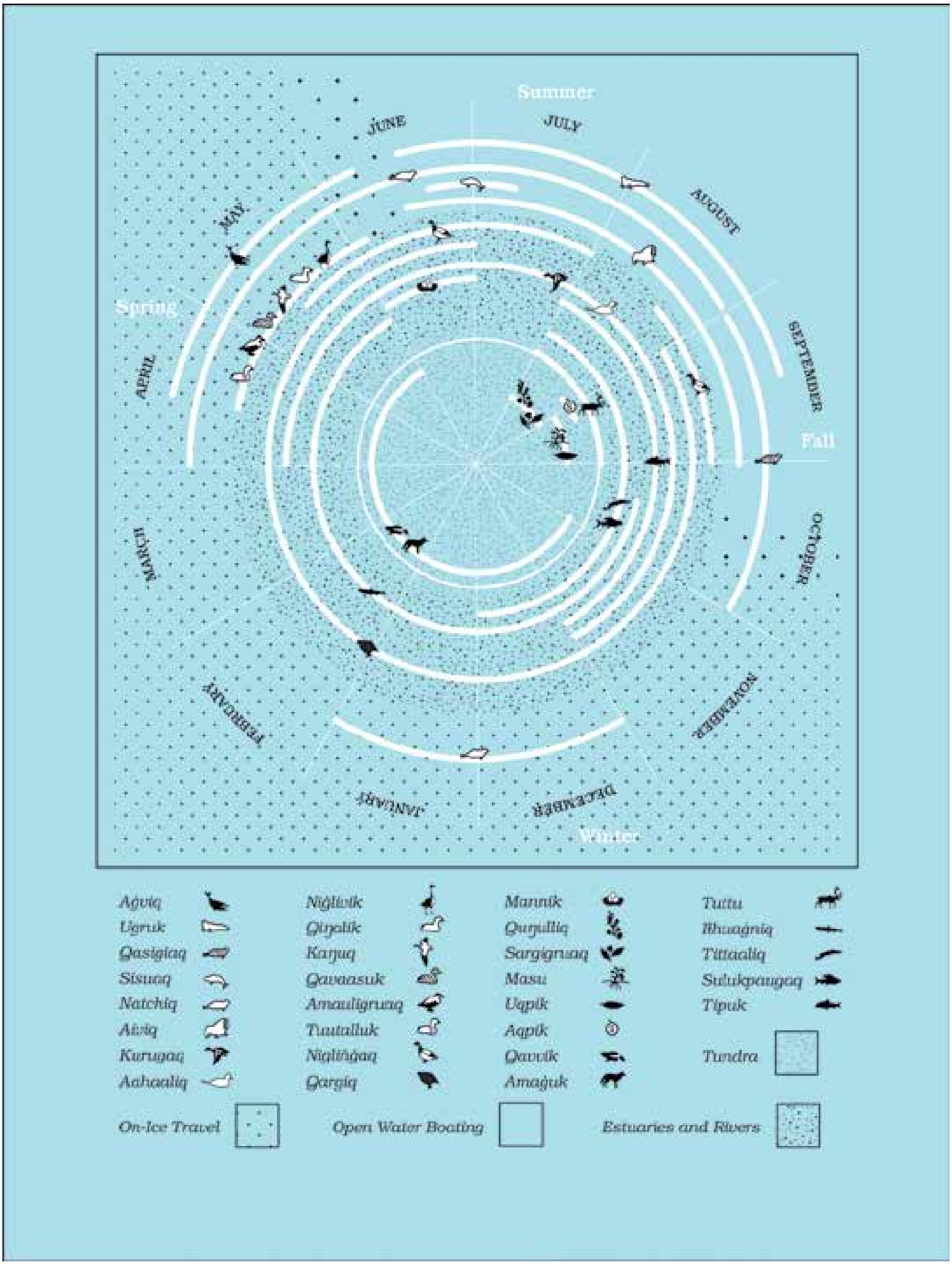

Fig. 3. Seasonal profile of subsistence harvesting in Wainwright, Alaska.

3.1.3 Context

Climate change significantly affects Iñupiat habitat. The formation of sea-ice is context-dependent: any change in temperature, winds and currents alters sea-ice formation. Unlike Point Barrow and Point Hope, Alaska, where wind patterns are primary drivers for sea-ice formation, the concave formation of the coast of Wainwright makes currents in combination with wind the primary drivers (See Figure 2). Hence, indigenous knowledge of sea-ice formation is also context-specific. As noted earlier, alterations in climate, resulting in unsafe sea-ice conditions may put the safety of Iñupiat hunters at risk, inhibiting engagement in subsistence hunting. Therefore, climate change has a direct impact on the food security of the Iñupiat.

3.1.4 Phronesis

Practical wisdom emerges from the Iñupiat's ecological relations to their environment and enables them to know *how* to interact with sea-ice and other elements of their habitat. Due to variable climatic conditions of the Arctic, such as seasonal changes in average daylight hours and temperature, Iñupiat knowledge is highly adaptive.

Iñupiat knowledge of sea-ice contains specific understanding of ice formation, grounding of pressure ridges, opening of leads in ice, and the dynamic relationships between winds and currents necessary for navigating sea-ice. Climate change is leading to increasing uncertainty in patterns of sea-ice formation. Changes in the timing of sea-ice formation are challenging the predictive capacity of Iñupiat knowledge of sea-ice. This is an example of changing context affecting the relevance of practical knowledge.

When the context-dependent knowledge of a community is challenged, it can be useful to incorporate new context-independent knowledge to facilitate the process of adaptation. For example, Synthetic Aperture Radar (SAR) images contributed by researchers from the North Slope Borough's Geographic Information Systems division corroborated Iñupiat observations of sea-ice. When indigenous knowledge was combined with SAR data, both the community and researchers had a better understanding of sea-ice. While this science-indigenous commensurability is usually made to demonstrate the significance of indigenous knowledge, we think this also indicates that scientific data can contribute to practical wisdom of communities in a changing environmental context.

3.1.5 Practical wisdom, agency, and adaptation

Although the Iñupiat have high adaptive capacity, assistance in developing strategies in response to the current magnitude of climate change is crucial. A recent example of adaptation to adverse circumstances in the circumpolar North involving Iñupiat communities of the North Slope Borough took place in response to the collapse of the Soviet Union’s centralized economy in the mid-1990s. Resulting shortages of food and fuel in the polar regions of the former USSR threatened the survival of indigenous communities. Assistance was not available from the Russian government; instead it came from other circumpolar indigenous communities. Diverse indigenous groups including the Inuit, Iñupiat, Inuvialuit and Yupik came to the assistance of the Chukchi and Yupik on the Chukotka Peninsula.

While this assistance provided by circumpolar indigenous groups bore some likeness to international emergency relief efforts, their responses were unique because they involved a transfer of tools and knowledge to facilitate subsistence hunting and gathering (i.e. knowing *how*). In this circumstance, the ability to hunt was vital to feeding members of one's community and household (*oikos*). Knowledge of *how* to maintain a subsistence lifestyle was only present in a few individuals, after decades of neglect due to Soviet industrialization and collectivization. To counter decades of Soviet discouragement of local resource use, Alaska's Iñupiat needed to send supplies to their neighbours across the Bering Sea. They also invited community leaders, hunters, and scientists from the Chukotka to Alaska's North Slope Borough to facilitate the transfer of knowledge and strengthen local institutions that would become stewards of hunters' rights and capacities to use local resources effectively (Kassam, 2009a).

While the adaptation outlined above took place in response to a shift in the political ecology of the region, this model of co-operation and knowledge transfer between indigenous communities has potential applications to the current context of climate change. Increasingly, circumpolar Arctic communities will need to work together across international borders to respond to mutual vulnerabilities and developing adaptive responses.

3.2 High-altitude case study: the Afghan and Tajik Pamirs

Complementing the previous case study's high-latitude context, a case study from the Pamir Mountains of Central Asia highlights the human ecological implications of climate change as they relate to vulnerability and adaptation at high altitudes. This case study is based on data collected in 14 villages in Afghanistan's Badakhshan province and the Gorno-Badakhshan Autonomous Oblast of Tajikistan, at elevations ranging from 2,365 to 3,852 meters above sea level. The region has been influenced by European colonization, Soviet collectivization, civil war, and is currently the setting of the global war on 'terror' localized to Central Asia. Continued presence of violence and food insecurity, including the threat of famine, have been recurrent problems in the region, and continue to be major concerns (Aga Khan Foundation Tajikistan, 2005).

The Pamir Mountains are considered to be a global center of biodiversity, supporting, for example, more than 5,500 species of plants, of which 1,500 are endemic (Conservation International, 2007). Located in this diverse mountain system along the Silk Road, the Badakhshan region of Afghanistan and Tajikistan is also an area of high cultural, linguistic and religious diversity. A single valley can be home to several distinct ethnic groups, who speak different languages and practice a variety of interpretations of Islam (Kassam, 2009b). For example, the Wakhan corridor of Afghanistan is home to the Kyrgyz and Wakhi. The Kyrgyz are nomadic pastoralists, tending livestock such as camels, yaks and goats. They speak Kyrgyz and are Sunni Muslims. The Wakhi, are sedentary farmers, growing mainly barley, wheat and peas, and keeping small amounts of livestock. They speak Wakhi, and are Shia Ismaili Muslims. Being primarily nomadic pastoralist and agro-pastoralist communities respectively, the Kyrgyz and Wakhi fundamentally depend on their immediate habitat to survive; thereby, making them acutely aware of change (Kassam, 2010).

3.2.1 Perception and diversity

Communities in the region recognize ecological changes that impact agricultural and pastoral practices through their perception of diversity. Observations by villagers and nomads in the region indicate dramatic evidence of climate change (Kassam, 2009b). Many of the observed changes have important implications in terms of increased vulnerability, such as food insecurity and violence. The character of specific impacts of climate change differs within a region, depending upon ecological context.

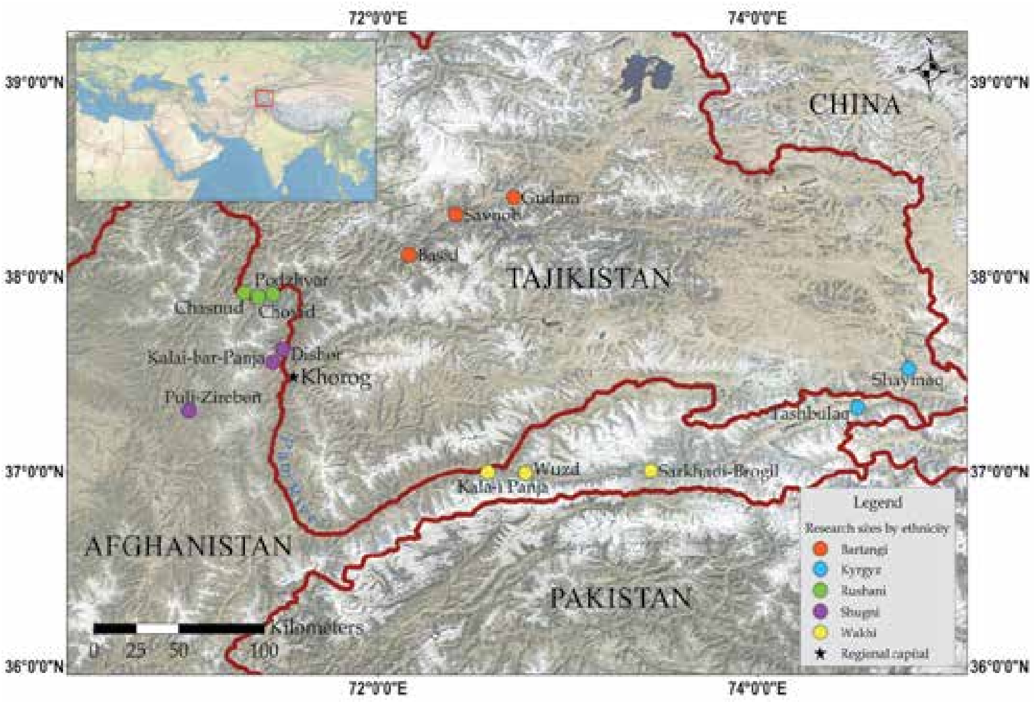

Fig. 4. Map of Study Area, Badakshahan region of Afghanistan and Tajikistan. Fourteen communities were visited.

Local observations of glacial activity concur with Dyurgerov and Meier's (2000) findings of an increase in the volume of glacial melt in the northern hemisphere (including the Pamirs) since the 1970s, accompanied by a rapid lowering of glacial density. Villages at lower elevations report the loss of rich agricultural land and certain crops due to changing river patterns and higher water levels. Observed shifts in precipitation type and intensity, from steady snows to concentrated rains, has negatively impacted wheat production at lower elevations. At high elevations, high-volume rain events also stress the physical integrity of structures such as the walls and roofs of schools and homes, which were built to withstand heavy loads of snow, but not rain. In addition, community members also identified issues of safety due to avalanches and rockslides caused by rains. Rockslides also threaten food security, as blocked roads prevent the delivery of food and other supplies to remote villages.

In addition, both agriculturalists and pastoralists in the Badakhshan region complain that they can no longer predict the weather. Dependent upon location, both warming and cooling trends in temperature have been noted in the region. Warmer spring temperatures in high elevation Pamiri villages results in plowing and sowing of wheat and barley 15 to 30 days earlier than a decade ago. At the same time, some villages at lower elevations that once grew certain fruits successfully, now see changes in quality or are no longer able to cultivate them at all. While some of this change is related to loss of varieties and knowledge of cultivation during Soviet rule, some fruit trees also require chilling days in the winter (vernalization) to produce fruit in the summer (Nabhan, 2009). Along with warmer weather, farmers have observed more insect infestations affecting their fruit crops, especially apricots. At higher elevations, Kyrgyz nomadic pastoralist communities report that spring is a continuation of winter. Furthermore, fodder in summer pastures is drying up before animals are able to gain the weight necessary to sustain them through the winter. All of these observations of climate change are enabled by the ability to perceive differences between past and current conditions (Kassam, 2009b).

3.2.2 Relations

Diverse ethnic groups of the Badakhshan region demonstrate complex connectivity with their habitat. Human ecological relations may make them less vulnerable to adverse impacts of climate change. For example, Kyrgyz pastoralists and Wakhi agriculturalists maintain dynamic relationships with each other as well as their surrounding environments. Social relations are strengthened between the two communities by exchange of animals, wheat, and trade goods from lower elevations. Such trade can reduce the vulnerability to food insecurity resulting from climate change impacts. Social relations are linked to ecological and cultural relationships. For example, in the spring and summer, the Kyrgyz and Wakhi's ecological niches overlap as they share high-elevation pasturelands. Although ethnically distinct, practicing different interpretations of Islam, the Kyrgyz and Wakhi are also connected through shared sacred sites, demonstrating complex connectivity between the sociocultural and ecological (Kassam, 2010).

Another example of complex connectivity is the calendar of the human body. To mark the passage of the year and seasons, village elders assigned a certain number of days to different parts of the body, starting from the toenail, and culminating with the head. Agricultural activities correspond to different parts of the body through this calendar. These correlations are based on observations of relations in time, such as the day of the year when the sun illuminates a designated point on a mountainside, which then corresponds to a specific part of the body. Villagers' bodies are related to the land through both working with it, and acting as organic clocks to mark the movement of time. The specific timing of the calendar of the human body is context-dependent, and differs from valley to valley. Although no longer widely used due to the impacts of Soviet rule, the complex interrelationships represented by the calendar of the human body demonstrate potential for adaptive capacity to climatic variation (Kassam et al., 2011).

3.2.3 Context

Context provides the basis for which vulnerability and adaptation to climate change in the Pamirs can be understood. People of the Badakhshan region shared a similar ecological and cultural context until the late nineteenth century, when an international border was established, furthering colonial interests. More recently, this division has resulted in the differentiation of knowledge systems on either side of that border (Kassam, 2009b).

Pamiri communities on the Tajik side experienced dramatic contextual changes in the twentieth century. The impacts of those changes can help us understand factors contributing to climate change vulnerability. Starting in the 1920s, Tajikistan became part of the centralized Soviet agricultural system, which emphasized collectivization, monoculture cropping, and intensive irrigation on an industrial scale. These practices resulted in the destruction of millions of acres of arable land across Central Asia, including Tajikistan, due to processes such as soil erosion and salinization (Bekturova & Romanova 2007). Another consequence of Soviet agricultural policy was the devaluation and loss of context-specific indigenous agricultural knowledge, in favor of context-independent agro-industrial knowledge promoted by the Soviet command economy. Several generations of participation in a centralized industrial agriculture system resulted in the loss of seed varieties adapted to local conditions, and the loss of knowledge of *how* to cultivate a greater diversity of plants. For example, the Pamiri villages of Savnob and Basid have lost both the indigenous variety of seed and the knowledge to cultivate that watermelon type once grown in the area. The need for local knowledge in the Badakhshan region of Tajikistan began to reestablish itself as state employees returned to the area to become farmers following the collapse of the Soviet Union, and a subsequent civil war. In contrast, people of Afghan Badakhshan have always relied upon their local knowledge as a means of subsistence. This local knowledge has allowed for continued survival through dramatic shifts in the political ecology of the region.

3.2.4 Phronesis

As previously stated, human ecological knowledge is relational. Like the Arctic, climatic conditions in the Pamir Mountains are highly variable. Practical wisdom developed by local agricultural and pastoral inhabitants has allowed them to know *how* to grow crops and raise livestock in a challenging environment. In addition, community members demonstrate local, context-dependent knowledge through knowing *how* to identify, harvest and utilize at least 58 different species of plants for medicinal purposes (Kassam et al., 2010). Knowing *how* in this case study includes detailed knowledge about river flow patterns and phenological cues that villagers use to decide when to plough, plant and harvest. As weather patterns shift due to climate change, vulnerability can increase if the workability of local knowledge declines.

However, *phronesis* is an adaptive process, and knowing *how* changes along with shifting context. For instance, people who have recently returned to Tajik Badakhshan are utilizing context-independent knowledge, a knowing *that* agriculture has been possible in the area, to develop new ways of knowing *how* to farm. In addition, scientific knowledge can contribute important *knowing that* to the cycle of *phronesis* (See Figure 1) in Badakhshan. Expeditions to the Pamirs by Korzhinsky and Vavilov in the late 19th and early 20th centuries provide an important baseline for understanding changes in the ability to cultivate wheat at progressively higher elevations (Vavilov, 1951, 1957, 1997). Local observations about increasing glacial flow and other climate change impacts can corroborate scientific observations where long-term weather records do not exist.

3.2.5 Practical wisdom, agency and adaptation

Villagers in the Badakhshan region are already demonstrating agency through agricultural adaptations that reduce vulnerability to the impacts of climate change. Such adaptations are responses to contextual shifts, made possible through keen observations of change combined with agriculture knowledge held by community members (knowing *how*). Communities at higher elevations, where wheat was rarely harvested because of frost damage, have begun to regularly harvest wheat. Villages reporting these changes include Ghudara in Tajikistan, and Pul-i Zirabon and Sarhad-i Broghil in Afghanistan. Conversely, at lower elevations, villagers have begun to replace wheat with barley and potatoes, which are more suitable to new patterns of precipitation (See Figure 4). As these changes in food production are quite recent, it is too soon to determine the cultural implications of such shifts in diet. However, traditional agricultural festivals designated according to the solar calendar, no longer correspond to planting and harvest times. This creates a fissure between established practices and changing ecological rhythms. Pamiri communities are generally affected by such sociocultural impacts of climate change like the Iñupiat.

4. Discussion: Case study synthesis

In the communities we have considered, we have identified three vulnerabilities to climate change:[3] safety, food security, and the bearing the previous two have on social structures and cultural systems (see Table 1). These case studies demonstrate that safety and food security of communities are vulnerable to increased unpredictability of bio-physical processes that render practical wisdom less applicable for knowing *how* to maintain subsistence activities. It is noteworthy that both the Pamiris and the Iñupiat have been affected by changes in their respective political ecology resulting from the collapse of the Soviet Union. This illustrates that the issue of climate change cannot be viewed in isolation from inequities and changes occurring globally.

Vulnerability/ Adaptation	High-Latitude Case Study of Wainwright, Alaska	High-Elevation Case Study, Pamir Mountains
Safety	Concern for safety of hunters resulting from erratic weather conditions affecting sea-ice formation, robustness, and decay.	Concern for safety related to increased glacial melt affecting river patterns, glacial lake bursts, rock and landslides, and road blockages. Changing precipitation compromises building integrity.
Food Security	Implications for subsistence activities leading to concerns for food security.	Implications for transhumant agro-pastoral activities leading to concerns for food security.
Sociocultural Relations	Specific impact on the cultural value of sharing through changes in social relations.	Earlier seeding and harvest times are no longer in synch with traditional agrarian festivals, which are based on the solar calendar.
Adaptations	Transfer of knowledge and tools through co-operative assistance between circumpolar indigenous communities in response to food and fuel shortages in the former USSR.	Experimentation by farmers in growing wheat at higher elevations and transfer of knowledge about cultivating crops that are suitable for new contexts.

Table 1. Vulnerabilities and adaptations to climate change impacts.

Cultural values and social structures are integral to human ecological relations. Safety and food security illustrate the impact of climate change on social systems and cultural values. In the Arctic, social structures are linked to relations with key animals, such as the bowhead whale. The cultural value of sharing is reinforced by festivals honoring the whales and hunters, while also enabling the distribution of food. With changes in sea-ice formation and its impacts on whaling, social structures and cultural values that sustain the community are

[3] This list is by no means exhaustive: we present only vulnerabilities that emerged strongly from our case studies.

also at risk. In the Pamirs, as arable land area is reduced due to climate change, the social relations that allow for the sharing of pasturelands become vulnerable. Shifts in knowledge and relations brought about by climate change may result in complex feedbacks to coupled sociocultural-ecological systems.

Indigenous knowledge is adaptive because individuals have learned to sustain complex sets of responses within dynamic systems (Berkes et al., 2000). Through the human ecological lens, we identify three processes of adaptation to shifting contexts: perception of change, shifts in relations, and *phronesis*. Indigenous communities are keen observers of their habitat, and their ability to recognize change contributes to effective responses. A diversity of human ecological relations allows communities to focus on new relations in order to adapt. The dynamic nature of *phronesis* is inherently adaptive and allows communities to incorporate new knowledge into practical responses. While predictions for future impacts of climate change are grim, perception, relations, and *phronesis* provide opportunities for human agency.

While indigenous knowledge has often been contrasted with science, the heterogeneity within both knowledge systems has shown any dichotomy drawn between the two to be facile (Agrawal, 1995). The concept of *phronesis,* with its context-dependent and context-independent components, illuminates some possibilities for the integration of indigenous and scientific knowledge in developing adaptive strategies for communities. When communities experience dramatic change, they need to know *how* to maintain human ecological relations in their evolving context. To anticipate climate change, communities must build on previous experience and acknowledge a variety of theoretical possibilities for the future. Anticipatory capacity therefore emerges from *phronesis*, because knowing *how* to act requires knowing *that* certain impacts are likely. Both local knowledge and climate science research can help communities anticipate those impacts and develop appropriate plans and responses.

While we are optimistic, we should not underestimate the potential implications of climate change. Multiple stressors, such as economic inequities add to the complexity of building anticipatory capacity for climate change. *Communities of inquirers* (applied researchers) have an ethical obligation to support processes of adaptation in communities experiencing the disproportionate impacts of climate change. Meaningful contributions will require interdisciplinary teams of social, biological, and physical scientists in order to understand the complexity of human ecological dimensions in these contexts.

Furthermore, applied research aimed at understanding the implications of global climate change within local contexts will require active engagement with *communities of social practice* such as village members, civil society institutions, and government institutions (Argyris et al., 1985). In normative terms, practitioners have the right and responsibility to shape the research agenda so that outcomes meet their community needs. At the same time, these *communities of social practice* have the potential to enrich our global understanding of climate change. People who have operated in a place for multiple generations develop specific knowledge based on observations of gradual and acute change. This can be particularly important in areas where the effects of climate change are already being realized and instrumentalized observational data (e.g. temperature and precipitation) is limited, such as in the Pamir Mountains.

One of the most significant contributions that *communities of inquirers* can make in active engagement with *communities of social practice* is to help build 'anticipatory capacity' in response to climate change. The etymology of the verb 'anticipate' indicates: (1) 'realization' that a response is needed; (2) preparation for a response 'beforehand'; and thus, (3) the act of 'dealing with' the situation[4]. To anticipate encapsulates the coupled ideas of 'mitigation' and 'adaptation' while reinforcing the role of human agency in dealing with sociocultural-ecological change. The word 'anticipate' is useful to convey preparatory capacity of communities at the local scale where climate change will have its most immediate impacts. The word also conveys the anxiety experienced by human societies (such as those in the Arctic and Pamirs) as they face the consequences of climate change.

In climate change literature, the idea of anticipatory capacity is qualitatively different from prediction, which is increasingly associated with development of technical models at a regional or global scale (Adger, 2001). Predictions can contribute to anticipatory capacity by presenting a variety of future scenarios to help communities prepare. However, anticipatory capacity seeks to be more applied to local nuances and less generalized. Anticipatory capacity acknowledges the role of science and simultaneously involves human agency in terms of the role of cultural systems and social structures that provide meaning and mechanisms for human action. In both of the case studies presented, anticipatory capacity of local communities is being enhanced through engagement with *communities of inquirers*.

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Climate Change in Spain: Phenological Trends in Southern Areas

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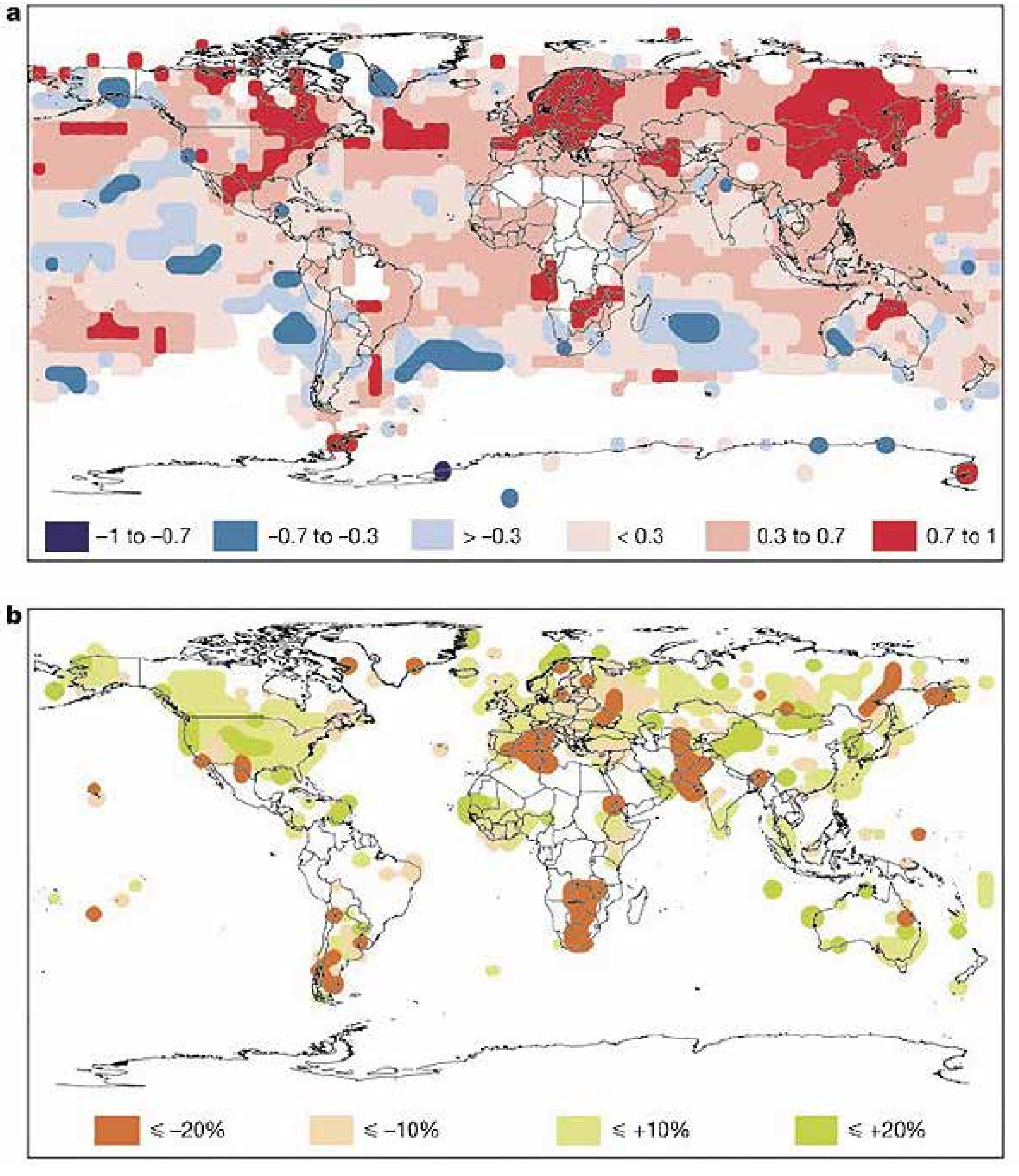
1. Introduction

Global average surface temperatures increased by 0.6±0.2ºC over the twentieth century, and a further increase of 1.4 to 5.8ºC is projected by 2100 (Figure 1). Europe recorded its warmest decade from 1990 to 1999 (IPCC, 2001; IPCC, 2007). The rate of warming during this period has been approximately double that the previous one and, greater than at any other time during the last 1,000 years. Organisms, populations and ecological communities do not, however, respond to approximated global averages. Rather, regional changes, which are highly spatially heterogeneous (Figure. 1), are more relevant in the context of ecological response to climatic change. In many regions there is an asymmetry in the warming that undoubtedly will contribute to heterogeneity in ecological dynamics across systems. Diurnal temperature ranges have decreased because minimum temperatures are increasing at about twice the rate of maximum temperatures. As a consequence, the frost-free periods in most mid- and high-latitude regions are lengthening and satellite data reveal a 10% decrease in snow cover and ice extent since the late 1960s. Changes in the precipitation regime have also been neither spatially nor temporally uniform (Figure 1). In the mid- and high latitudes of the Northern Hemisphere a decadal increase of 0.5–1% mostly occurs in autumn and winter whereas, in the sub-tropics, precipitation generally decreases by about 0.3% per decade (IPCC, 2007).

The impact of climate change, and particularly of climate warming, is being tracked in many physical and biological systems. Phenology—the timing of seasonal activities of animals and plants—is perhaps the simplest process in which to track changes in the ecology of species in response to climate change. Birds, butterflies and wild plants, in particular, include popular and easily identifiable species and thus have received considerable attention from the public. Plant phenology is seen as one of the most important bio-indicators, since trends can provide considerable temporal and spatial information regarding ongoing changes (Menzel et al., 2006). As a result many long-term phenological data sets have been collected. Studies in Europe and North America have revealed phenological trends that very probably reflect responses to recent climate change . Common changes in the timing of spring activities include earlier breeding or first singing of birds, earlier arrival of migrant birds, earlier appearance of butterflies, earlier choruses and spawning in amphibians and earlier shooting and flowering of plants. In general, spring activities have occurred progressively earlier since the 1960s. Plant reproductive phenology is controlled by temperature, especially in tree species, and precipitation and photoperiod, especially in herbaceous ones (García-Mozo et al., 2000; 2009; Galán et al., 2005). It has been shown that plants flowering early in spring are more affected by warming than species flowering later in the year (Ahas et al., 2002; García-Mozo et al., 2002; Galán et al., 2005).



Source: IPCC 2007.

Fig. 1. Spatial variability of annual trends in temperature and precipitation since 1976 relative to 1961 to 1990 normals. a, Temperature (°C per decade); b, precipitation (% per decade).

In Spain, temperatures, especially minimum temperature, have increased over the last century by around 1.5ºC the annual average (Fernández-González et al., 2005). Climate change has had a particularly marked effect on southern Spain, increasing temperatures and reducing rainfall. Rainfall has also become increasingly torrential in recent years (Pita, 2003; De Castro et al., 2005).

Most long-term phenological studies to date have focussed on northern Europe, while comparatively few have addressed the Mediterranean region (Gordo & Sanz, 2005; Peñuelas et al., 2002). The projections proposed by the Intergovernmental Panel on Climate Change (IPCC) and confirmed by the Spanish Meteorology Agency (AEMET) for the future Spanish climate, point to a continuing increase in temperatures and a decrease in annual rainfall (IPCC, 2007).

The present study, carried out by the University of Córdoba Aerobiology Research Group and the AEMET, sought to chart phenological trends in response to climate in the Andalusia region of southern Spain, and to compare *in-situ* phenological data with airborne pollen counts in the same area. For this purpose, special attention was paid to the reproductive phenophases of anemophilous species.

2. Materials and methods

2.1 Phenological data

Andalusia boasts considerable climatic and topographical diversity. Regular phenological data series dating back to the mid-1980s from four sites were selected for this study, on the basis of unbroken data series availability, presence of anemophilous species and distance from pollen traps: Bujalance and Pozoblanco, in the province of Cordoba, central Andalusia; Charcones and Huescar, in the province of Granada, a more elevated area of eastern Andalusia (Table 1).

Province	*Localities*	*Distance*	*Altitude*	*Coordinates.*	*Tº*	*Rf*
Córdoba	Córdoba		123	37º 50' N, 4º 45' W	18.0	674
	Bujalance	42	222	37º 54' N, 4º 23' W	17.5	550
	Pozoblanco	86	649	38º 23' N, 4º 51' W	16.0	505
Granada	Granada		685	37º 11' N, 3º 35' W	15.5	462
	Charcones	62	1280	37º 40' N, 2º 94' W	13.9	300
	Huescar	100	1115	37º 48' N, 2.33' W	14.8	367

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Table 1. Characteristics of the study sites including distance to the province capital (km) where pollen monitoring was performed, altitude (m.a.s.l.), latitude & longitude coordinates, annual mean temperature (Tº) and annual mean cumulated rainfall (Rf).

The following species were studied in the indicated dates: 2 oak species: holm oak *(Quercus ilex* subsp. *ballota* (Desf.) Samp.) from 1989 to 2008 and gall oak *(Quercus faginea* Lam.) from 1989 to 2000; olive tree (*Olea europaea* L.) from 1986 to 2008; grape *(Vitis vinifera* L.) from 1986 to 2007; and 3 Poaceae crop species: rye (*Secale cereale* L.) from 1989 to 2008, wheat *(Triticum vulgare* L.) from 1987 to 2008, and common barley *(Hordeum vulgare* L.) from 1987 to 2008. Studied periods varied depending on the site and phenophase.

The analysed species were chosen given their ecological or agricultural importance to the region. Typical vegetation of southern Spain is basically formed by Mediterranean forest and dehesas where the main arboreal genus is *Quercus* (estenopalynous genus), and specially holm-oak. This species is the first flowering oak in Andalusia, being the main species contributing to the pollen curve where there are included pollen grains from all the *Quercus* species (García-Mozo et al., 2002; Gómez-Casero et al., 2004; Gómez-Casero et al., 2007). Apart from its ecological importance, in Iberian Mediterranean ecosystems holm-oak acorn production is of vital economic importance due to acorns are the major component in the feeding systems of high-quality Iberian domestic pigs. Regards to olive tree, Spain produces 33% of the world's olive oil, and Andalusia accounts for 80% of total Spanish output being the world's leading olive-oil-producing region. The largest olive-growing areas are concentrated in the provinces of Jaén and Cordoba. Another economically important species analysed in this work is the grape. Spain is the third worldwide winemaker country counting with the largest surface devoted to vineyards, being Andalusia the sixth region in Spain. The analysed variety was "Garnacha", one of the most abundant in the region, which has a medium range flowering time. Finally, although cultivated grass species contribute in a lower percentage than wild species to the grass pollen curve (estenopalynous family), the analysed grass species selected for the present work were indicated as the crop species more represented in the Poaceae airborne pollen curve in Spain (Muñoz et al., 2000).

The following phenophases, taken directly at the field, were analysed once a week: flowering (appearance of first flowers in some individuals), fruit ripening (several ripe fruits present in several individuals), leaf unfolding (appearance of first leaves in some individuals) and leaf falling (branches have lost half their leaves).

Daily airborne pollen counts were monitored in the cities of Córdoba and Granada (Table 1). Hirst volumetric traps were used (Hirst, 1952). Daily samplings were stained and analysed by using optical microscopy following the rules laid down by the Spanish Aerobiological Network (REA) (Galán et al., 2007, http://www.uco.es/rea/infor_rea/manual_eng.pdf). Two important dates of the pollen season were analysed in the present work as indicators of the flowering period from the aerobiological data. The Pollen season Start date (PS) defined as the first day on which 1 pollen grain/m^3 was recorded and the 5 following days recorded 1 or more pollen grains/m^3 (García-Mozo et al., 2000), and the Pollen season Peak day (PP) defined as the day when the maximum concentration was recorded.

2.2 Climate data

Daily temperature and rainfall data (1986-2008) from the study sites were used to evaluate the impact of climate on phenology, these variables being considered the most relevant for this purpose (Peñuelas et al., 2002; Gordo & Sanz, 2005). The warming index, anomalies from average temperature, for both cities from the start of the 20th century (Figure 2) reveals a progressive rise in temperature, especially over recent years. During the study period (1986-2008), mean annual temperature increased by 4ºC in Córdoba and 3.2ºC in Granada.

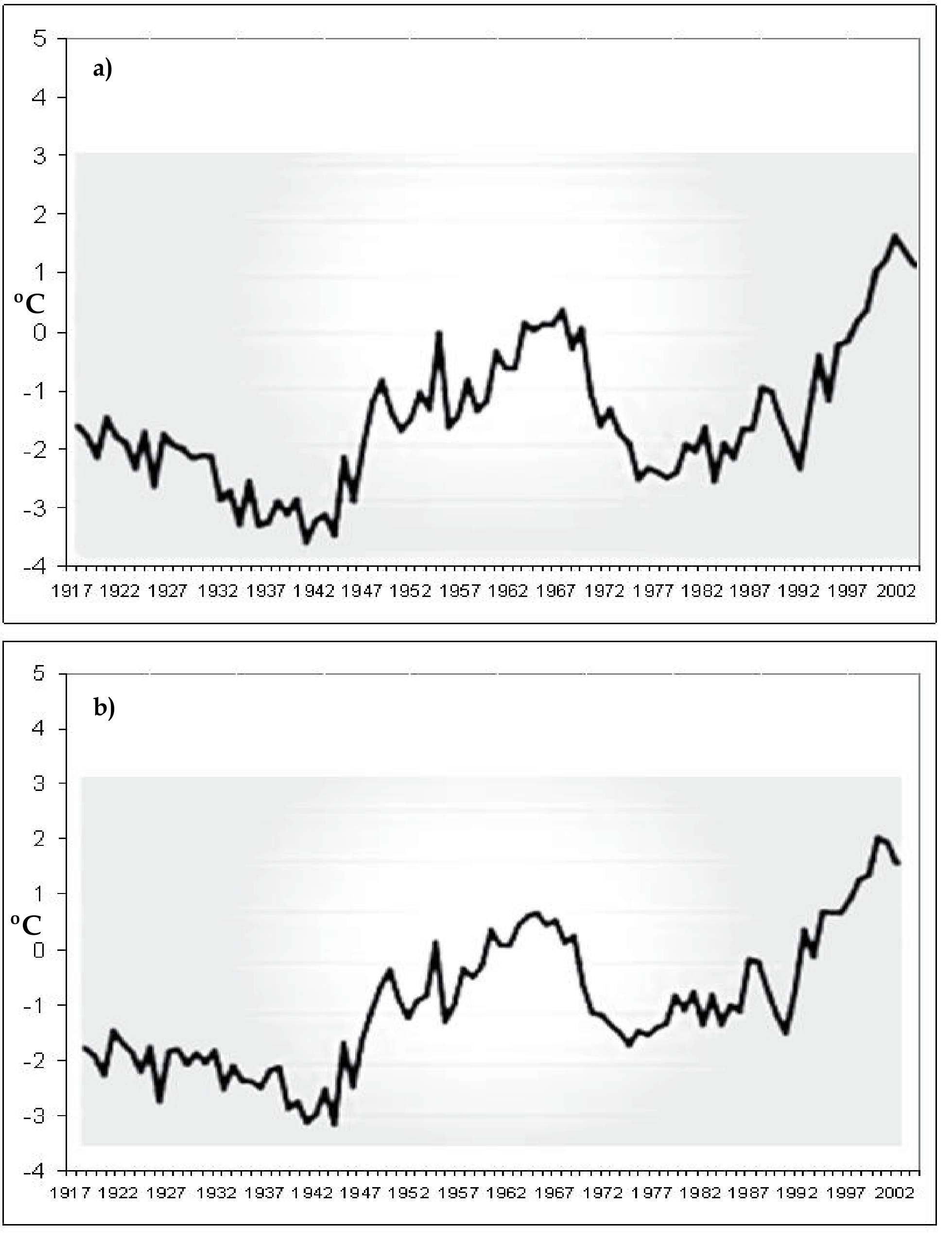

Fig. 2. Warming Index, anomalies from average temperature, in Cordoba (a) and Granada (b) from 1917 to 2005.

2.3 Statistical analysis

Phenological events and weather data were subjected to a Spearman correlation test. Linear regression analysis was performed to calculate trend lines where R^2 values were given and also p values in order to estimate the significance of these trend lines. The Excel Microsoft

2007 and STATISTICA 6.0 software packages were used. Results were considered significant at a 95% confidence interval.

3. Results

Phenological trends for the study species are shown in Table 2. Through the studied period, the flowering dates of holm oak varied up to 60 days, with a significant average advance of 1.6 days per year (27 days during the studied period). The PP in Córdoba city better matched field data at study sites in Córdoba province than the PS date. Although the PP trend line does not show a significant statistics due to the high variability in the data, both aerobiological dates are occurring increasingly earlier, with an overall advance of 7 and 12 days respectively over the period. In this species, fruit ripening advanced by 24 days at Pozoblanco and 36 at Huescar (significant trend gradient, $p<0.05$), leaf unfolding advanced by 25 days in *Quercus faginea* at Huescar (significant trend gradient).

In situ observations of olive flowering advanced at the three studied sites, being significant in the two last ones (Table 2): Pozoblanco (6 days), Bujalance (40 days) and Huescar (40 days). Airborne pollen data suggested a less marked advance, nevertheless the PP curve better matched field data at study sites in Córdoba province than the PS dates, except for the years 1998 to 2001 in Pozoblanco. In the case of Huescar (Granada) phenological data trend was more similar to PS dates. Also olive fruit ripening advanced significantly in the sites located in the province of Córdoba although no significant trend gradient was revealed in Huescar (Granada).

Over the period 1989-2000, *Vitis vinifera* leaf unfolding advanced an average of 10 days, and leaf life was extended up to 20 days in the case of Huescar; although an advance in the fruit ripening time was observed in Charcones (40 days) there was no significant change in the timing of fruit ripening in Huescar. Regarding herbaceous species, *Secale cereale* flowering advanced an average of 16 days between 1989 and 2006 at the Granada province sites. Field data suggested a great delay with regard to pollen dates, although the trend was similar and significant except for the Start date values. Fruit ripening in *Secale cereale* did not display any noteworthy trend between 1989 and 2008. Results for *Triticum vulgare* in Córdoba province revealed a general advance in flowering, significant in the case of field data of Pozoblanco whereas no significant trends were detected in fruit ripening. Finally phenological data for *Hordeum vulgare* indicated a flowering delay of 7 days in Pozobanco and 31 days in Bujalance. By contrast, flowering in Charcones (Granada) showed a slight advance and fruit ripening at all sites appeared largely unchanged over the study period. It is noticeable that the herbaceous species showed the less coincident trends of field phenological data and aerobiological data and the lower significance values for both types of data. In the case of *T. vulgare* and *H. vulgare* the aerobiological phase most coinciding with field phenological data was the PS curve.

Spearman analysis results showed in Table 3 indicated a negative correlation between various cumulative sums of average daily temperature and most of the flowering and fruiting events, especially in tree species. *Vitis vinifera* leaf fall displayed significant positive correlation with temperature (Tables 3b and 3c). Temperature over the preceding autumn correlated positively with most phenological phases in tree species. For some herbaceous species, there was also some correlation with temperature over the preceding months, as well as a weak but still-significant correlation with rainfall over previous months.

Site	Species	Phenophase	Gradient	R^2	*p*	N
Cordoba	*Quercus* spp.	Pollen season start	-0.77	0.21	0.05	17
		Pollen season peak	-0.41	0.04	0.41	17
	Olea europaea	Pollen season start	-0.31	0.03	0.49	20
		Pollen season peak	-0.34	0.04	0.38	20
	Poaceae	Pollen season start	-0.42	0.02	0.45	22
		Pollen season peak	-0.9	0.15	0.07	22
Pozoblanco	*Quercus ilex*	Flowering	-1.58	0.24	0.04	17
		Fruit ripening	-1.17	0.15	0.08	20
	Olea europaea	Flowering	-2.04	0.18	0.06	20
		Fruit ripening	-1.25	0.72	0.03	22
	Triticum vulgare	Flowering	-0.71	0.33	0.01	21
		Fruit ripening	-0.24	0.06	0.51	21
	Hordeum vulgare	Flowering	0.49	0.10	0.17	20
		Fruit ripening	0.07	0.00	0.74	21
Bujalance	*Olea europaea*	Flowering	-1.63	0.37	0.00	20
		Fruit ripening	-1.86	0.81	0.00	22
	Vitis vinifera	Leaf fall	0.16	0.00	0.74	15
	Triticum vulgare	Flowering	-0.12	0.00	0.74	21
		Fruit ripening	-0.13	0.05	0.32	21
	Hordeum vulgare	Flowering	1.59	0.55	0.00	21
		Fruit ripening	-0.14	0.00	0.20	21
Granada	Olea europaea	Pollen season start	0.43	0.19	0.07	19
		Pollen season peak	-0.08	0.00	0.57	19
	Poaceae	Pollen season start	-0.13	0.00	0.88	16
		Pollen season peak	-1.70	0.29	0.04	16
Huescar	*Quercus faginea*	Foliation	-2.30	0.46	0.01	11
		Fruit ripening	-1.79	0.84	0.00	20
	Olea europaea	Flowering	-1.99	0.66	0.00	19
		Fruit ripening	0.07	0.00	0.00	22
	Vitis vinifera	Foliation	-0.40	0.31	0.07	11
		Leaf fall	1.16	0.46	0.01	15
		Fruit ripening	-0.25	0.09	0.19	19
	Secale cereale	Flowering	-0.99	0.92	0.00	16
		Fruit ripening	-0.04	0.00	0.70	20
Charcones	*Vitis vinifera*	Foliation	-1.26	0.17	0.19	11
		Fruit ripening	-0.09	0.00	0.49	19
	Secale cereale	Flowering	-0.95	0.42	0.01	15
		Fruit ripening	-0.01	0.00	0.99	20
	Hordeum vulgare	Flowering	-0.29	0.06	0.32	20
		Fruit ripening	-0.18	0.00	0.87	20

Table 2. Trends for different phenological stages. Site, species, phenological stages, gradient, R2, significance (p value) and number of years (N) are represented.

	Phase	Tmx	T	Tmn	T_{j-a}	T_{j-jn}	T_{s-n}	T_{s-n}^{-1}	Rf	Rf_{j-a}	Rf_{j-jn}	Rf_{s-n}	Rf_{s-n}^{-1}
Quercus ilex	Fl	**-0.35**	0.22	0.03	0.18	0.07		**0.50**	0.29	-0.10	0.03		-0.12
	PS	-0.12	-0.20	-0.14	-0.08	-0.16		-0.15	0.17	-0.19	**-0.33**		**-0.46**
	PP	**-0.24**	**-0.38**	**-0.27**	**-0.23**	**-0.24**		**0.15**	0.03	0.01	0.00		**-0.47**
	FR	**-0.62**	**-0.41**	**-0.34**	**-0.26**	**-0.54**	-0.15	**0.34**	**-0.35**	**-0.46**	**-0.28**	**-0.42**	-0.13
Olea europaea	Fl	**-0.38**	**-0.22**	**-0.33**	**-0.20**	**-0.44**		**0.37**	-0.29	**-0.55**	**-0.49**		**-0.48**
	PS	**-0.53**	**-0.53**	**-0.54**	**-0.38**	**-0.51**		-0.14	0.19	**-0.24**	**-0.32**		**-0.62**
	PP	**-0.46**	-0.17	-0.09	0.10	**-0.35**		0.09	0.22	**0.32**	**0.33**		0.08
	FR	**-0.54**	**-0.47**	**-0.37**	**-0.31**	**-0.35**	-0.01	**0.17**	**-0.37**	**-0.56**	**-0.46**	-0.08	-0.21
Triticum vulgare	Fl	**-0.28**	**-0.21**	-0.02	0.02	**-0.15**		**0.47**	0.20	**-0.26**	-0.10		-0.25
	PS	0.18	0.14	-0.04	-0.15	-0.05		-0.14	**-0.26**	**-0.25**	**-0.33**		-0.02
	PP	**-0.19**	-0.08	-0.04	0.19	0.06		-0.08	0.17	-0.02	0.04		0.09
	FR	**-0.21**	0.28	0.04	-0.05	**-0.19**		-0.05	-0.05	-0.04	0.01		-0.02
Hordeum vulgare	Fl	0.29	-0.02	-0.11	0.29	-0.03		0.03	0.30	**0.23**	0.07		-0.18
	PS	0.18	0.14	-0.04	-0.15	-0.05		-0.14	**-0.26**	**-0.25**	**-0.33**		-0.02
	PP	**-0.19**	-0.08	-0.04	0.19	0.06		-0.08	0.17	-0.02	0.04		0.09
	FR	-0.02	0.35	0.16	0.16	-0.09		-0.05	0.06	-0.04	0.09		0.21

Table 3. a.

	Phase	Tmx	T	Tmn	T_{j-a}	T_{j-jn}	T_{s-n}	T_{s-n}^{-1}	Rf	Rf_{j-a}	Rf_{j-jn}	Rf_{s-n}	Rf_{s-n}^{-1}
Olea europaea	Fl	**-0.40**	**-0.45**	**-0.32**	**-0.23**	**-0.37**		0.26	0.17	0.04	0.04		0.24
	PS	-0.17	-0.16	-0.06	-0.08	-0.18		**-0.30**	0.02	0.22	0.11		0.01
	PP	-0.13	0.03	**0.32**	0.21	0.22		0.30	0.16	0.05	0.11		-0.02
	FR	**-0.57**	**-0.62**	**-0.38**	**-0.32**	**-0.38**	**-0.56**	**0.56**	0.24	0.09	0.06	0.13	0.11
Triticum vulgare	Fl	0.04	-0.11	**-0.35**	**-0.30**	**-0.30**		-0.18	**-0.27**	**-0.24**	-0.20		0.23
	PS	-0.21	**-0.27**	**-0.24**	0.06	**-0.23**		**-0.33**	-0.11	**-0.25**	**-0.30**		0.22
	PP	-0.13	-0.02	0.21	0.12	0.09		**0.37**	0.15	-0.20	-0.12		0.03
	FR	-0.17	-0.02	**-0.29**	-0.03	-0.09		0.21	**-0.33**	-0.11	-0.19		0.17
Hordeum vulgare	Fl	**-0.38**	**-0.33**	-0.07	-0.12	-0.22		-0.32	-0.11	0.11	-0.02		-0.04
	PS	-0.21	**-0.27**	**-0.24**	0.06	**-0.23**		**-0.33**	-0.11	**-0.25**	**-0.30**		0.22
	PP	-0.13	-0.02	0.21	0.12	0.09		**0.37**	0.15	-0.20	-0.12		0.03
	FR	-0.05	0.09	-0.29	-0.25	-0.19		**0.51**	-0.05	0.28	-0.08		0.07
Vitis vinifera	LF	**0.63**	**0.34**	**0.16**	0.09	0.04	**-0.22**	0.09	0.21	0.06	0.03	**0.30**	0.10

Table 3. b.

	Phase	Tmx	T	Tmn	$T_{j\text{-}a}$	$T_{j\text{-}jn}$	$T_{s\text{-}n}$	$T_{s\text{-}n}^{-1}$	Rf	$Rf_{j\text{-}a}$	$Rf_{j\text{-}jn}$	$Rf_{s\text{-}n}$	$Rf_{s\text{-}n}^{-1}$
Quercus faginea	FO	**-0.33**	**-0.40**	**-0.41**	**-0.75**			0.17	**-0.33**	-0.13			0.03
Quercus ilex	PS	-0.11	-0.08	-0.04	-0.10	**-0.33**		0.01	**0.33**	0.07	-0.05		**-0.61**
	PP	**-0.52**	**-0.42**	-0.25	0.02	-0.22		-0.07	**0.48**	**0.52**	**0.44**		0.29
	FR	**-0.70**	**-0.72**	**-0.64**	**-0.58**	**-0.69**	-0.60	-0.31	-0.16	-0.08	-0.12	-0.03	-0.28
	Fl	**-0.74**	**-0.71**	**-0.59**	**-0.73**	**-0.78**		-0.18	-0.25	-0.08	-0.01		-0.05
	PS	0.09	0.15	0.18	-0.01	**-0.39**		**0.33**	**0.47**	**0.28**	**0.36**		**-0.47**
Olea europaea	PP	-0.08	**-0.27**	**-0.47**	**-0.36**	**-0.27**		-0.36	**-0.34**	-0.18	-0.12		**-0.26**
	FR	-0.10	-0.04	0.06	0.12	-0.03	0.15	**0.66**	0.20	0.24	**0.33**	**-0.31**	0.12
	Fl	**-0.59**	**-0.57**	**-0.44**	-0.63	-0.67		**-0.46**	0.03	0.02	0.03	-0.02	-0.17
	PS	**-0.36**	**-0.44**	**-0.46**	**-0.26**	-0.19		**-0.39**	-0.34	-0.41	-0.43	0.08	0.21
Secale cereale	PP	-0.17	**-0.31**	**-0.44**	-0.36	-0.16		-0.27	-0.23	-0.28	-0.33	0.13	-0.25
	FR	**-0.52**	**-0.42**	-0.25	0.02	-0.22		-0.07	**0.48**	**0.52**	0.44	0.20	0.29
	LF	**0.27**	0.21	0.09	0.18	0.20	**0.25**	**-0.39**	-0.18	-0.42	-0.45	-0.18	0.17
Vitis vinifera	FR	**-0.32**	**-0.30**	-0.24	-0.14	**-0.39**	-0.16	0.23	0.00	0.11	0.12	-0.24	-0.25
	FO	**-0.63**	**-0.62**	**-0.48**	-0.53	**-0.57**		**0.36**	-0.07	0.05	0.22		-0.04

Table 3. c.

	Phase	Tmx	T	Tmn	$T_{j\text{-}a}$	$T_{j\text{-}jn}$	$T_{s\text{-}n}$	$T_{s\text{-}n}^{-1}$	Rf	$Rf_{j\text{-}a}$	$Rf_{j\text{-}jn}$	$Rf_{s\text{-}n}$	$Rf_{s\text{-}n}^{-1}$
	Fl	-0.01	-0.20	**-0.38**	**-0.50**	**-0.24**		0.17	0.31	0.12	**0.33**		**0.28**
	PS	0.21	-0.01	**-0.23**	0.05	0.03		0.21	0.10	**0.31**	0.11		0.09
Hordeum vulgare	PP	-0.03	-0.07	-0.08	-0.13	0.02		0.16	0.10	-0.13	0.31		**0.34**
	FR	**-0.37**	**-0.43**	**-0.39**	**-0.38**	**-0.39**		-0.30	**0.42**	**0.38**	0.22		**0.28**
	Fl	**-0.81**	**-0.80**	**-0.70**	-0.28	**-0.82**		-0.03	-0.04	**0.37**	0.14		0.26
	PS	0.21	-0.01	**-0.23**	0.05	0.03		0.21	0.10	**0.31**	0.11		0.09
Triticum vulgare	PP	-0.03	-0.07	-0.08	-0.13	0.02		0.16	0.10	-0.13	0.31		**0.34**
	FR	-0.11	-0.19	-0.23	0.12	-0.35		-0.08	**0.52**	**0.34**	**0.34**		0.06
	Fl	**-0.36**	**-0.45**	**-0.43**	-0.07	-0.16		0.17	0.14	-0.05	0.11		0.11
	PS	0.21	-0.01	**-0.23**	0.05	0.03		0.21	0.10	**0.31**	0.11		0.09
Secale cereale	PP	-0.03	-0.07	-0.08	-0.13	0.02		0.16	0.10	-0.13	0.31		**0.34**
	FR	**-0.36**	**-0.41**	**-0.36**	-0.25	**-0.39**		-0.24	**0.43**	**0.40**	0.19		0.19
Vitis vinifera	FR	**-0.29**	**-0.24**	-0.17	0.39	0.12	**-0.77**	**-0.53**	0.12	0.19	0.05	**0.33**	0.11
	FO	**-0.32**	**-0.09**	-0.17	-0.46	-0.32		-0.04	**0.60**	-0.19	0.27		-0.01

Table 3. d.

Phases: Fl, flowering; PP, Pollen Start; PP, Pollen Peak; FR, Fruit Ripening; FO, Foliation; LF, Leaf Fall. **Meteorological factors**: Tmx, Annual Maximum Temperature; T, Annual Mean Temperature; Tmn, Annual Minimum Temperature; Tj-a, Mean Temperature from January to April; Tj-jn, Mean Temperature from January to June; Ts-n, Mean Temperature from September to November; Ts-n-1, Mean Temperature from previous September to November; Rf, Annual Cumulated Rainfall; Rfj-a, Cumulated Rainfall from January to April; Rfj-jn, Cumulated Rainfall from January to June; Rfs-n, Cumulated Rainfall from September to November; Rfs-n-1, Cumulated Rainfall from previous September to November.

Table 3. Spearman correlation values for each species and phenophases in Pozoblanco (a), Bujalance (b), Huescar (c) and Charcones (d). p values < 0.05 are highlighted in bold.

4. Discussion

Although with some delay, probably due to the distance between field phenological stations and aerobiological stations, field phenological and aerobiological data showed similar patterns in the study species, especially in tree species. The higher differences in the herbaceous species patterns are probably influenced because cultivated grass species (as the observed in the present work) contribute in a lower percentage than wild species to the grass pollen curve (Muñoz et al., 2000; Subiza et al., 1992). In general the results indicated a general trend towards earlier onset of phenological phases, except for *Hordeum vulgare*. Shifts in leaf phenology were stronger than those previously reported for Europe by Menzel & Fabian (1999), who noted a 6-day advance in leaf unfolding and a 4.8-day delay in leaf fall over a 30-year period. The increase in growing-season length due to the earlier start recorded here also exceeds the 7 days reported for Europe between the 1960s and the 1990s, but largely coincides with the effect reported from the 1980s onwards (Keeling et al., 1996). The observed advance was also more marked than that found in North America by Bradley et al. (1999) and Abu-Asab et al. (2001). Also the observed trends are stronger that those reported in other Mediterranean areas such as California and Australia (Denisson & Roberts, 2003; Sadrasa & Monzon, 2006). The findings of the present study agree with those reported for other areas of southern Europe, in pointing to a bringing-forward of pollen-season start-dates and peak pollen counts in *Olea europaea* and *Quercus* species, and to a lesser extent in Poaceae (García-Mozo et al., 2008a; 2008b; 2009).

Although we must take into account the low significance in some of the results due to a high degree of variability in the analysed dates, the data recorded here suggest a more marked advance in southern than in north-eastern Spain, where Peñuelas et al. (2002) report during 1952-2000, an advance of 7.8 days for *Quercus ilex* flowering and 17 days for *Vitis* leaf unfolding, while flowering for *Olea europaea* and *Quercus faginea* displayed no significant trends. Data for a north region of Spain, show a lack of any apparent trend in the phenology of herbaceous crops, similarly to the results obtained in the present work.

The increase in mean annual temperatures over the study period appears to be the most marked since the mid-1970s, thus matching Mediterranean and global trends (Jones et al., 1999; IPCC, 2001). The detected increment of temperature in Spain (1.5ºC) during the last century has been greater than those calculated for the world global average (0.6±0.2ºC) or for Europe (0.5ºC). (IPCC, 2001; IPCC, 2007). Climate change has had a particularly marked effect on southern Spain, increasing temperatures up to 4ºC in last years (INM, 2002; De Castro, 2005; Ayala-Carcedo, 2004). Changes in rainfall patterns have been less pronounced, although a slight drop in annual rainfall was recorded for Andalusia over the last few years. Also during this period rainfall has also become increasingly torrential (Pita, 2003; De Castro et al., 2005).

Phenological changes displayed a strong correlation with temperature changes and especially with temperature over the months prior to the reproduction phase. The months preceding any given phenological event appeared to be the most important for the majority of the species. It was noteworthy that the previous autumn temperature influenced flowering in tree species, probably due to temperature in this period is related to vernalisation and to chilling requirements; the amount of chilling the plant receives in autumn is related to heat accumulation in spring. The correlations between flowering and fruit ripening and rainfall were mostly slight, although the correlation was more marked for grass species – which displayed fewer phenological changes over the study period – than for tree species. The shift towards more arid conditions, owing to increased temperatures and to the slight drop in rainfall recorded in Andalusia, may strengthen this correlation in the near future (Peñuelas et al., 2002).

At the same time, the potential effects of airborne CO_2 levels on phenological phases such as flowering and fruiting cannot be ruled out (Peñuelas et al., 1995). Global climate warming seems to be the main cause of phenological changes, but other factors - including less rainfall and CO_2 enrichment – may also affect them. Field phenological and aerobiological data are important bio-indicators of the ongoing ecosystem change, and can provide a general idea of how future climate change may be the major driver of changes in biodiversity.

5. Conclusions

Flowering patterns matched aerobiological data for the study species, and particularly for trees. Preliminary results suggested a general advance in flowering, foliation, and fruit ripening for most of the species examined in this study, especially significant for flowering dates. That general advance was more marked in trees than in herbaceous species, in which flowering dates – more closely determined by water availability – displayed little change. The advance of phenological phases in trees was more evident than in the rest of the studied species. Increased temperature was the main factor affecting the advance in foliation, flowering and fruit ripening and the delay in leaf fall dates. Potential effects of the change in phenology on the growth and yield of these species can lead to an increase of crop size. Herbaceous species were more affected than tree species by changes in rainfall patterns. In conclusion, field phenological data and aerobiological data are important bio-indicators of ongoing ecosystem changes, and can provide a general idea of how future climate change may be the major driver of changes in biodiversity.

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14

Climate Change Impacts on Czech Agriculture

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1. Introduction

Chapter summarizes the major impacts of changing climatic conditions in the Czech agriculture. Specific case studies are performed for the whole country (arable land) and are processed through GIS in the spatial grid 500 x 500 m respectively 1 x 1 km if middle Europe is considered. Contribution presents the impacts of climate change on the production of two major field crops (winter wheat and spring barley) in the Czech Republic for different future time horizons (2030, 2050 and 2100). The yield study includes not only the effect of climatic conditions but also the fertilization effect of carbon dioxide. Study is completed by effects of rising temperatures on the spread of temperature-depending biotic factors (selected pests) and changes in agroclimatic conditions for field crops. The basic data which are needed and used are long-term database of the national meteorological service and agricultural organizations which was used for evaluation of growth models (e.g. CERES). Other used tools are models which allow describe the evolution of pests in new climate conditions (e.g. CLIMEX or ECAMON) and various meteorological indieces. Description of expected weather conditions are based on two emission scenarios, according to the IPCC (mostly SRES-A2 and -B1) and three GCM models (NCAR-PCM, ECHAM5 and HadCM3). Their open access monthly outputs are published for the individual time horizons (e.g. 2030, 2050 and 2100) and are prepared in the daily time step by stochastic weather generator. The impacts of climate change are determined by comparing the current and expected state observed phenomena.

2. Climate change scenarios for the Czech Republic

In assessing impacts of the climate change on agriculture, various models (e.g. crop growth models) are used. These models need for their simulations multivariate weather series

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representing present and future climates. As the presently available climate models [either solely Global Climate Models (GCMs) or Regional Climate Models (RCMs) driven by selected GCM)] used to project the future climate do not satisfactorily reproduce the structure of the required surface weather series (in terms of probability distribution functions of individual variables, as well as in terms of correlations and lag-correlations among the variables), alternative approaches are employed to create the surface weather series with a real-world statistical structure: statistial downscaling (Benestad et al., 2008) and weather generators (Beersma & Buishand, 2003; Dubrovský et al, 2004; Wilks, 2009; Semenov et al., 1998) Both methodologies rely on statistical approaches. In case of the statistical downscaling (SDS), the surface weather series is modelled conditionally (using, e.g., regression-based relationships) on the larger-scale characteristics (e.g. circulation indices, weather types, and upper-air atmospheric characteristics). Once the SDS model is calibrated with the present climate data, the future-climate weather series is created by applying the SDS model to GCM-simulated future-climate predictors. In our experiments, we use the latter approach - the weather generators (WGs). Specifically, we use the stochastic daily weather generator M&Rfi (more advanced follower of the earlier Met&Roll generator [Dubrovský et al., 2004]), which models the multivariate surface daily weather series using the mixture of statistical models: in the first step, precipitation is simulated using Markov chain for precipitation occurrence and Gamma distribution for daily precipitation amount. In the second step, solar radiation (SRAD), and daily temperature extremes (TMAX and TMIN) are simulated using the first order autoregressive model. To generate weather series representing the future climate, the WG parameters are modified according to the GCM-based climate change scenario (Dubrovský et al., 2000; Žalud & Dubrovský, 2002), which consists of the changes in monthly climatic characteristics (means and variabilities of the surface weather characteristics) and is derived from latest available GCM simulations.

The development of the climate change scenario is affected by various uncertainties (Dubrovský et al., 2005). Of these, we account for uncertainties in climate sensitivity (CS), emission scenario (ES) and inter-GCM uncertainty. This is done by using the pattern scaling method (Santer et al., 1990), in which the changes in individual climatic characteristics (ΔX) are defined as a product of standardized changes ($\Delta_s X$) and change in global mean temperature (ΔT_G):

$$\Delta X = \Delta T_G \times \Delta_s X \quad (1)$$

The standardised scenarios are derived from the GCMs (we used GCMs from IPCC-AR4 database), the ΔT_G values are determined by the simple climate model MAGICC (Harvey et al., 1997; Hulme et al., 2000) assuming user-selected emission scenario and climate sensitivity. To account for the above uncertainties, we use 3 GCMs to represent uncertainty in the standardized scenario (~ inter-GCM uncertainty), and 3 values of ΔT_G to represent uncertainty in the scaling factor.

The choice of the triplet of the GCMs was based on assessing the fit between the observed and GCM simulated annual cycles (Dubrovský et al., 2005). Based on the results of these validation tests, we chose ECHAM5, HadCM3 and NCAR-PCM models (ECHAM, HadCM, NCAR in next text). The standardized climate change scenarios derived from the three selected GCMs are shown in Fig.1. To represent uncertainty in ΔT_G, we use the low, middle

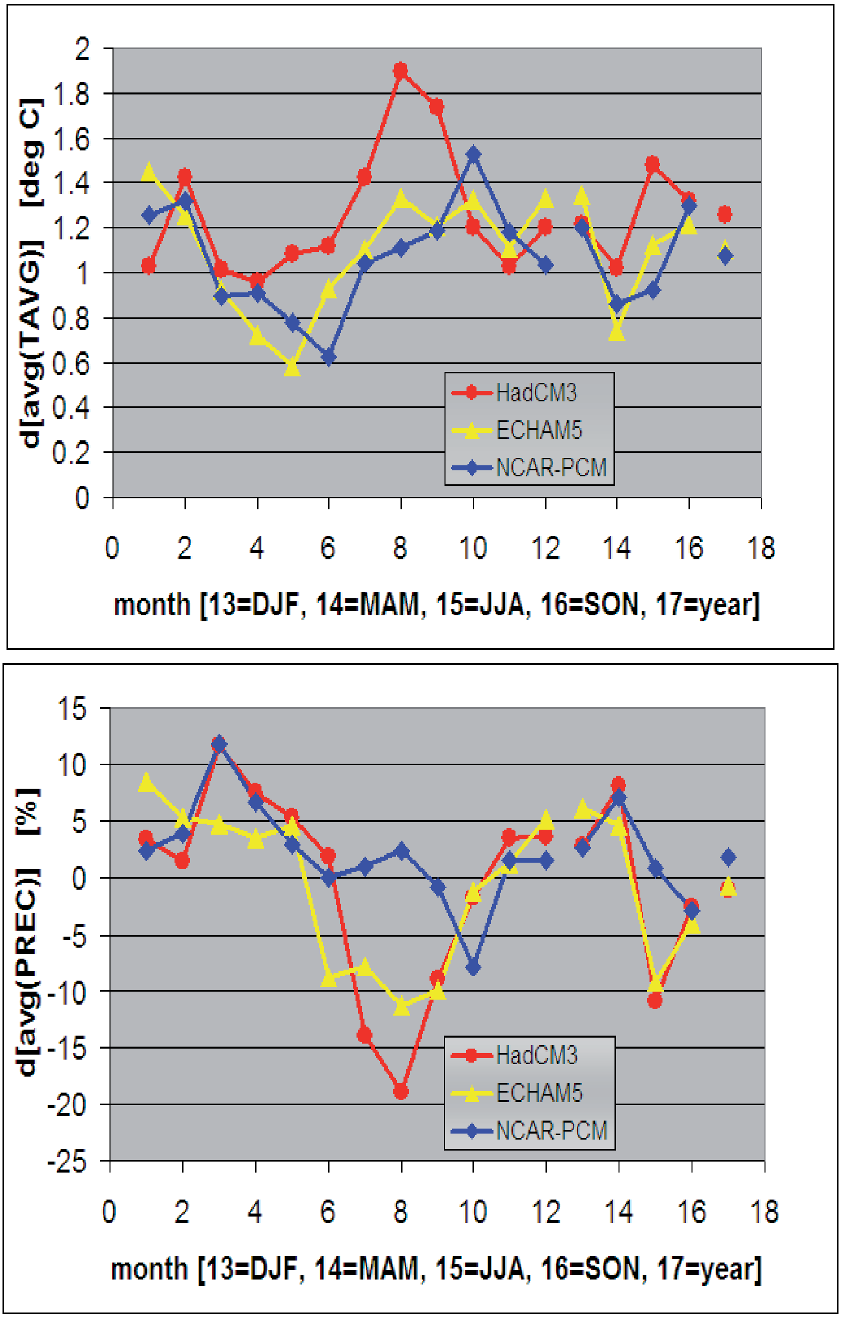


Fig. 1. Standardized scenarios of changes in monthly, seasonal (month = 13 to 16) and annual (month = 17) means of temperature (top) and precipitation (bottom)

and high values, which represent combined uncertainty in emission scenario and climate sensitivity (Fig.2): The low value is defined as a minimum of ΔT_G related to 4 emission scenarios (SRES-A1b, -B1, -A2, -B2) and low climate sensitivity (1.5 K), the high value is defined as a maximum of ΔT_G related to the 4 emission scenarios and high climate sensitivity (4.5 K), and the middle value relates to the average of two middle values related to the four emission scenarios and middle climate sensitivity (2.6 K).

In modifying the parameters of the WG, the above scaling equation (1) is applied differently to individual WG parameters: To modify annual cycle of mean temperature (both *TMAX* and *TMIN*) values, the standardized scenario values $\Delta_s T$ are identical with the temperature changes expressed in terms of Kelvin degrees, which implies additive modification of the annual temperature cycle:

$$<T_{\text{future}}> \; = \; <T_{\text{present}}> + \Delta T, \;\; \text{where } \Delta T = \Delta T_G \times \Delta_s T \tag{2}$$

In modifying the mean precipitation cycle, we assume the multiplicative modification:

$$<P_{\text{future}}> = <P_{\text{present}}> \times (1 + \Delta P/100) \tag{3}$$

where ΔP is a percentage change in precipitation. When the pattern scaling method (eq.1) is used to determine ΔP, the problem arises how to define the standardised change $\Delta_S P$ and how to apply the scaling procedure. In a most straightforward way and in accordance with eq.1, we may assume that ΔP is linearly proportional to ΔT_G:

$$\Delta P = \Delta T_G \times \Delta_S P \tag{4}$$

which may work for small values of ΔT_G. However, in case of the larger values of ΔT_G (for example, it takes value of about 5 for SRES-A2 and high climate sensitivity) and modest standardised decrease of precipitation $\Delta_S P$ (say -25%), the above equation would imply senseless $\Delta P < -100\%$. In result, we apply a different formula when applying the pattern scaling method for precipitation changes. Instead of the above assumed linearilty between ΔT_G and ΔP we assume $dP / P = k \times \Delta T_G$, where d$P$ indicates an infinitesimal change, which in turn implies a linear relationship between ln$P$ and ΔT_G and thereby an exponential dependence of P on ΔT_G:

$$\ln P_{\text{future}} = \ln P_{\text{present}} + k \times \Delta T_G \quad \rightarrow \quad P_{\text{future}} = P_{\text{present}} \times \exp(k \times \Delta T_G) \tag{5}$$

where k is, in fact, a standardised (related to 1K rise in global mean temperature) change in ln$P$ and may be determined by applying linear regression to [ln$P$, ΔT_G] data. In applying the pattern scaling equation, another problem arises: if the standardised change is positive (k > 0) and ΔT_G is close to the high end of or even beyond the calibration interval (values simulated by the given GCM) of ΔT_G, we deal with a problem of extrapolation. Also considering the not-so-high correlation between P and T_G, which implies relatively high errors in estimating the regression parameters, we must be very careful in this extrapolation. To address this problem, we use a linear (instead of the exponential) rise when k is positive and ΔT_G rise beyond 1:

$$\Delta P \; = \; [\exp(k \times \Delta T_G) - 1] \times 100 \, [\%]; \quad \text{for } \Delta T_G < 1 \tag{6}$$

$$\Delta P \; = [1 + k \times (\Delta T_G \; - 1)] \times [\exp(k) - 1] \times 100 \, [\%]; \quad \text{for } \Delta T_G > 1 \tag{7}$$

The relationships between ΔP and ΔTG for both positive and negative values of k are shown in Fig.3. If k is negative, the curves shown in Fig.3 are mirror-symmetric with curves for positive k along the x = 0 line and therefore the exponential dependence is used for ΔTG > −1 and the linear relationship for ΔTG < −1. The changes in the mean global solar radiation

(SRAD) and in variabilities of SRAD, TMAX and TMIN (if applied) are determined in the same way as the changes in the precipitation amount.

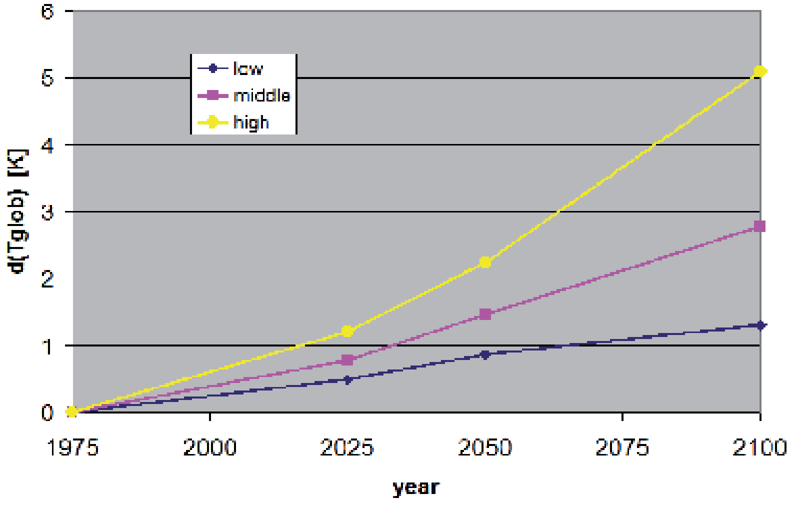


Fig. 2. Low, middle and high values of change (with respect to 1975, which is the center of the common reference period 1961-1990) in global mean temperature for 2025, 2050 and 2100 according to MAGICC (v.5.3) model. The low value relates to minimum of ΔT_G related to 4 emission scenarios (SRES-A1b, -B1, -A2, -B2) and low climate sensitivity (1.5 K), the high value relates to maximum of dTglob related to the 4 emission scenarios and high climate sensitivity (4.5 K), and the middle value relates to the average of two middle values related to the four emission scenarios and middle climate sensitivity (2.6 K).

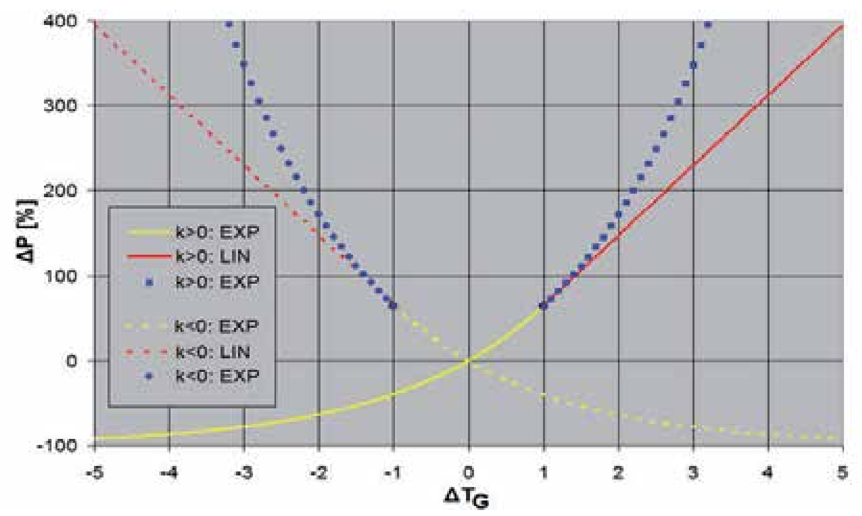


Fig. 3. The dependence of ΔX on ΔT_G according to the pattern scaling method. The solid lines represent the dependence for k>0, the dashed lines for k<0 The blue dots indicate the exponential dependence, which is rejected for dTG>1 AND k>0 and dTG<−1 AND k<0 to avoid the extrapolation problem.

3. Using growth models for climate change impact assessment on crop yield

Crop growth models are widely accepted tools for plant production assessing (under various conditions or management strategies) and have been used since the 1960s. They are designed as a set of algorithms on various bases for assessing agricultural potential, crop development and yield forecasting (Perdigão & Suppit 1999). They could be applied at local (field), regional or wider spatial level and used for analysis and optimization of agricultural practices, such as various sowing date, nitrogen fertilization (e.g., Rinaldi 2004) or within climate change impact assessment (e.g., Alexandrov & Hogenboom 2000; Trnka et al., 2004a; Wolf et al., 1996). The effect of expected future climatic conditions (namely changes of solar radiation, air temperature and precipitation) and higher concentration of carbon dioxide are analyzed by this way. Generally, the direct influence of higher carbon dioxide (as a crucial source of carbon) is connected with photosynthesis stimulation (Mitchel et al., 1999). Simultaneously, the higher concentration of CO_2 influences the stomata activity (causing its higher resistance) and the water use efficiency (WUE). The experiments with higher CO_2 concentration confirmed the biomass production increase within C_3 plants (Amthor, 2001). On the other hand, according to some of recent studies the influence of CO_2 in real conditions will be lower (Ainsworth & Long, 2005). Moreover, the conducted studies usually neglected the influence of CO_2 concentration within higher air temperature and some yields increase could be expected also due to agro-technological improvement and breeding (Berntsen et al., 2006). If only temperature increase is assumed (without adaptation measures such as breeding or sowing date shift), than the expected yields (e.g. winter wheat) will be lower as a consequence of shorter growing period (e.g. Batts et al., 1997).

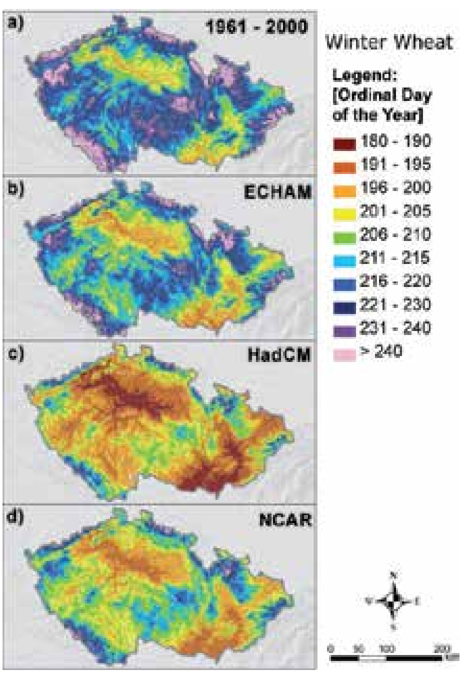
For the purpose of presented study the CERES-Wheat (Godwin et al., 1989) and CERES-Barley (Otter-Nacke et al., 1991) models were selected as they were successfully used within several studies through the central Europe (e.g. Hlavinka et al., 2010; Eitzinger et al., 2004) including the analysis of climate change impact on yields (Trnka et al., 2004a, b). They are process-oriented varieties of crop models and works within the framework of the DSSAT - Decision Support System for Agrotechnology Transfer (Hoogenboom et al., 1994). Phenological development and growth in the CERES models are directed by cultivar-specific genetic coefficients depending on the photoperiod, thermal time, temperature response and dry matter partitioning. CERES models calculate dry matter accumulation as a linear function based on intercepted photosynthetically active radiation. Potential dry matter accumulation depends on the amount of biomass already produced and the actual leaf area index. This is then corrected for actual daily biomass by applying factors for water and/or nitrogen stress and non-optimal temperature.

For the spatial analysis the Czech Republic was divided into grids 500 x 500 m with information about altitude, landuse, soil type and texture and hydrolimits. The present climatic conditions were represented by daily measured maximum and minimum temperatures, precipitation and global radiation from 125 stations during the period 1961-2000. If the pyranometer was missing than the sunshine duration in combination with Angström method was used for global radiation estimates.

For the future climatic conditions the measured weather data were replaced by the data derived from selected GCM models (ECHAM, HadCM, NCAR) in combination with SRES-A2 and SRES-B1 emission scenarios. Moreover SRES-A2 was connected with high climate sensitivity to increased CO_2 concentration and SRES-B1 with low climate sensitivity. Consequently, the daily weather data were prepared using stochastic weather generator Met&Roll (Dubrovský, 1997) and the spatial analysis was conducted using ArcGIS software.

3.1 Climate change and winter wheat (case study)

The basic task for the assessment of future climatic conditions within selected crops is the analysis of the expected changes of plant development (i.e. start and duration of selected phenological stages) and attainable yields (influenced by the water stress and nutrient concentration). For the purpose of presented study the cultivar Hana was selected as it was successfully calibrated and verified within seven various locations through the Czech Republic by Trnka et al. (2004b). Within submitted study the expected terms of sowing, anthesis and physiological maturity (for selected scenarios of future climatic conditions) were predicted. Generally, the later term of winter wheat sowing (as it is driven mainly by available soil moisture) could be expected due to increasing drought. The last two of mentioned phases were simulated by the CERES-Wheat model. Based on HadCM model the anthesis within South-Eastern part of country could be expected about 25 days earlier for the year 2050 (for ECHAM 7-8 days earlier). The similar situation is apparent also for physiological maturity (see Fig.4). The conditions according to HadCM will lead up to 23 days (for warmer regions) and 36 days earlier maturity (for colder regions). This is in accordance with results of Olessen et al. (2000), that 1°C air temperature increase during the grain filling phase reduced its duration by 5%. The total duration of growing period (from sowing to physiological maturity) could be up to 6 weeks shorter (according to SRES A-2 for 2050 as the most pessimistic scenario) within the numerous Czech Republic districts. Similar results were reported by number of other studies (e.g. Harrison et al., 2000; Tubiello et al., 2000).



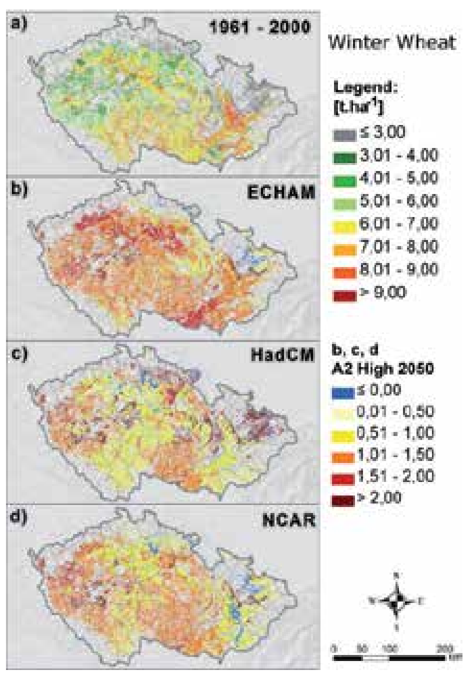


Fig. 4. (left) The term (described by the day of year/ Julian day – JD) of physiological maturity of winter wheat (a) for present climatic conditions and (b, c, d) for the year 2050 according to SRES-A2 and three selected GCM (as a median of 99 simulations).

Fig. 5. (right) The yields (t.ha^{-1}) of winter wheat simulated by the CERES-Wheat at arable land (a) for the present climatic conditions (1961-2000) and (b, c, d) expected differences for the period around 2050 according SRES-A2, high climatic sensitivity and three selected GCM.

For the combined effect of increased carbon dioxide (i.e. changed meteorological conditions and fertilization effect of CO_2) positive trend within winter wheat yields could be expected. From the conducted analyses is apparent that winter wheat will prosper from the new climate conditions and attainable yields could be about 14% higher within 2050 according to SRES-B1 and over 20% according SRES-A2 (Fig. 5). Also in the conditions of Slovakia (neighboring country) the increased yields of winter wheat and spring barley are expected according to CGCM and all SRES scenarios (Takáč & Šiška, 2008). On the other hand, the selected GCM and SRES scenario has a big influence on achieved results (Olesen et al., 2007). The extend of combined influence in the conditions of the Czech Republic is also dependent on the particular soil and climatic conditions.

The highest relative increase of yields could be expected in the regions with high quality of soils and sufficient precipitation. The increased yields could be achieved also with conditions Czech-Moravian Highlands, Northern Moravia and Bohemia where are presently suboptimal (lower) temperatures, higher precipitations and sufficient soil quality. Generally, the winter crops show lower susceptibility to the negative impacts of climate change against to the spring crops.

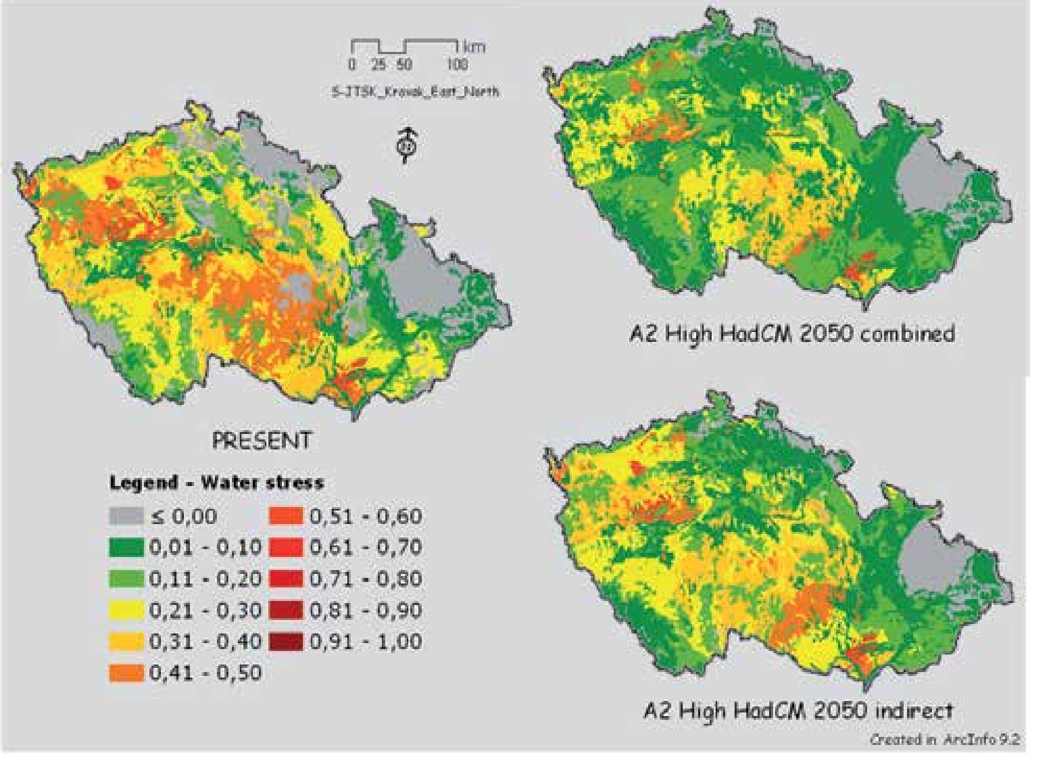


Fig. 6. Spatial distribution of water stress with 20 year return probability based on SWDF2 parameter (CERES-Wheat) for winter wheat under present and expected (HadCM, SRES-A2 and high climate sensitivity) conditions. The indirect effect of higher greenhouse gases concentration and combined effect were assessed. The higher number in legend indicates the higher value of water stress (1 equals 100% stress and 0 is without any water stress).

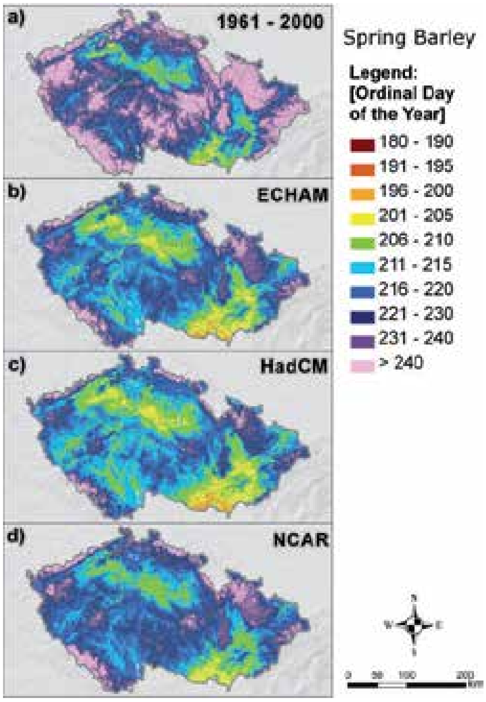
The CERES models also offer the methods for crop specific water stress quantification (during the various parts of vegetation) through the set of parameters. One of the CERES models advantages for drought impact assessment under future climate is the incorporation of direct effect of increased CO_2 concentration leading to higher WUE.
The results regarding 20 years return probability of drought was investigated by CERES-Wheat through the Czech Republic (HadCM model, SRES A2 scenario and high climate sensitivity). This analysis was based on SWDF2 parameter (describes water deficit effects on plant physiological processes) assessed from anthesis to maturity. The results indicate reduced water stress in most regions of the Czech Republic around 2050 both for combined effect (connected indirect impact of higher greenhouse gases concentration and direct fertilization effect of increased CO_2) and even for solely indirect effect (see Fig. 6). The lower water stress within combined effect could be explained by the higher WUE, shorter vegetation season and its partial shift from drought occurrence periods. The water stress reduction under isolated indirect effect could be explained only by the last two mentioned reasons.

3.2 Climate change and spring barley (case study)

For the climate change impact assessment within spring barley development and cultivation, the analogical approach as in the case of winter wheat was applied. The cultivar Akcent was used as it was validated within three localities through the Czech Republic with various soil and climatic conditions (Trnka et al., 2004a). The expected higher temperatures will lead to earlier sowing date and the shorter phenological phases (especially for the model HadCM). These changes partly enable to avoid the vegetation during the period with negative water balance (i.e. drought stress). The present and expected date of physiological maturity according to the SRES-A2 and three GCM for the period around 2050 is depicted within Fig. 7. This shortening of vegetation phases (without the assumption of CO_2 direct fertilization effect) is mostly negative for yields. On the other hand, when also fertilization effect was included, the positive trend within attainable yields could be expected for the period around 2050 (see Fig. 8). The highest yields under present conditions are achieved (as well as simulated) within lowlands. The spatial distribution of expected trends within yields is very similar through various regions and altitudes. According to ECHAM and NCAR the yield increase could be about 1000 $kg.ha^{-1}$ for majority of our country. The driest scenario (using HadCM model) will lead to the lowest yield increase together with the highest variability. It could be explained by the higher negative influence of extreme years. The aim of this study is not accurate prognosis of yields in future, but to assess possible impact of future conditions according to selected scenarios. For this purpose the attainable yields were estimated. It is clear that it will be influenced also by the breeding, technological improvement or economic situation and priorities. According to presented results the attainable yields of these two investigated crops will be higher. On the other hand the future climate conditions will lead to the various changes such as higher pest and diseases occurrence which together with higher probability of extreme weather events such as drought or rainstorms will lead to the attainable yields reduction in some years.

4. Pest development in climate change conditions

Productivity of crops grown for human consumption is at risk due to the incidence of pests, especially weeds, pathogens and animal pests: for instance, without crop protection almost



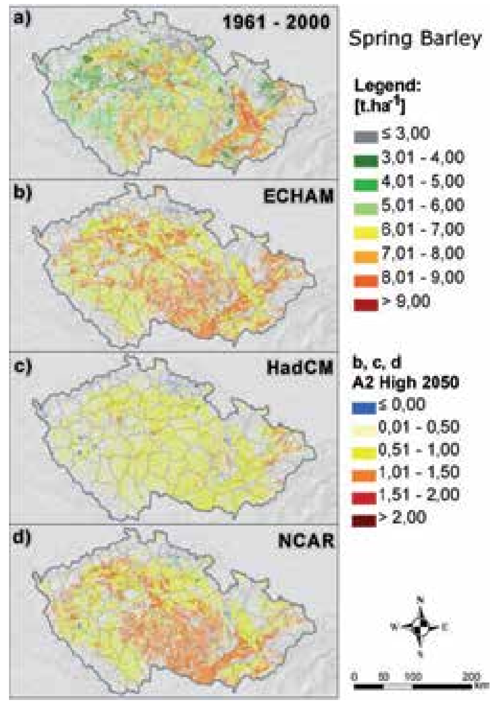


Fig. 7. (left) The term (described by the day of year/ Julian day – JD) of physiological maturity of spring barley (a) for present climatic conditions and (b, c, d) for the year 2050 according to SRES-A2 and three selected GCM (as a median of 99 simulations).

Fig. 8. (right) The yields ($t.ha^{-1}$) of spring barley simulated at arable land (a) for the present climatic conditions (1961-2000) and (b, c, d) expected differences for the period around 2050 according SRES-A2, High climatic sensitivity and three selected GCM.

75% of attainable potato production would be lost to pests (Oerke, 2006). Climatic conditions have a significant influence on the population dynamics, life-cycle duration, infestation pressure and overall occurrence of the majority of agricultural pests and diseases. This is particularly true for pest species whose development is directly linked with the climatic conditions and for whom a shift in their climatic niche or their infestation capability is expected during changing climate. In climate warming the number of insect species per unit area tends to decrease with increasing latitude, a similar trend is usually found with increasing altitude (Gaston & Williams, 1996). Climatic warming will allow the majority of temperate insect species to extend their ranges to higher latitudes and altitudes. Species which currently have wide latitudinal ranges, already encounter considerable temperature variation and are preadapted to cope with temperature change (Bale et al., 2002). Except the changes in geographical distribution of the species climate change may result in alterations in the overwintering, changes in population growth rates, increases in the number of generations per season, extension of the development season, changes in crop-pest synchrony, changes in interspecific interactions and increased risk of invasion by migrating pests (Porter et al., 1991). An increase in the number of generations per season means an increase in the number of reproductive events per year. If the mortality per generation does not change, then the population of thermophile insects will potentially become larger under global warming (Yamamura & Yokozawa, 2002). This could play an important role in the case of multivoltine species (Pollard & Yates, 1993). A higher survival rate during the overwintering period could result in an increase in the overwintering population and consequently a greater abundance of insects on crops in the summer. At the same time, the increasing temperature could probably support an earlier diapauses termination of overwintering species which will consequently appear earlier. This will influence the intensity of crop–insect interactions (Yamamura & Yokozawa, 2002).

Following case study estimates the impact of climate change on two pests: the Colorado potato beetle (*Leptinotarsa decemlineata* Say) and the European corn borer (*Ostrinia nubilalis* Hübner). According to Hare (1990), *L. decemlineata* is one of the most important insect pests of potato crops around the world; it is present and widespread in the countries covered in the present study (European and Mediterranean Plant Protection Organization (hereafter EPPO) 2007). The occurrence of *O. nubilalis* across some of the regions in the present study has also been recorded by the EPPO (2007). These two species are expected to gain new territory and lead to an increase in infestation pressure under climate change because their survival is closely related to climate conditions and, in particular, temperature.

4.1 Modelling as the estimation method of climate change impact on the pests' distribution

Modelling the life stages of insect species is most often done using accumulated degree-days, while socalled climate matching is a common modelling tool for estimating the impact of climate change on the extension of the range of a species. Climate matching identifies locations currently not invaded that could be colonized by a potential invasive species on the basis of similarity to climates found in the species' native range (Rodda et al., 2007). Several models that belong to the group of climate matching tools have been developed and applied in the past. For example, BIOCLIM (Nix, 1986) is a general model for the assessment of the favourability of a given climate for the occurrence of a species. HABITAT is a model for the analysis of the environmental conditions related to the distribution of plants and animals (Walker & Cocks, 1991). DOMAIN is a flexible tool for the modelling of the potential distribution of plants and animals (Carpenter et al., 1993). ANN and SPECIES are used for the estimation of the impact of climate change on plant species in the UK (Berry et al., 2002; Pearson et al., 2002, 2004). The assessment of climate favourability for univoltine and bivoltine population of the European corn borer is performed by ECAMON (Trnka et al., 2007). Régnière & Sharov (1998) used the stochastic generator BioSIM in the model of the geographical distribution of the gypsy moth to obtain the daily temperature data (Régnière et al., 1995).

Mechanisms by which climate conditions affect the development of a species can also be analysed with the CLIMEX software tool. CLIMEX is a world renowned software that has recently been applied in various scientific studies considering the potential distribution and spread of animal or plant species (Sutherst, 2000a, b; Bell & Willoughby, 2003; Kriticos et al., 2003; Lockett & Palmer, 2003; Pethybridge et al., 2003; Rafoss & Sæthre, 2003; Zalucki & Furlong, 2005; Olfert & Weiss, 2006, among many others).

4.2 Potential distribution of Colorado potato beetle and European corn borer (case study)

The climate-matching software program CLIMEX estimates the geographical distribution of a species based on the climate conditions of a given location. CLIMEX is based on the assumption that if you know where a species lives you can infer what climatic conditions it can tolerate (Sutherst et al., 2000a). The CLIMEX model is designed to extract maximum information out of minimal field data on the response of a species to climate. It derives weekly and annual indices that describe the responses of a nominated species to temperature and moisture, and, in the case of plants, light (Sutherst, 2003). Knowing the climatological requirements of a given species allows us to assess the suitability of a particular area for population growth and to determine the stress induced by unsuitable climate conditions. These are expressed in terms of the ecoclimatic index (EI), which describes the overall suitability of climate conditions for the establishment and long-term presence of a pest population at a given location:

$$EI = GI_A \times SI \times SX \quad (8)$$

where GI_A is the annual growth index describing population growth under favourable conditions, SI is the annual stress index describing survival during unfavourable periods, and SX represents stress interactions. The calculation of GI_A and stress indices is based on the ranges of threshold parameters for species development adjusted by the user (Table 1).
Temperature parameters include the lower and upper thresholds and optimal range of air temperature for development, and similar parameters are used for soil moisture. In the present study, soil moisture thresholds were set to values representing the optimal moisture conditions for the pest species' development. In the model validation procedure, we found that this approach was most appropriate because it prevented the incorrect estimation of high dry/wet stress, which would cause an undesirable decrease in EI. In addition to temperature and moisture limitations, CLIMEX also takes into account the process of diapause, which is driven by temperature (initiation and termination temperature) and day-length thresholds. The number of generations is calculated based on the number of degree-days above the lower temperature threshold per generation. Generally EI ranges from 0 to 100, where EI = 0 indicates climate conditions unfavourable for long-term species occurrence and EI > 30 represents very suitable climate conditions for species occurrence (Sutherst & Maywald, 1985; Sutherst et al., 2001). Hoddle (2004) considers locations with EI > 25 as very favourable for species occurrence, 10 < EI < 25 as favourable, and EI < 10 as limiting for species survival and occurrence. CLIMEX models use input data on a monthly scale (minimum and maximum temperature, relative humidity at 09:00 and 15:00 h, and precipitation), which are readily available.
Model validation was carried out by comparing the modelled range of a particular pest to the current area of occurrence obtained from field observations for the period from 1961 to 1990 (weather series prepared by a weather generator, Dubrovský et al., 2000, 2004). In the present study, the CLIMEX models were first validated using observed occurrence data for ECB and CPB in the Czech Republic. The validated model was applied within the domain of the regional climate model (RCM) ALADIN, which covers the Central European area between 45° and 51.5°N and 8° and 27°E and includes Austria, the Czech Republic, Hungary, Poland, and parts of Germany, Romania, Slovakia, Switzerland, and Ukraine,

Slovenia and northern parts of Serbia, parts of Croatia and northern Italy. The ALADIN model was run at a resolution of 10 km over the whole domain and the final maps were interpolated to 1 km resolution using a digital terrain model. The input weather series for the CLIMEX model was prepared by a weather generator (Dubrovský et al., 2000, 2004), which was calibrated with the RCM-simulated weather series (for the period of 1961–90). To generate weather series representing possible climate conditions in 2050, the WG parameters were modified according to climate change scenarios (Dubrovský et al., 2005) (more detailed description in Kocmánková et al., 2011).

Development thresholds	CPB	ECB
Lower temperature threshold (°C)	12	10
Optimum range of temperatures (°C)	15 – 28	18 – 28
Higher temperature threshold (°C)	33	38
Diapause induction temperature (°C)	13	12
Diapause induction daylength (h)	10	10
Diapause termination temperature (°C)	13.5	14.5
Degree-days per generation	400	726

Table 1. Parameters of the CLIMEX model for the development of Colorado potato beetle (CPB) and European corn borer (ECB)

4.2.1 Colorado potato beetle's (*L. decemlineata*) geographical distribution

The current climate conditions in the European region allow for the occurrence of one to four pest generations. Four generations currently occur in a small area in the north of Italy (Fig. 9), while only one generation is found in the northern and eastern part of the region, mainly in Poland and Ukraine. Populations in the lowlands of Germany, the Czech Republic and Slovakia can produce a partial second generation. The main areas with the climate conditions suitable for the development of three generations include Hungary, northern parts of Serbia, Croatia, Italy and the eastern part of Romania.

In altitudes higher than 600 m a.s.l, the number of degree-days for the completion of one generation of the pest is not reached, which makes these areas unfavourable for the development and survival of a viable pest population.

The results of the simulations for the expected climate scenarios show an apparent widening of the pests' climatic niche and an increase in the number of generations per year based on the temperature increase predicted by various scenarios. Fig. 10 shows the change in the number of *L. decemlineata* generations according to the HadCM-high scenario in 2050. In this scenario, there is an increase of about one generation per year in the northern part of Europe up to an altitude of 800 m a.s.l. In addition, there is a marked increase of about two generations per year in the lowlands, with a significant occurrence of three generations per year. In contrast, a marked decrease in the climate conditions favourable for *L. decemlineata* development under ECHAM-high is simulated in northern Serbia (Vojvodina region), where the significant temperature increase, according to this scenario, causes the high-temperature limitation for the pest's development and subsequent decrease of about one generation per year. A similar trend in the increase of the high temperature limitation is also seen in the NCAR-PCM-high and HadCM-high scenarios, which show all of Hungary, Croatia and the north of Italy having a decrease in the number of generations per year. Detail figures depicting results of ECHAM-high and NCAR-PCM-high scenarios see in Kocmánková et al., 2011).

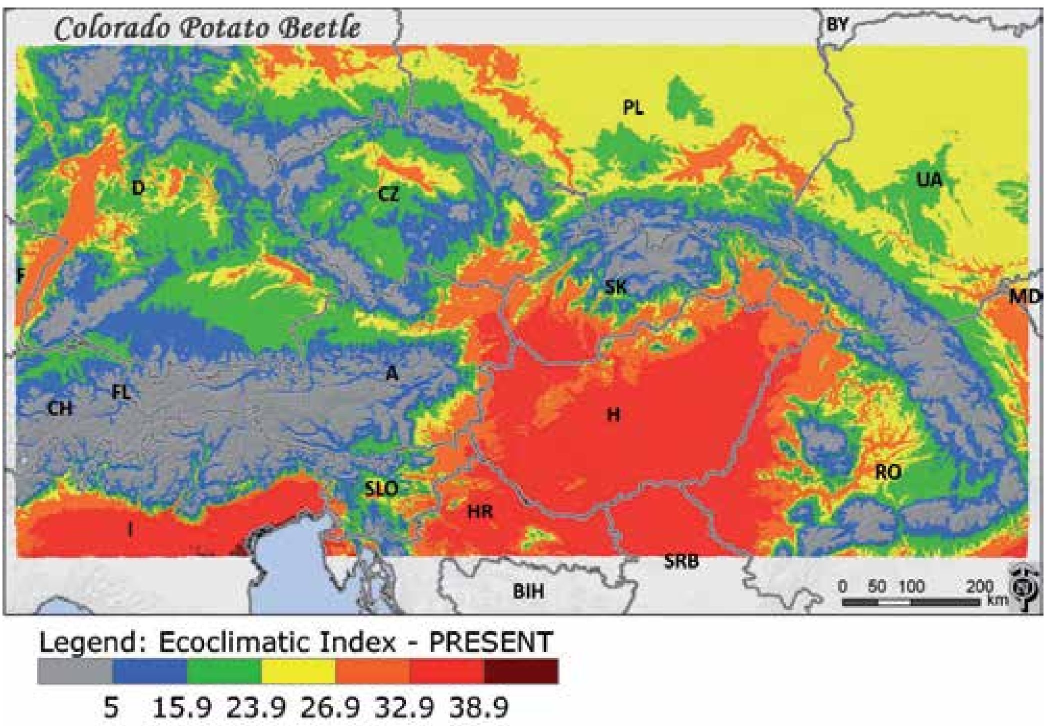


Fig. 9. Potential geographical distribution of the Colorado potato beetle (*L. decemlineata*) in current climate conditions expressed by meteorological data between 1961 and 2000. The yellow grey colour (EI 23.9–26.9) represents the area occupied by first generation of the pest, orange (EI 26.9–32.9) is the second generation, red (EI 32.9–38.9) third generation and dark red (EI>38.9) indicates the fourth generation. Abbreviations: D, Germany, CZ, Czech Republic, PL, Poland, UA, Ukraine, SK, Slovakia, Moldova, BY, Belarus, R, Romania, H, Hungary, A, Austria, CH, Switzerland, F, France, I, Italy, SLO, Slovenia, HR, Croatia, BIH, Bosnia and Herzegovina, SRB, Serbia.

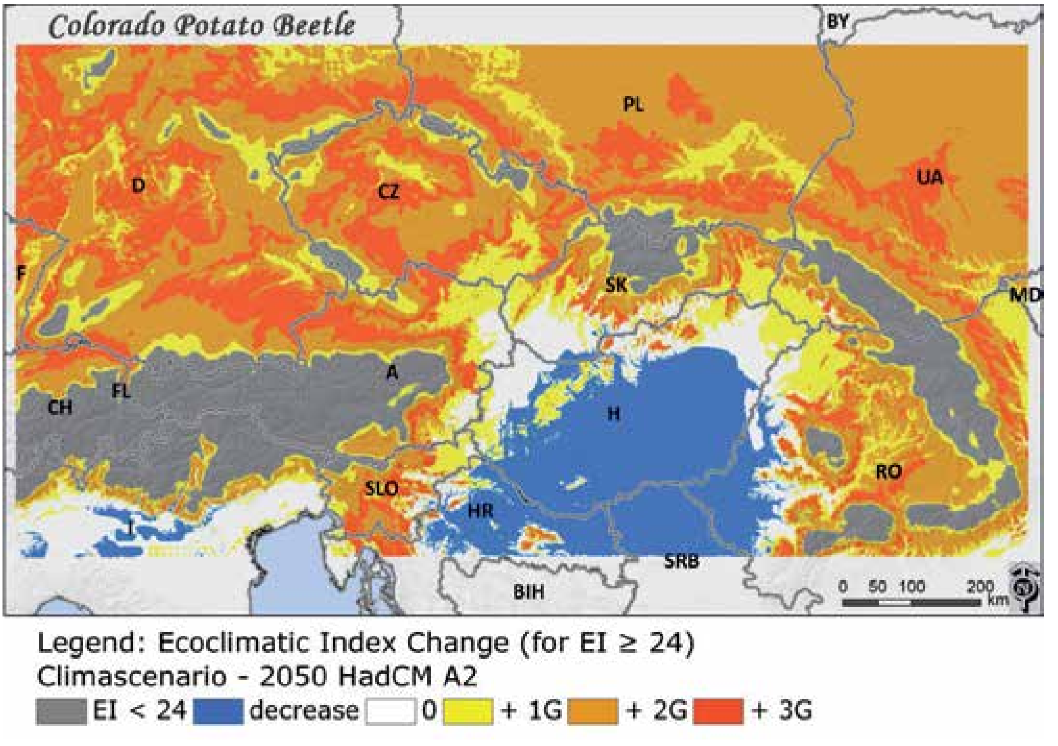


Fig. 10. Potential geographical distribution of the Colorado potato beetle (*L. decemlineata*) in the expected climate conditions expressed by meteorological data according to the HadCM-high scenario in 2050. Grey areas represent the area without an occurrence of the pest due to the incomplete first generation, blue areas show a recorded decrease in EI, i.e., the shift to less favourable climate conditions for the pest development, white colour marks the areas without any change and the colour scale (yellow to orange) points the increase in the number of particular generations. Abbreviations as in Fig. 9.

4.2.2 European corn borer's (*O. nubilalis*) geographical distribution

In the European region examined in the present study, the model indicates the presence of one or two generations per year of *O. nubilalis* under the reference climate conditions (1960–90). A higher number of generations are found in the southern part of the domain, in areas more climatically favourable for the development of *O. nubilalis* (Hungary, the northern part of Croatia, Serbia and Italy and the eastern part of Romania) (Fig. 11). Under future climate conditions, with their expected temperature increase and prolonged vegetative season, the widening of the area of univoltine population is simulated. Areas occupied by the univoltine population are likely to be replaced by a bivoltine population, which only slightly exceeds the original areal of univoltine one. At the same time, the emergence of bivoltine populations and a further increase to a third generation per year in the warmest areas is indicated. Fig. 12 depicts the expected change in the number of generations according to the HadCM-high scenario in the 2050s. It clearly shows that the pest would, for example, colonize areas recently unoccupied by the univoltine population, up presently. HadCM-high presumes a prevailing increase of about one generation, which will probably result in the presence of a third generation in the eastern part of Austria, the north of Italy and the western part of Germany (Rhine valley), where there are currently two generations per season. The NCAR-high climate sensitivity scenario (see in Kocmánková et al., 2011) assumes a wider spread, covering a major part of Hungary, Croatia and the whole simulated part of Italy.

Under the expected future climate conditions in Central and Eastern Europe, as expressed by selected climate change scenarios, crop damage by both the Colorado potato beetle (*L. decemlineata*) and European corn borer (*O. nubilalis*) is likely to increase. The increase in temperature will relocate the pests' development limitations and enable the pests to colonize higher altitudes, thus widening the area over which they occur. In the case of *L. decemlineata*, there will probably be a decrease in the number of generations per year in the warmest areas, due to the limitations of high temperature, which negatively influence the pest population.

The method presented here plays an important role in estimating species' occurrence depending on their climate requirements, but the method is limited by its lack of field- or population-level interactions. Climatic mapping may therefore be a very useful tool in pest risk analyses under changing climate because it allows us to estimate the risk of introduction, colonisation, and spread of various pest species and their economic impacts. However, the present case study also demonstrates, using two pest species as examples, that any long-term pest risk analysis must take climate change into account because of the possible changes in climatic niches.

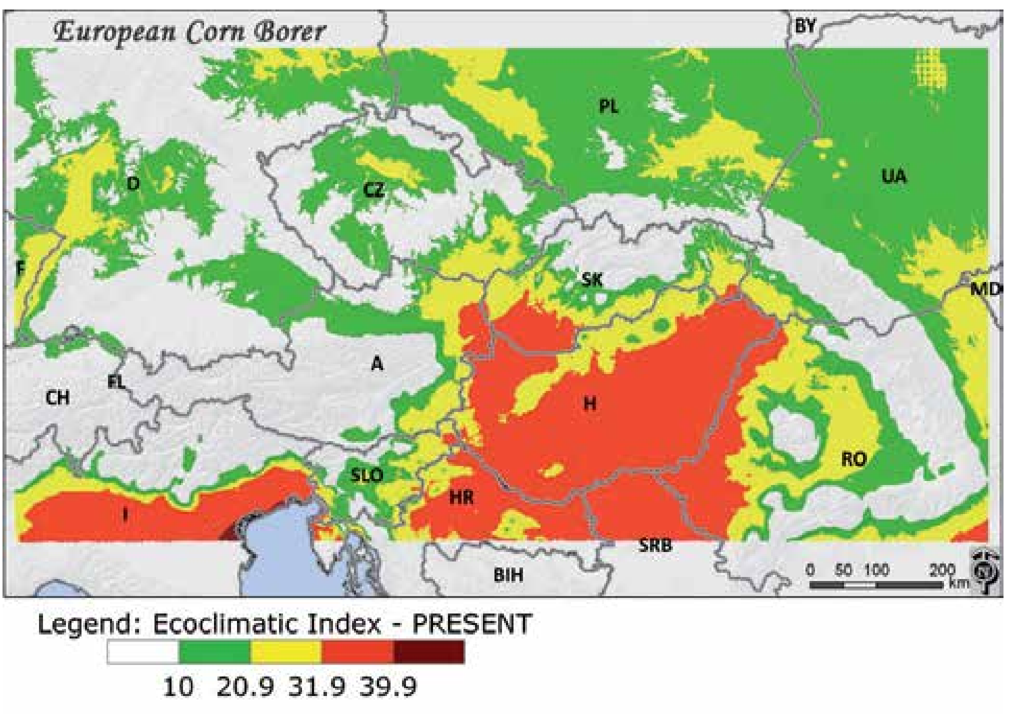


Fig. 11. Potential geographical distribution of the European corn borer (*O. nubilalis*) in current climate conditions expressed by meteorological data of the period 1961–2000. Yellow (EI 20.9–31.9) corresponds to first generation, red (EI 31.9–39.9) the second generation and dark red (EI>39.9) represents third generation of the pest. Abbreviations as in Fig. 9.

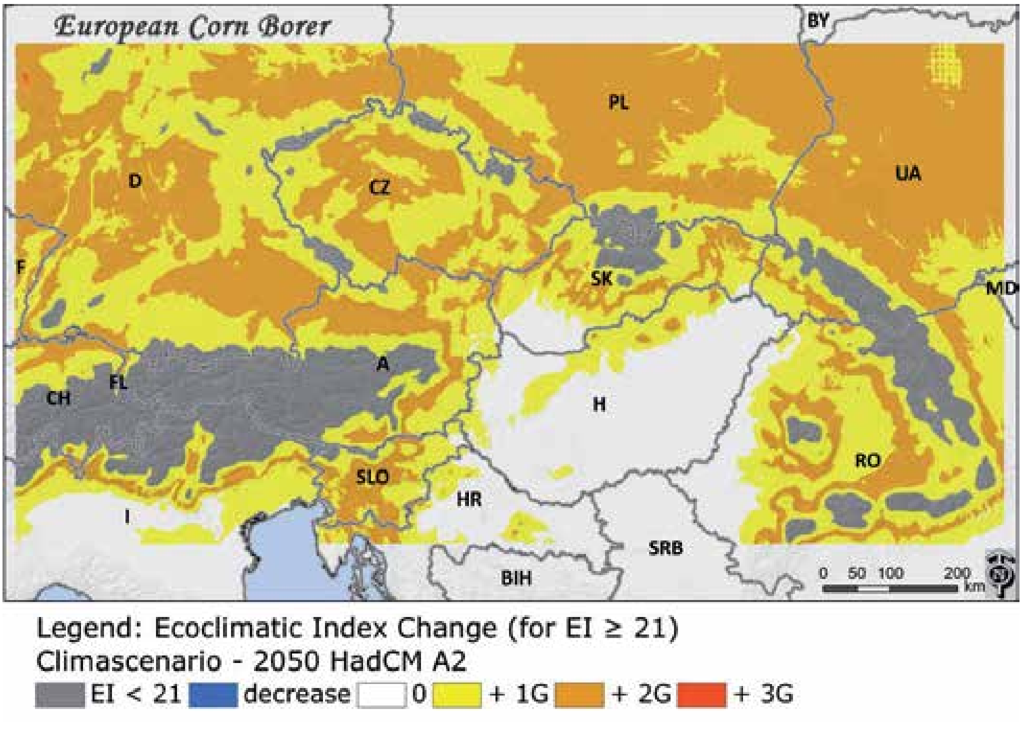


Fig. 12. Potential geographical distribution of the European corn borer (*O. nubilalis*) in the climate conditions according to the HadCM-high scenario in 2050. Grey areas indicate a lack of occurrence of the pest due to an incomplete first generation, blue areas represent a decrease of EI, i.e., the shift to less favourable climate conditions for the pest's development, white colour marks the areas without any change and the colour scale points the increase in the number of particular generations. Abbreviations as in Fig. 9.

5. Estimation of effects of climate change on agroclimatic conditions

Agroclimatic indices attempt to describe complex relations existing between climate and crops (their development and/or production) as well as the agrosystems as a whole (Orlandini et al., 2008). In order to describe agroclimatic conditions, a total of nine agroclimatic indicators were selected. The goal was to use a set of key indices that would be relevant for various aspects of crop production and complement other tools (e.g. process-based crop models).

The selected indicators include: **(a)** sum of effective global radiation, **(b-c)** water balance during the climatological spring (March-May) and summer (June-August), **(d)** thermal conditions as a proxy determing suitable areas for producing particular wine varieties based on the Huglin index and **(e)** conditions during winter in particular number of days with snow cover and **(f)** number of days with potential for severe frost damage.

All agrometeorological parameters described above were calculated with a software package, *AgriClim* (Trnka et al., 2011). The software uses daily inputs of global radiation, maximum and minimum temperatures, precipitation, air water vapor pressure and mean daily wind speed to calculate a whole range of indices as presented. When calculating actual soil water content, we assumed homogenous soil conditions and a soil water-holding capacity of 20 mm in the top 0.1 m to estimate the number of days suitable for sowing and harvest operations. The soil profile necessary for calculating effective global radiation and proportion of sowing/harvest suitable days assumed maximum rooting depth of 1.3 m and soil water holding capacity of 270 mm.

To allow grid-to-grid comparability, the same soil profile was used at all sites. While calculating evapotranspiration, an adjustment for the increased CO_2 concentration was always made using the method proposed by Kruijt *et al.* (2008), and the CO_2 ambient air concentration for the time horizon of the study (i.e. 2050) was set at 536 ppm with the "baseline" calculations set at 360 ppm. As the reference surface is defined as spring C_3 crop, accounting for the CO_2 effect resulted in a considerable decrease in reference evapontranspiration rates compared to runs not considering increase in the CO_2 levels. The whole set of agroclimatic indicators were calculated for all 99 years in each grid for the horizon of 2050. In most cases, the median value of the parameter was analyzed as well as the 5th and 95th percentile in order to determine 20-year extremes of the given agroclimatic index. The values in the 10 x 10 km grids were re-gridded at 1x1 km resolution using co-kriging techniques with altitude used as an additional parameter.

Effective global radiation for crop growth

The sum of the effective global radiation was calculated as the sum of global radiation during the period with mean air temperature continuously above 5°C (and without snow cover or frost occurrence) and with sufficient soil water available for evapotranspiration

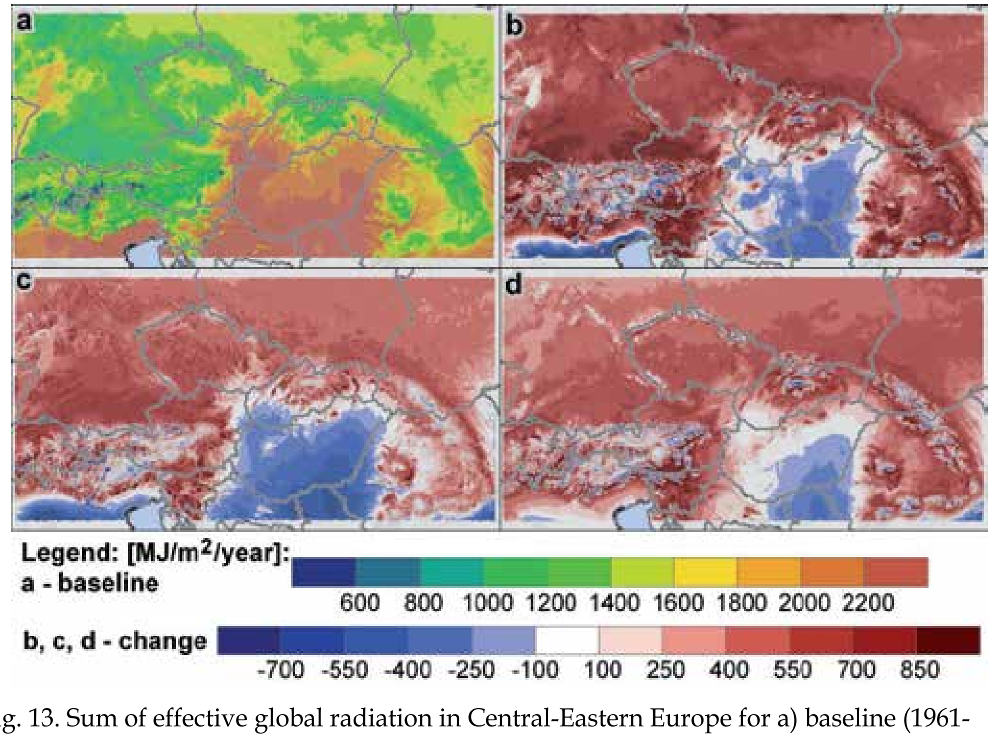


Fig. 13. Sum of effective global radiation in Central-Eastern Europe for a) baseline (1961-1990) and for increase of global mean temperature by 2.3°C with three standardized scenarios based on HadCM, ECHAM and NCAR global climate models (b-d).

(ratio between the actual and potential evapotranspiration had to be above 0.4). The temperature thresholds used followed suggestions by Brown (1976), Chmielewsky and Köhn (2000), Mitchell & Hulme (2002), and Larcher (2003). The direct effect of drought stress on crop growth is often expressed as the ratio between actual and potential transpiration (van Ittersum et al., 2003). However, in situations where evaporation from soil is not a large component, the use of evapotranspiration values will provide reasonable results. According to a number of studies (e.g. Eliasson et al., 2007), growth of the crop on a given day is not considered water limited if the ratio of daily actual and potential evapotranspiration exceeds 0.5. For this study we deliberately chose a lower threshold (0.4), to limit over-reporting drought by the used indices.

According to the applied climate scenarios the annual sum of effective global radiation will increase through increases in the duration of the potential growing period (i.e. with mean air temperatures continuously above 5°C). Additionally, the effective annual global radiation would be affected in some cases by the increase in global radiation as a result of decreased cloudiness associated with precipitation decreases, especially during the summer months. Although these changes may increase crop production potential the decrease in precipitation also increases the probability of water deficit, leading to a lower overall value of this key parameter. As shown in Fig. 13a under present conditions the southern and south-eastern parts of the domain have the highest values of effective global radiation, indicating the potential productivity of rainfed agriculture. It is the western and northern parts of the domain that would benefit most from the changed climate conditions, with areas in Germany, Poland, parts of Austria, Slovakia and Czech Republic showing sustained increase in the values of this parameter (Fig. 13b-d). The largest decreases are to be expected within the Pannonia lowland, which includes almost all of Hungary, northern Serbia and Croatia as well as parts of southern Slovakia, eastern Austria and western parts of Romania. The most marked changes (both positive and negative in regard to growing conditions) within the regions are to be expected under HadCM-driven scenarios, while the NCAR-based results indicate a much lower rate of change. The overall spatial pattern of these changes remains the same regardless of the scenario used.

Drought intensity

As an indicator the availability of water was assessed with the help of climatological water balance (i.e. difference between reference evapotranspiration ETr and the precipitation) during the spring i.e. period from March to May (MAM) as well as during the summer (JJA) when this deficit is usually the highest.

The spatial patterns of 20-year drought intensity during spring (MAM) and summer (JJA) months are similar (Fig. 14a-b) with the highest water deficit being found in Pannonian region and lowest in the Alps and mountain regions in general. The climate change (presented here by HadCM based scenario) shows an increase in the present spatial gradients during spring (i.e. dry areas become drier and wet wetter), while in summer months significant changes are to be expected over the whole region (Fig. 14c-d). The magnitude of the changes has a south-east gradient, where the arable land in the Czech Republic would be affected least, and Hungary and Slovenia show the most marked changes. On the other hand, in the NCAR scenario a slight easing of the 20-year drought intensity in the Czech Republic, Austria, Slovakia and Slovenia is shown, leaving only the arable lands in Hungary worse off.

Wine growing conditions

The Huglin index (HI) enables different viticultural regions to be classified in terms of the sum of temperatures required for vine development and grape ripening (Huglin, 1978). The HI value was calculated for the period from April 1 until September 30 using the following formula:

$$HI = \sum_{i=0}^{n}((T_{max} - 10) + (T_{mean} - 10) * K))/2 \quad (9)$$

where Tmax corresponds to maximum daily temperature, Tmean to mean daily temperature and K represents the coefficient for latitude that changes linearly from 1.02 at 40°N to 1.06 at 50°N. Different grape varieties are thus classified according to the minimal thermal requirement for grape ripening. The minimal Huglin index for vine development is defined between 1500 - 1600. As the HI considers only thermal conditions during the growing season, the results must be interpreted with caution especially in the eastern part of the domain where continental climate is predominant as wine growing is prevented by frequent occurrence of winter temperatures below -20°C. The attribution of the particular variety to thermal conditions estimated with the use of Huglin index was based on Schultz et al. (2005) and should be treated as an approximation.

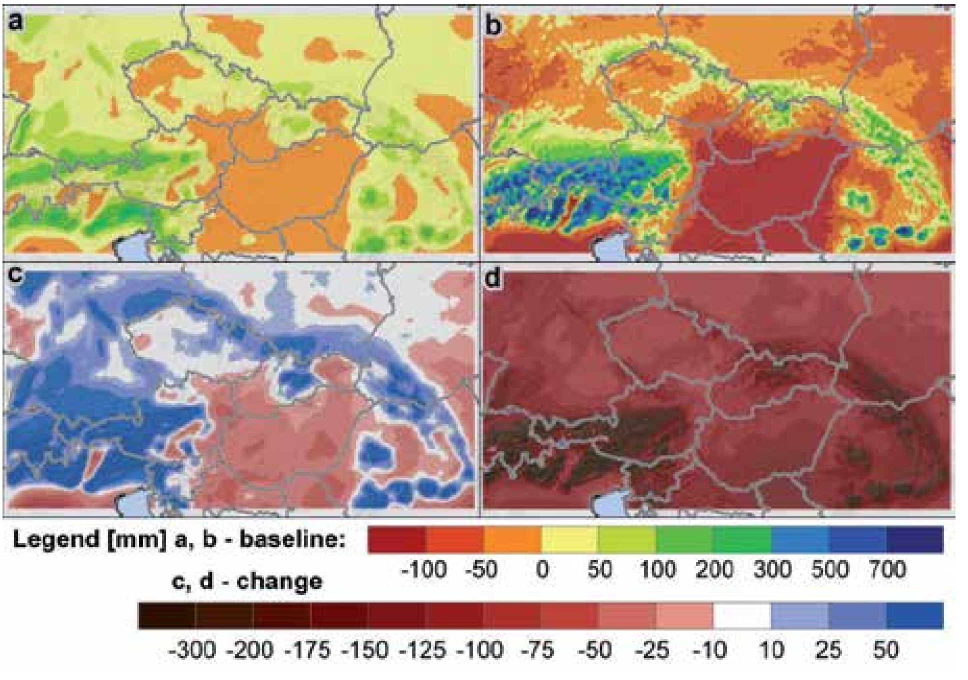


Fig. 14. Water deficit with 20-year return period for spring i.e. March-May (a,c) and summer i.e. June-August (b,d) in Central-Eastern Europe for baseline i.e. period between 1961 and 1990 (a,b) and for increase of global mean temperature by 2.3°C with HadCM standardized scenario.

The Huglin index indicates growing degree day changes for wine. Significant increase in the Huglin index value across the whole domain (Fig.15) is a direct consequence of the expected temperature increase according to climate projections used. Fig. 15 shows that the present mean value of Huglin index would not allow a permanent successful production of grapes across most of the domain except in areas established as wine growing regions already and those very good thermal conditions for wine growing are to be found especially in the southeastern part of the domain. Under the changed climate, the potential wine growing area would increase substantially, providing Huglin index values sufficient for wine production across much of the region with the exception of mountainous areas (however, other limitations such as soil conditions and small scale local climatic variations based on terrain effects such as the slope effects on temperature or cold air lake conditions are not considered in this study). It must be stressed that the Huglin index takes into account only temperature requirements during the summer period, which is not by any means a sole factor affecting wine production. The results clearly show that the present wine growing regions in Central Europe will be faced overall with much warmer conditions, requiring in some cases different cultivars than those grown nowadays. They also indicate that there is a prospect of wine growing even in the northern latitudes where wine production is off limits due to the present climate.

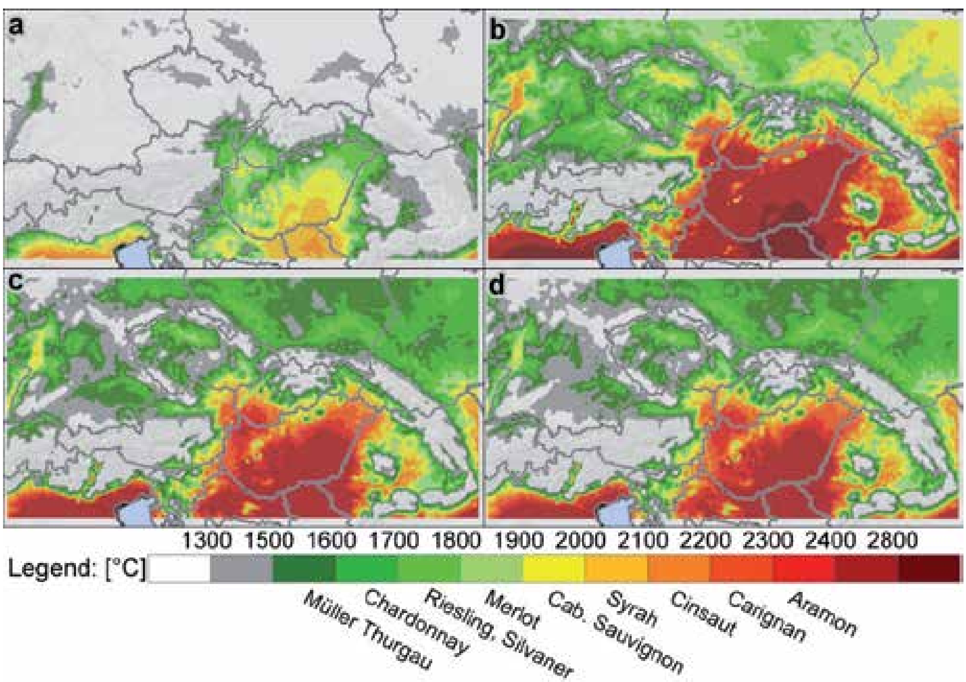


Fig. 15. Value of HUGLIN index serving as a proxy for wine cultivar suitability in Central-Eastern Europe for a) baseline (1961-1990) and for increase of global mean temperature by 2.3°C with three standardized scenarios based on HadCM, ECHAM and NCAR global climate models (b-d).

Agroclimatic conditions during winter

The number of days with snow cover was estimated with the help of SnowMAUS model (Trnka et al., 2010) that estimates snow cover absence/presence using daily temperature and precipitation total.

The days between September-April during which minimum daily temperature (at 2 m height) decreased below -10 °C and there was no snow cover were evaluated as period with likely frost damage to field crops using also approach described in more detail by Trnka et al. (2010).

The effect of changed climate on the number of days with the snow cover (Fig. 16a,c) indicates that by 2050 more than 80% of the domain will have on average snow cover on less than 50 days while at one third of the domain it is going to be less than 25 days. The related risk of severe frost damage to field crops by low temperatures (less than -10°C) is likely to decrease (Fig. 16b,d) as well across most of the domain despite the reduction of snow cover that acts as quite reliable protection in these events. On the other hand the occurrence of late frost (especially radiation type frost) is likely not to altered so significantly that will pose different sort of risk to field (but especially to perennial crops such as orchards) that will tend to start their growing season earlier and as a consequence will lose their frost tolerance.

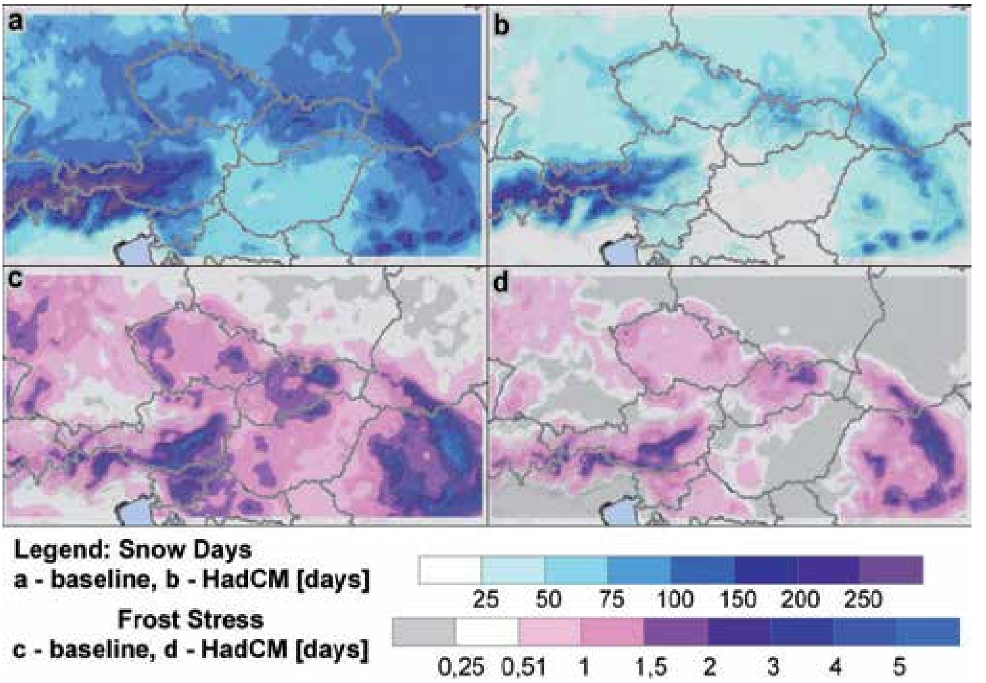


Fig. 16. (a) Mean number of days with snow cover in Central-Eastern Europe for baseline i.e. period between 1961 and 1990 and (b) expected change for increase of global mean temperature by 2.3°C with HadCM standardized scenario; (c) number of days with high risk of frost damage with 20-year return period for the baseline period and (d) expected change for increase of global mean temperature by 2.3°C with HadCM standardized scenario

6. Conclusions

It can be concluded that rainfed agriculture in Czech Republic as representative of Middle Europe region may face higher climate-related risks. However, the analyzed agroclimatic indicators will likely remain at levels that permit acceptable yields in most years.

Concurrently, our findings also suggest that the risk of extremely unfavorable years, resulting in poor economic returns, is likely to increase in many years. This projected increase in the variability of climatic suitability for crop production is particularly challenging for crop management and for agricultural policy, which aims to ensure stable food production and viable conditions for farmers. This therefore suggests that agricultural policy should encourage the adoption of both agroecological techniques and a diversification of production

To increase crop resilience to climatic variability as well as the implementation of various instance schemes (e.g. strategic grain stocks, farmer drought and flood insurances) and improvements in the efficiency of agricultural water use. An analysis of yield development, agrometeorological conditions in combination with agroclimatic projections under different climate-change scenarios across Europe offers the possibility of supporting early decision-making with regard to opportunities and risks. The analysis presented here should be conducted at regional and local levels to better reflect how specific localities may be affected.

7. Acknowledgement

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15

Variability of the Course of Tomato Growth and Development in Poland as an Effect of Climate Change

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1. Introduction

The course of phenological phases play an important role in the shaping of yield quantity and quality (Mozny et al., 2009; Peiris et al., 1996; Tao et al., 2006). The length of the development stages is important for the proper formation of both vegetative and reproductive organs. The main meteorological factor affecting the rate of plant development is air temperature (Ahmed et al., 2004; Chmielewski et al., 2005; Popov et al., 2003; Schleip et al., 2009b; Sysoeva et al., 1997).

Since the mid-20th century significant changes in temperature values have been observed in the growing season of crop plants. For instance, in the years 1961-2000, the average increase in air temperature in Germany, in the February-April period, amounted to 0.41°C/10 years (Chmielewski et al., 2004). In Poland, an increase in average air temperature during each April-October period in 1973-2002, on average, amounted to 0.54°C/10 years (Kalbarczyk E. & Kalbarczyk R., 2010). Similarly, positive temperature trends have been confirmed for the growing seasons of, e.g., onions and cucumber (Kalbarczyk, 2009a, 2009b, 2010a). Positive trends of air temperature in the growing seasons of crop plants have also been confirmed in other parts of the world (Bonofiglio et al., 2009; Matsumoto, 2010; Parey, 2008; Peng et al., 2004).

Since the mid-20th century changes in air temperature values have had influence on the course of the growth and development of plants. All over the world research studies focused on the reactions of fruit trees (Chmielewski et al., 2004; Fujisawa & Kobayashi, 2010), wild-growing plants (Gordo & Sanz, 2009; Kalvāne et al., 2009; Moiseev et al., 2010; Yoshie, 2010), and crop plants (Ahas et al., 2002; Dalezios et al., 2002; Kalbarczyk, 2009a; Mazurczyk et al., 2003; Menzel, 2000) have been conducted. Changes in temperature values lead to changes in duration of particular stages and the whole growing season of plants (Peiris et al., 1996; Song et al., 2008; Tao et al., 2006). Shifts in the course of the phenological phases may be radically different. The phenological phases are influenced by climate change, and depend on the species and a region of the world. Differences include acceleration to time delay of the date of a phenophase (Chmielewski et al., 2004; Jorquera-

Fontena & Orrego-Verdugo, 2010; Lobell et al., 2007; Wang et al., 2008; Xiao et al., 2008). In the summer, a 1°C increase in the minimum temperature resulted in acceleration of the date of maize flowering by 4.2 days (Tao et al., 2006). In Poland, an increase in the average April temperature by 1°C caused acceleration of the emergence date by 2.5 days (medium-early potato) or 1.7 days (medium-late potato) (Kalbarczyk E. & Kalbarczyk R., 2010). An increase in the average May temperature by 1°C caused acceleration of flowering by about 2.5 days for both cultivars of potato. According to Chmielewski et al. (2004) in Germany a 1°C increase in air temperature in the period from February to April caused the beginning of the growing season and flowering of fruit trees to accelerate by about 5 days and the beginning of winter rye shooting to accelerate by 3.8 days. On the other hand, in north-west China, an increase in the minimum temperature by 1°C caused the analysed development stage of cotton to lengthen by 12 days (budding - anthesis) and 9 days (anthesis - boll - opening) (Wang et al., 2008).

Acceleration in the course of plant development caused by a temperature increase, most often leads to reduction in yield quantity. The negative influence of rising temperature, in the period of plant growth and development was discovered, e.g. in the case of winter wheat and rice (Peng et al., 2004; Tao et al., 2006; Wang et al., 2008). Rising temperature, however had a positive effect on the quantity of maize yield in north-east China (Tao et al., 2006). According to the research conducted with the use of simulation models, the influence of rising temperature on crop plant yields may be diverse, as the kind of plant and region of cultivation must be taken into account. Both reduction in yield quantity, as in the case of winter and spring wheat and beans, (Peiris et al., 1996; Wang & Connor, 1996), and its increase, as in the case of potato in the EU, are possible (Peiris et al., 1996; Wolf & Oijen, 2002). Differences in the harvested yield caused by temperature change may be minor or may be a several dozen % yield difference.

The relationship between temperature change and changes in the phenology of crop plants have been researched. The studies on the field cultivation of vegetable plants, however, are relatively rare. Considering the size of production, calculated by means of the yield volume, tomato ranks second to potato, globally. In 2007, over 126.5 m tonnes of tomato were harvested in the world (FAO, 2008). The leading producers among the European Union countries are: Italy (6.0 m tonnes), Spain (3.7 m tonnes) and Greece (1.5 m tonnes). Poland ranks eighth in the EU, with a tomato production of 0.25 m tonnes. Crop plant cultivation plays an important role in Polish vegetal production. In the domestic structure of cultivated vegetables the share of tomato is relatively small, namely about 6% (GUS, 2010). The high thermal requirements of this plant are the reason for its low ranking. The optimum growth temperature is within a range of 22-27°C during the day and 16-18°C at night, and is determined by tomato development stage and light intensity. Temperatures above 30°C and below 10-12°C constitute the so-called developmental maximum and minimum. Reduction in yield is already observed when the temperature exceeds 25°C (Tshiala & Olwoch, 2010). Tomato is sensitive to the cold (0-5°C) and frost. When temperatures drop below 0°C, the plants freeze and die. At least a 4 month frost-free duration period is needed (Babik, 2004). Thus, in Poland, the climate thermal requirements are limited. A wide strip of central Poland, the Wrocław region, and the Sandomierz-Lublin region, situated in the south, are considered the most favourable areas for ground cultivation (Skąpski & Borowy, 2000). The best yield is harvested in the years which are considered by Polish terms, as warm and dry. In Poland, tomato yield slightly exceeds 20 $t \cdot ha^{-1}$ (GUS, 2008).

The domestic cultivated surface of the plant since 2001 has remained almost at the same level. Predicted adaptation of Polish agriculture to climate changes till 2030, depending on the direction of the changes, show the possibility of a considerable lengthening of the farming season. The farming season is defined as the period when doing field work is possible (Kundzewicz & Kowalczak, 2008). A 2-3 month lengthening of the climatic growing season of plants, and more of a possibility for thermophilous plant cultivation are also forecast. Therefore, more years with favourable weather conditions for good yield of field-cultivated tomato is possible.

The first goal of the undertaken study was to determine changes occurring in the course of tomato growth and development. The second goal was to determine tomatoes' dependence on air temperature during its growing season.

2. Material and methods

The results of field experiments on tomato (*Lycopersicon esculentum* Mill), carried out in 22 stations of the Research Centre for Cultivar Testing (COBORU) in Poland in the years 1965-2004 were used in this study. Our study was based on data concerning tomato growth and development. Agrotechnical dates used were: planting up (Pu), the beginning of harvesting (Bh) and the end of harvesting (Eh). Phenological dates used were: the beginning of flowering (Bf) and the beginning of fruit-setting (Bfs). In order to standardise the description of tomato development, the development stages (Bf, Bfs) determined according to the instructions of COBORU were additionally characterised by means of the numerical scale BBCH (Meier, 2001). This scale is employed in European Union countries. A method of determining development stages of monocotyledonous and dicotyledonous plants is used. The analysis in the study also included tomato development stages; four short ones: planting up – the beginning of flowering (Pu-Bf), the beginning of flowering – the beginning of fruit-setting (Bf-Bfs), the beginning of fruit-setting – the beginning of harvesting (Bfs-Bh), the beginning of harvesting – the end of harvesting (Bh-Eh); and a long one: planting up – the end of harvesting (Pu-Eh).

The experimental data of COBORU were collected for all the most commonly cultivated varieties of dwarf, flexible-stemmed tomato examined in a given year. After averaging, the data were accepted as a collective standard of the described plant. The use in the research of the collective standard was based on an assumption that intra-species differences do not obfuscate the sought after general regularities of the species. The field experiments took place in the whole area of Poland, except the submountainous regions located in the south-west and south-east of the country. The submountainous regions were excluded from the analysis on the grounds that field cultivation in Poland does not usually occur 500 metres above sea level.

Field experiments in the years 1965-2004 were conducted according to the methodology of COBORU (Domański, 1998). Tomato was cultivated on soils typical for this plant, i.e. soil rich in nutrients, not very heavy and easily warmed up. Depending on present soil richness, mineral fertilization application fluctuated from 150 to 625 kg per 1 hectare of crop. The average mineral fertilization amounted to 405 kg per 1 hectare of the crop, including N and P_2O_5 which were sown at 120 and 95 kg respectively, and K_2O – at 190 kg each. When full autumn organic fertilization with well-decomposed organic manure or compost at a dose from 20 to 30 t ha^{-1} was used for tomato cultivation, the dose of mineral fertilizers was reduced to 200 kg of NPK per 1 hectare.

In the years 1965-2004, average air temperature data in the period from May to October were collected from all meteorological posts operating at the experimental stations of COBORU. If there was no meteorological post at the location of the tomato experiments, the results coming from a meteorological station of the Institute of Meteorology and Water Management (IMGW) were used in the analysis. The selected IMGW station was situated closest to the COBORU station and best reflected the weather conditions of the conducted experiments. In addition, to determine spatial variability of air temperature, the research used data from 52 stations of IMGW, evenly distributed throughout Poland.

Agrotechnical dates, the dates of phenological phases, tomato development stages, and also thermal conditions of air were characterised with the use of the following statistical indexes: multi-annual average, the value of the highest and the lowest average, absolute minimum and maximum values, the range and standard deviation. Multi-annual average and standard deviation in the 40-year research period were calculated on the basis of data from all considered experimental stations of COBORU, or all meteorological stations of IMGW for the dates and duration of tomato development stages and in the case of air temperature. The range was determined between the highest average value (longest, latest) and the lowest average value (shortest, earliest). Temporal and spatial distribution of the change in the course of tomato development and air temperature were also determined on the basis of their linear trend, determined on the basis of linear regression equation. The study calculated deviations from the average, in the subsequent years of the analysed multi-annual period, in relation to the accepted basic period 1965-2004. Identification of the course of tomato development was carried out on the basis of two statistical parameters: the arithmetic mean and standard deviation. The parameters were determined for the basic period 1965-2004. Criteria and classes are presented in Table 1.

Class	Criterion	Date	Duration of development stages
1	$\xi > \Pi + 2.0\delta$	anomalously late	anomalously long
2	$\Pi + 1.5S < \xi \leq \Pi + 2.0S$	very late	very long
3	$\Pi + 1.0S < \xi \leq \Pi + 1.5S$	late	long
4	$\Pi - 1.0S \leq \xi \leq \Pi + 1.0S$	normal	normal
5	$\Pi - 1.5S \leq \xi < \Pi - 1.0S$	early	short
6	$\Pi - 2.0S \leq \xi \leq \Pi - 1.5S$	very early	very short
7	$\xi < \Pi - 2.0S$	anomalously early	anomalously short

Π - average value from the basic period of 1965-2004, S - standard deviation from the basic period of 1965-2004, ξ - average value from a given year.

Table 1. Classification scale of the agrotechnical dates and duration of tomato development stages in the years 1965-2004.

For example, the date of the beginning of tomato harvesting was considered average (normal) when the date in a given year fulfilled the following condition: $\Pi - 1.0S \leq \xi \leq \Pi + 1.0S$, where Π denotes the average date, δ the value of standard deviation, with both parameters calculated for the basic period 1965-2004. ξ denotes the date recorded in a given year. Similar classifications, but concerning thermal and precipitation conditions were made, among others, by: Pokladníková et al. (2008), Węgrzyn (2007) and Żmudzka (2004).

The relationship between agrotechnical dates and the dates of tomato phenophases, and the average air temperature was determined by means of the simple linear regression analysis. Statistical assessment of the equations was done on the basis of the *t*-Student and *F*-Snedocor tests, the Pearson's correlation coefficient, and a coefficient describing the difference between standard deviation of a dependent variable and a standard error of equation estimation (*S-Sy*) (Dobosz, 2001; Sobczyk, 1998). The occurrence of autocorrelation of random components was checked by means of the Durbin-Watson test. To verify regression equations, the study also used relative forecast error, determined according to the formula:

$$RFE = \frac{y - y_p}{y} \cdot 100\% \tag{1}$$

and average relative forecast error, for all the analysed stations of COBORU and the considered years 1965-2004. An average relative forecast error was calculated according to the formula:

$$ARFE = \frac{1}{n}\sum_{i=1}^{n}\left|RFE\right| \tag{2}$$

where:
y – actual date (day),
y_p – date calculated according to the formula (day),
n – number of years accepted in a time series (number of stations x number of years).
Also determined, were how many times relative forecast error in the analysed multi-annual period 1965-2004 amounted to $\left|RFE\right| \le 2\%$ and $2\% < \left|RFE\right| \le 4\%$.

3. Results

3. 1 Temporal and spatial variability of tomato growth and development

3.1.1 Agrotechnical dates and phenological phases

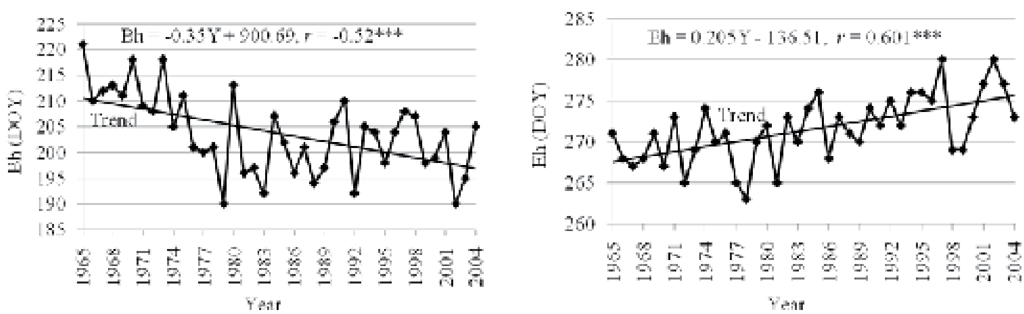
In Poland, in the years 1965-2004, the average date of planting up (Pu) tomato seedlings in the field fell on 21st May (Table 2). The absolute minimum date was 3rd May and the maximum 2nd June. The beginning of flowering (Bf) of the described plant was observed on average on 7th June, and the beginning of fruit-setting (Bfs) on 19th June. The average date for the beginning of harvesting (Bh) fell on 21st July, and the end of harvesting (Eh) on 27th September. The earliest average date was 8th July for the beginning of harvesting and 19th September for the end of harvesting. The latest average date – for the beginning of harvesting was 8th August and 6th October for the end of harvesting. Both absolute minimum and absolute maximum dates of the subsequent agrotechnical dates and the dates of tomato phenophases, were generally different by 2-5 weeks from the average dates. For minimum dates, the bigger differences were in the dates: Pu, Bf and Bfs and in the case of maximum dates: Bh and Eh. The standard deviation of agrotechnical dates and the dates of tomato phenophases fluctuated from about 2 to 8 days. The date of tomato planting up was marked by the lowest standard deviation and the date of the beginning of harvesting by the highest one. The range of the described dates calculated between the average latest and the average earliest date, like standard deviation, was the smallest for planting up and the biggest for the beginning of harvesting. The range swung from a low 7 to as high as 31 days.

Agrophase	BBCH scale	Date (day)						Absolute date (day)	
		mean	latest	earliest	range[2]	S	trend (day/10a)	max	min
Pu[1]	-	21-05	25-05	18-05	7	2.0	-0.6*	2-06	3-05
Bf	61601	7-06	15-06	31-05	15	3.6	-0.7*	23-06	17-05
Bfs	71701	19-06	30-06	10-06	20	4.8	-1.1*	9-07	26-05
Bh[1]	-	21-07	8-08	8-07	31	7.8	-3.5***	26-08	28-06
Eh[1]	-	27-09	6-10	19-09	17	4.0	2.1***	27-10	30-08

Pu – planting up, Bf – beginning of flowering, Bfs – beginning of fruit-setting, Bh – beginning of harvesting, Eh – end of harvesting, S – standard deviation, max – absolute maximum date, min – absolute minimum date, * significant at $p \le 0.1$, *** significant at $p \le 0.01$, [2]between the latest and the earliest date.

Table 2. Statistical characteristics of the agrotechnical[1] dates and the phenological phases of tomato in Poland, in the years 1965-2004.

The analysis of the linear trend of agrotechnical dates and the dates of tomato phenological phases showed a statistically significant, negative temporal tendency. This was a tendency for a year by year acceleration of almost all the considered dates, except for the end of harvesting (Table 2, Fig. 1). The biggest acceleration was found for the beginning of harvesting (-3.5 days /10 years, $p \le 0.01$), and next for the beginning of fruit-setting (-1.1 days /10 years, $p \le 0.1$), definitely the smallest for planting up (-0.6 days /10 years, $p \le 0.1$) and the beginning of flowering (-0.7 days /10 years, $p \le 0.1$). The end of tomato harvesting showed significant delay (2.1 days /10 years, $p \le 0.01$), year by year, in the years 1965-2004. Out of all the analysed tomato dates, the highest correlation coefficient for the linear trend in the years 1965-2004 for all of Poland was determined for the end of harvesting ($r = 0.601$), and next for the beginning of harvesting ($r = -0.52$).

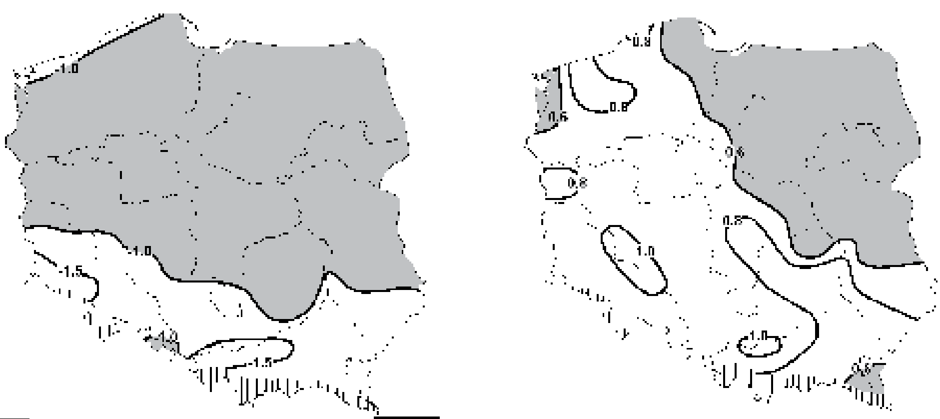


Y – year, r – correlation coefficient, *** significant at $p \le 0.01$.

Fig. 1. Temporal distribution of the dates of the beginning of harvesting (Bh) and the end of harvesting (Eh) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

Acceleration of the date of the beginning of tomato harvesting did not occur evenly throughout the whole country (Fig. 2). Significant acceleration of the beginning of harvesting was proved only in the north-west and in the south (over -1.0 day /10 years). The biggest significant acceleration of the beginning of harvesting was in the south-west and in the Kraków region (over -1.5 days /10 years). Delay of the end of harvesting date, like acceleration of the beginning of harvesting, did not have an even occurrence throughout the whole country. Significant delay of the last date of tomato harvesting was recorded in the western and southern parts of Poland, where it usually oscillated from 0.6 day /10 years to 1.0 day /10 years. The biggest delay of the date (over 1.0 day /10 years) occurred in the Kraków and Wrocław regions.
During the 40-year research period, the date of the beginning of tomato harvesting was decidedly delayed 6 times in comparison with the average domestic date, and accelerated 6 times (Fig. 1, Fig. 3). The results are from agrotechnical dates showing that only once in the first half of the research period, in 1965, the beginning of harvesting was anomalously late. It was very late 2 times; in the years 1970 and 1973. It was late 3 times; in 1967, 1968, 1980. The beginning of harvesting was very early in 1979 and early in 1983. In the second half of the research period, delay of the harvesting date was not recorded, but 4 times the date was accelerated. In 1992 and 2002, the beginning of harvesting date occurred very early. The beginning of harvesting date was early in 1988 and 2003. The end of harvesting date of tomato was marked by the opposite temporal structure. In the first half of the analysed multi-annual period, only the years in which acceleration of the date was recorded, were identified, and in the second half of the analysed multi-annual period only the delay of the date years were identified. The end of tomato fruit harvesting was anomalously early in 1978, very early in 1972, 1977, 1981, and early in 1967 and 1970. Tomato harvesting occurred late in: 1985, 1994, 1995, 2001, 2003, and anomalously late in 1997 and 2002.

beginning of harvesting end of harvesting



the area excluded from analysis, lack of significant influence at the level of $p \leq 0.05$

Fig. 2. Statistically significant, at least at the level of $p \leq 0.05$, linear regression coefficients for the trend of the beginning of harvesting date and the end of harvesting date of tomato in Poland, calculated for 10 years, in the years 1965-2004.

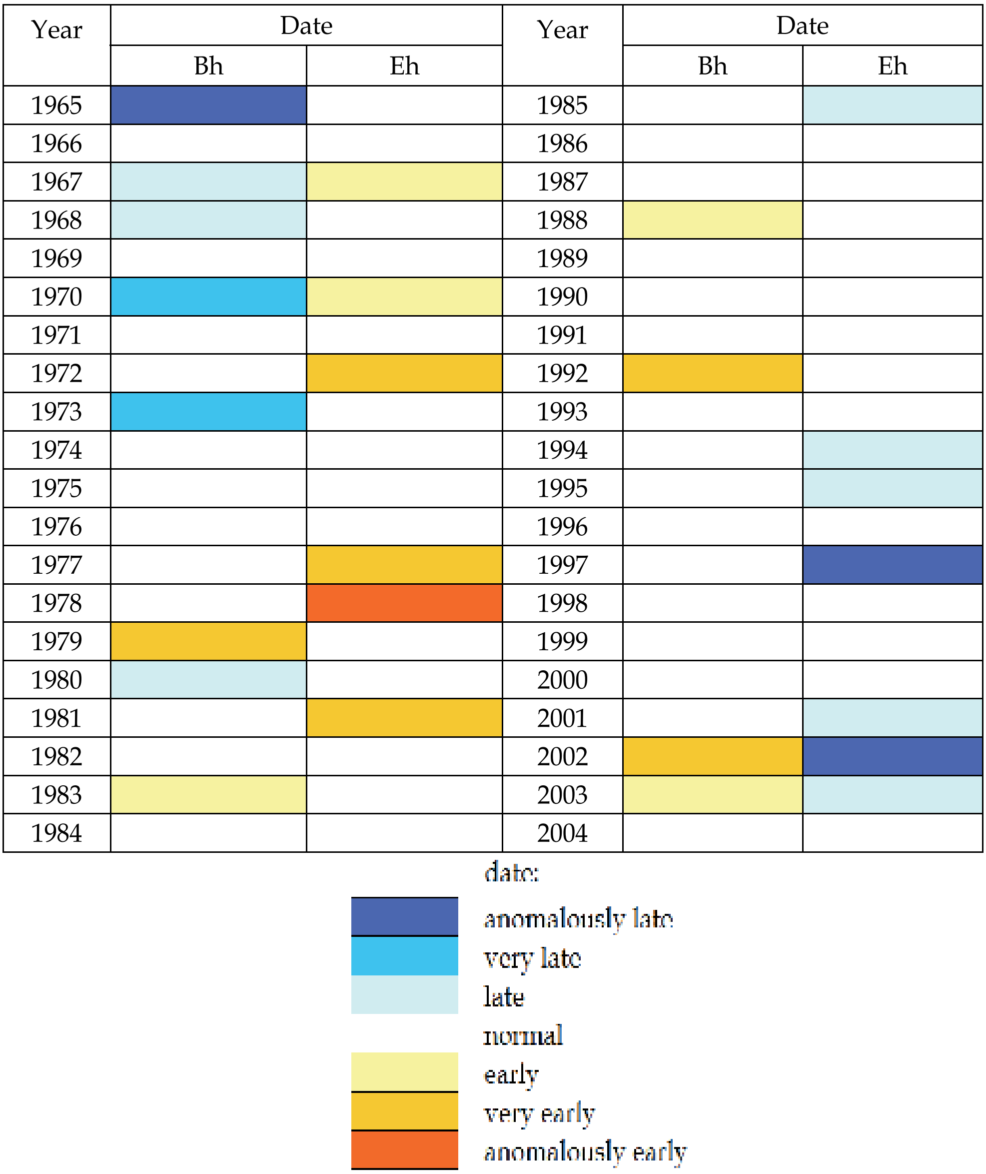


Fig. 3. Identification of the beginning of harvesting date (Bh) and the end of harvesting date (Eh) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

Tomato agrotechnical dates in anomalously extreme years were different from the average domestic date and varied across Poland (Fig. 3, Fig. 4). In 1965, when the date of the beginning of harvesting was identified as anomalously late, deviation from the average multi-annual (1965-2004) date oscillated from less than 4 days to even more than 8 days. The first tomato fruits were harvested in the north and in the south-west of the country at the latest date, 8 days later than the norm. The first tomato fruits were harvested at a slightly earlier date, 4 days later than usual, in the central west, the centre and the south-east. The end of harvesting, especially in 1978, 1997 and 2002 was significantly different from the average domestic date. In 1997 and 2002, deviation from the average multi-annual date for the end of harvesting in Poland, fluctuated mostly from 2 to 6 days in 1997 and from 4 to 8 days in 2002. The biggest delay was recorded in the northern part of the country (> 6 days) in 1997 and in the central-western part (> 8 days) in 2002. In 1978, the last field-cultivated tomato fruits were harvested about 6 to 8 days earlier than the average domestic date. The earliest end of harvesting was recorded in the north-east, north, south-west and locally in the Kielce region.

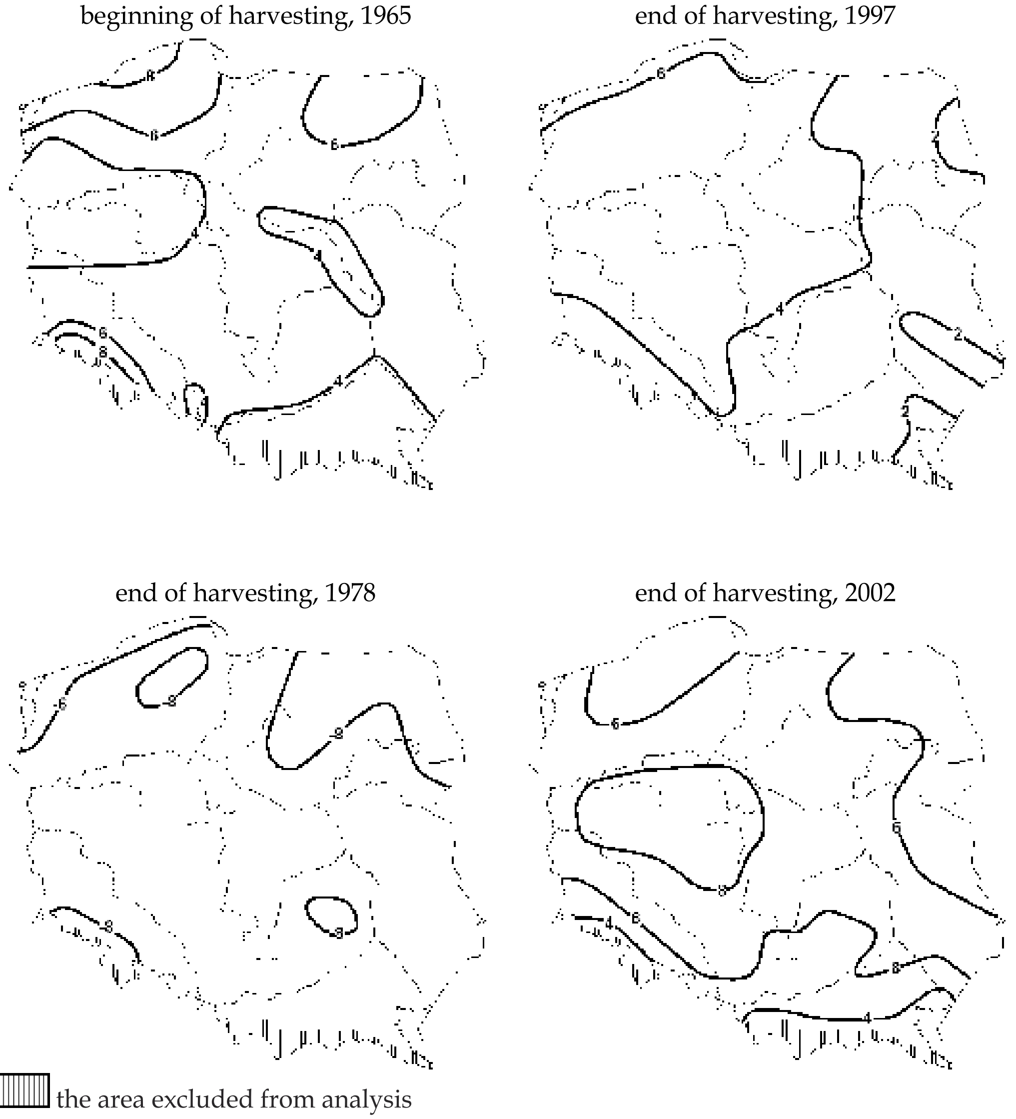


Fig. 4. Deviations from the multi-annual average (1965-2004) in Poland, of tomato agrotechnical dates: the beginning of harvesting in 1965 and the end of harvesting in: 1978, 1997 and 2002.

3.1.2 Development stages

On average, the shortest period of tomato development was the period from the beginning of flowering to the beginning of fruit-setting (Bf-Bfs), lasting only 12 days (Table 3). The longest period of tomato development was the period of tomato fruiting, i.e. from the beginning to the end of harvesting (Bh-Eh), which lasted 68 days. Tomato flowering occurs on average, 17 days after the date of planting up in the field. Tomato flowering occurs earliest after 9 days of planting up in the field and latest after 28 days. The beginning of fruit-setting occurred on average 29 days after the date of planting up. In Poland, the beginning of fruit-setting occurred on average, in the last ten days of May (Table 2). The beginning of tomato harvesting occurred on average, 62 days after the date of planting up. The end of harvesting occurred 130 days after the date of planting up. In the analysed multi-annual period there were also years in which the period from planting up to the end of harvesting (Pu-Eh) lasted 139 days, and at particular stations of COBORU it oscillated from 98 to even 161 days. Absolute minimum duration of development stages oscillated from 4 days in the case of the period Bf-Bfs, to 28 days in the case of the period Bh-Eh.

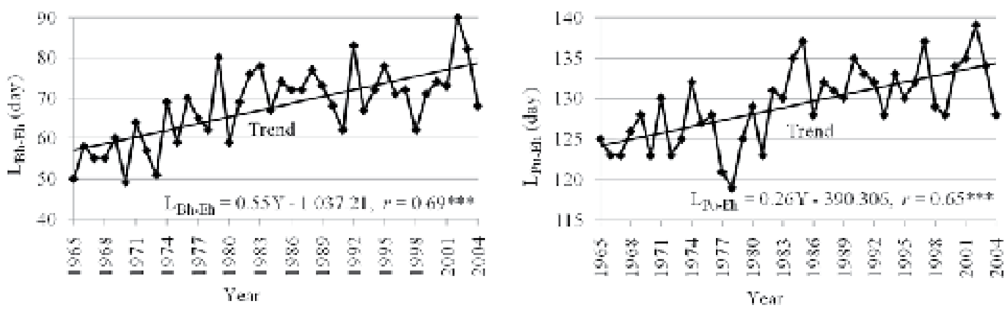
Out of the four considered short periods of tomato development stages, least diverse in terms of duration was the period from the beginning of flowering to the beginning of fruit-setting (Table 3). It was indicated not only by the lowest value of standard deviation (S = 2.0 days), but also by the lowest average value (12 days) and the smallest range (R = 8 days). On the other hand, the periods from planting up to the beginning of flowering (S = 3.6 days) and from the beginning of fruit-setting to the beginning of harvesting (S = 5.2 days) were marked by average diversity of duration. The highest standard deviation (S = 9.5 days) was characteristic of the period from the beginning of harvesting to the end of harvesting. The range between extreme (longest and shortest) average duration periods of tomato development stages, varied from 8 days in the case of the period from the beginning of flowering to the beginning of fruit-setting, to 41 days in the case of the period from the beginning of harvesting to the end of harvesting. In the period from planting up to the end of harvesting, this range amounted to 20 days.

Development stage	Duration (day)						Absolute duration (day)	
	mean	longest	shortest	range[3]	S	trend (day/10a)	max	min
Pu-Bf	17	28	9	19	3.6	n.s.	33	5
Bf-Bfs	12	16	8	8	2.0	n.s.	27	4
Bfs-Bh	33	44	23	21	5.2	-1.4*	80	14
Bh-Eh	68	90	49	41	9.5	5.6***	100	28
Pu-Eh	129	139	119	20	4.7	2.6***	161	98

Pu-Bf – planting up - beginning of flowering, Bf-Bfs – beginning of flowering - beginning of fruit-setting, Bfs-Bh – beginning of fruit-setting - beginning of harvesting, Bh-Eh – beginning of harvesting - end of harvesting, Pu-Eh – planting up - end of harvesting, max – absolute maximum duration, min – absolute minimum duration, n.s. – non-significant at $p \leq 0.1$, [3]between the latest and the shortest duration. The remaining explanations see Table 2.

Table 3. Statistical characteristics of duration of tomato development stages in Poland, in the years 1965-2004.

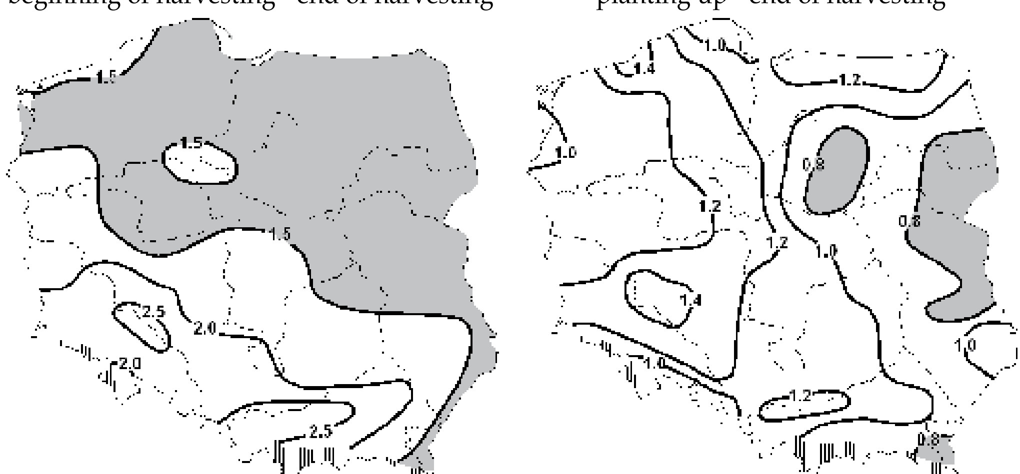
In the years 1965-2004, statistically significant lengthening, at the level of $p \leq 0.01$, of only one out of the analysed four short tomato development stages was seen (Table 3, Fig. 5). In Poland, the period from the beginning of harvesting to the end of harvesting, on average, lengthened by as much as 5.6 days /10 years. In the periods Pu-Bf and Bf-Bfs, no statistically significant examples of shortening or lengthening were found, as opposed to the period Bfs-Bh, which, year by year, became significantly shorter, on average by -1.4 days /10 years. Changes in duration of particular development stages of tomato meant that the whole period lasting from planting up to the end of harvesting, lengthened by as much as 2.6 days /10 years. The correlation coefficient, which was determined for the function best describing the linear trend of development stages, amounted to 0.69 for the period Bh-Eh and 0.65 for the period Pu-Eh.



Y – year, r – correlation coefficient, *** significant at $p \leq 0.01$.

Fig. 5. Temporal distribution of duration from the beginning to the end of harvesting (L_{Bh-Eh}) and from planting up to the end of harvesting (L_{Pu-Eh}) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

beginning of harvesting - end of harvesting planting up - end of harvesting



the area excluded from analysis, lack of significant influence at the level of $p \leq 0.05$

Fig. 6. Statistically significant, at least at the level of $p \leq 0.05$, linear regression coefficients for the trend of duration from the beginning to the end of harvesting and from planting up to the end of harvesting of tomato in Poland, calculated for 10 years, in the years 1965-2004.

Despite the fact that in the whole country, the period from the beginning of harvesting to the end of harvesting of tomato on average, lengthened by as much as 5.6 days /10 years, in particular regions of Poland, this lengthening predominantly oscillated from 1.5 days /10 years to 2.5 days /10 years (Fig. 6). The biggest lengthening occurred in the south of the country, especially in the Wrocław and Kraków regions (Fig. 2). These were the regions where the biggest acceleration of the beginning of harvesting and at the same time the biggest delay of the end of harvesting were recorded. Changes in duration of the period from planting up to the end of harvesting, in particular regions of the country, were also different than for the whole country (Fig. 6). In Poland, lengthening of the period Pu-Eh usually oscillated from 0.8 day /10 years to 1.4 days /10 years. The biggest changes in duration, over 1.4 days /10 years, of the period Pu-Eh, occurred in south-west Poland in the Wrocław region, and in the north-west in the Koszalin region. No proved significant changes in duration of the Bh-Eh periods took place in the northern, north-eastern and eastern parts of the country. No proved significant changes in duration of the Pu-Eh periods took place in the central-eastern part of the country. Spatial distribution of the duration-change of these two tomato development stages was partially consistent with the distribution of the change of these agrotechnical dates: acceleration of the date of Bh and delay of the date of Eh (Fig. 2).

Changes in duration of the periods Bh-Eh and Pu-Eh were also confirmed by identification of these periods, in the subsequent years of the analysed multi-annual period (Fig. 7). Out of the 40 examined years, there were seven years: 1965-1968, 1970, 1972-1973 with shorter than average Bh-Eh periods recorded. In three of the seven years, the Bh-Eh period was identified as very short, and in four years as short. The Pu-Eh period had a similar distribution of years as the Bh-Eh period, but periods shorter than the average were recorded in: 1966-1967, 1970, 1972, 1977-1978 and 1981. In 1978 the Pu-Eh period was even anomalously short and in 1977 – very short. In the remaining five years, the Pu-Eh period was short. On the other hand, in the years 1983-2004, long periods were recorded. The Bh-Eh period in the following six years: 1979, 1983, 1992, 1995, 2002-2003 and the Pu-Eh period in the following seven years: 1984-1985, 1990, 1997, 2001-2003 were longer than the average. Anomalously long Bh-Eh and Pu-Eh periods were recorded in 2002, and very long ones in 1992 and 1985 and 1997.

In Poland, deviation from the multi-annual average (1965-2004) of the length of the period from the beginning to the end of harvesting in 2002, usually amounted to 8 to 14 days (Fig. 8). The period lasted longest, over 14 days, in the central-western part of the country and in the Warsaw region. The period lasted much shorter – less than 8 days, in northern, south-western and south-eastern Poland. In the case of the long development stage of tomato, i.e. Pu-Eh, deviations from the average in 2002 were lower than in the case of the Bh-Eh period. The long development stage of tomato oscillated generally from 4 to 10 days. The Pu-Eh period lasted the longest; over 10 days, in the central-western part of the country. The Pu-Eh period was slightly shorter, less than 6 days, in the north and north-east. The Pu-Eh period was shortest, less than 4 days, in the south-west and south-east of Poland. In 1978, the Pu-Eh period was also different in its duration from the multi-annual average. The Pu-Eh period was the shortest out of the 40 considered periods in the years 1965-2004. In 1978 the Pu-Eh period was the shortest, less than 8 days, in the north, north-east, south-west and locally in the vicinity of Kielce and Mława.

Year	Development stage		Year	Development stage	
	L_{Bh-Eh}	L_{Pu-Eh}		L_{Bh-Eh}	L_{Pu-Eh}
1965			1985		
1966			1986		
1967			1987		
1968			1988		
1969			1989		
1970			1990		
1971			1991		
1972			1992		
1973			1993		
1974			1994		
1975			1995		
1976			1996		
1977			1997		
1978			1998		
1979			1999		
1980			2000		
1981			2001		
1982			2002		
1983			2003		
1984			2004		

development stage:

- anomalously long
- very long
- long
- normal
- short
- very short
- anomalously short

Fig. 7. Identification of duration from the beginning to the end of harvesting (L_{Bh-Eh}) and from planting up to the end of harvesting (L_{Pu-Eh}) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

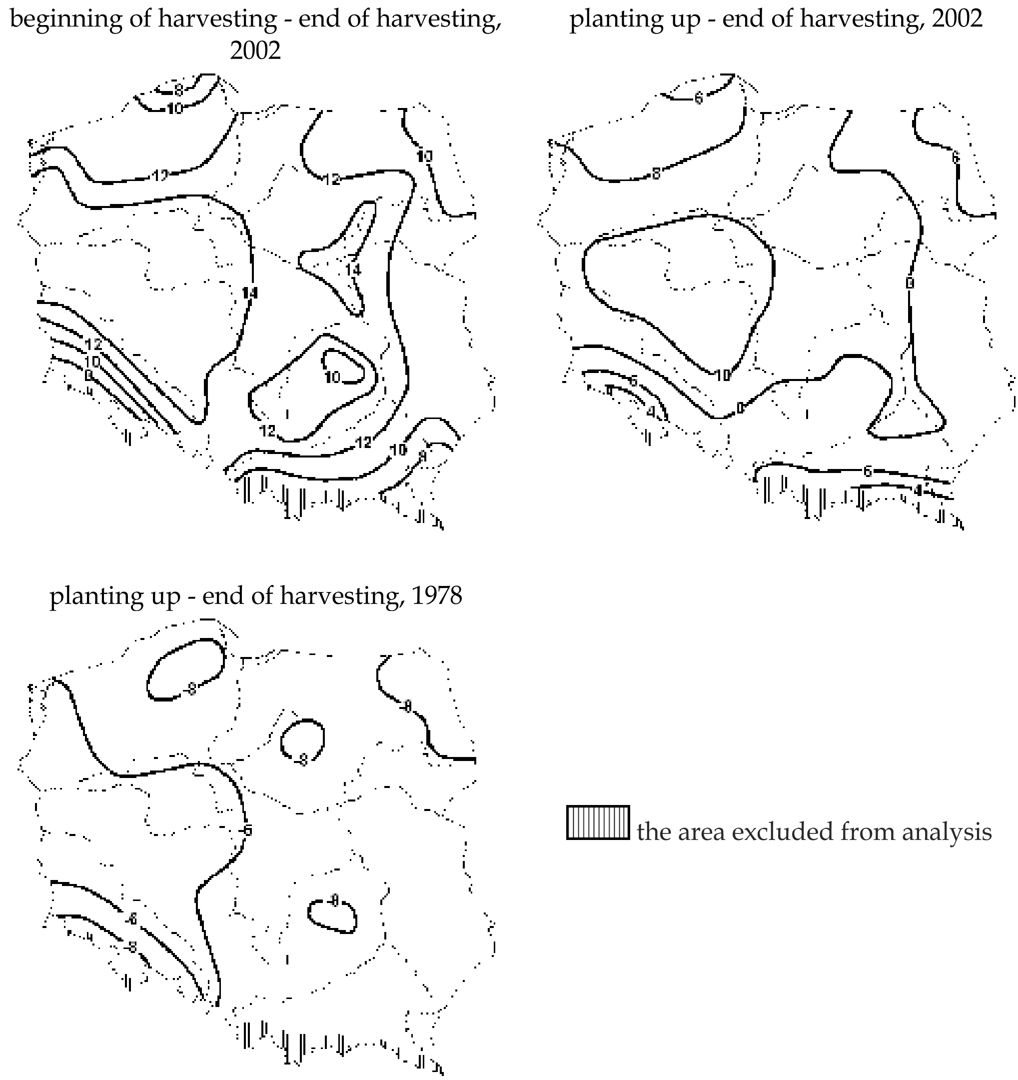


Fig. 8. Deviations from the multi-annual average (1965-2004) in Poland, of duration of tomato development stages: from the beginning to the end of harvesting in 2002 and from planting up to the end of harvesting in: 1978 and 2002.

3.2 Air temperature and its effect on the course of tomato growth and development

Changes in the occurrence of agrotechnical dates and the dates of phenological phases of tomato, which occurred during the 40-year research period (Table 2), are closely related to the course of air temperature (Table 4, Fig. 9). Out of the four dates: Bf, Bfs, Bh and Eh, the strongest relationship with air temperature was proved in the case of the phenological phases: the beginning of flowering (r = -0.77, $p \leq 0.01$) and the beginning of fruit-setting (r = -0.82, $p \leq 0.01$). A slightly weaker relationship with air temperature, but also significant at the level of $p \leq 0.01$, was proved in the case of the agrotechnical dates: the beginning of harvesting (r = -0.56***) and the end of harvesting (r = 0.61***). However, apart from thermal conditions of air, agrotechnical dates of vegetables to a large extent, depend on the course of other agrometeorological conditions. Agrotechnical dates of vegetables also depend on other factors, e.g. organisational work on the horticultural farm (Babik, 2004; Domański, 1998).

The best fitted regression function, in relation to empirical data, was the date of the beginning of fruit-setting (Table 4). This date is confirmed not only by the highest correlation coefficient but also by the values of the *t*-Student and *F*-Snedecor tests and also the coefficient describing the difference between the standard deviation of a dependent variable and equation standard error (*S-Sy*). The date of the beginning of fruit-setting in Poland can be predicted with average relative forecast error amounting only to 1.2%. The occurrence of relative forecast error in the analysed multi-annual period, 1965-2004 within a range of 0-2%, amounted to as much as 82,5%, and within a range of 2-4% - only 17.5%. Out of the four analysed dates of the described plant, three: Bf, Bfs, Bh are negatively affected by thermal conditions of air, i.e. with an increase in temperature there occurred acceleration of the date. If air temperature in May increases by 1°C, then the date of the beginning of flowering will be accelerated by 1.8 days. When air temperature increases by 1°C in the period from 10th May to 10th June, then the date of the beginning of fruit-setting will accelerate by 2.2 days. If air temperature increases in the period from 20th May to 20th June, then the date of the beginning of harvesting may even accelerate by 3.1 days. Only the date of the end of harvesting was positively correlated with air temperature in the period from 10th August to 10th September, a drop by 1°C may delay it by 2.1 days.

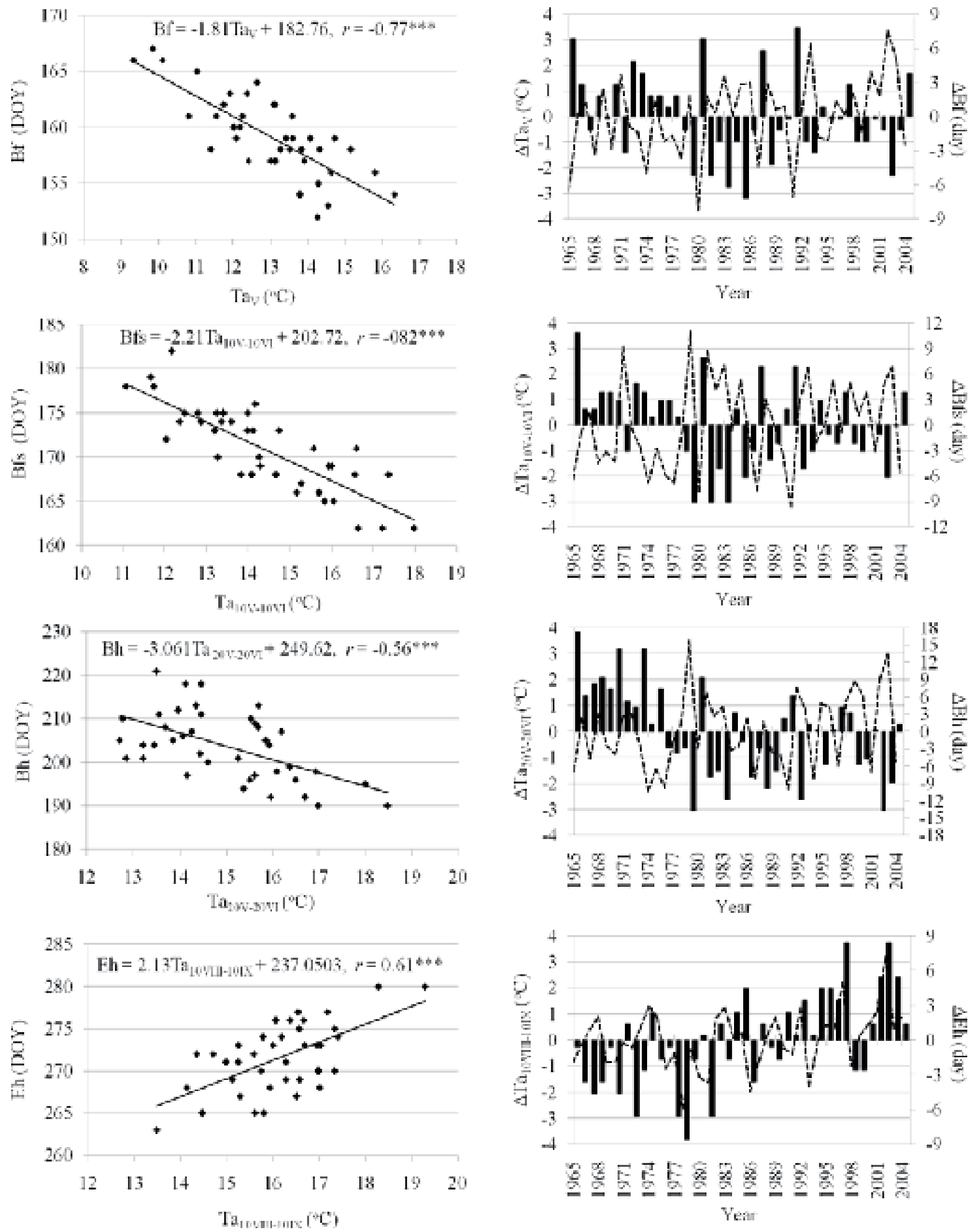
Regression equations	Characteristics						
	t	*F*	*r*	*S-Sy* (day)	*ARFE* (%)	frequency of the occurrence of |*RFE*| in range	
	bx / *a*					0-2 (%)	2-4 (%)
$Bf = -1.81Ta_{V} + 182.76$	-7.5 / 57.7	56.3	-0.77***	1.4	1.4	77.5	22.5
$Bfs = -2.21Ta_{10V-10VI} + 202.72$	-8.4 / 55.3	75.3	-0.82***	2.1	1.2	82.5	17.5
$Bh = -3.061Ta_{20V-20VI} + 249.62$	-4.2 / 22.5	17.6	-0.56***	0.8	2.6	40.0	37.5
$Eh = 2.13Ta_{10VIII-10IX} + 237.0503$	4.8 / 32.6	22.8	0.61***	1.3	1.8	75.0	25.0

t – value of the *t*-Student test, *F* - value of the *F*-Snedecor test, *r* – correlation coefficient, *S-Sy* - difference between a standard deviation of a dependent variable and a standard error of equation estimation (day), *ARFE* - average relative forecast error (%), *RFE* - relative forecast error (%), *bx* – regression coefficient, *a* – intercept, Ta - average air temperature (°C). The remaining explanations see Table 2.

Table 4. Regression analysis describing the relationship between the agrotechnical date (Bh, Eh) and the date of the phenological phase (Bf, Bfs) of tomato and average air temperature in Poland in the years 1965-2004.

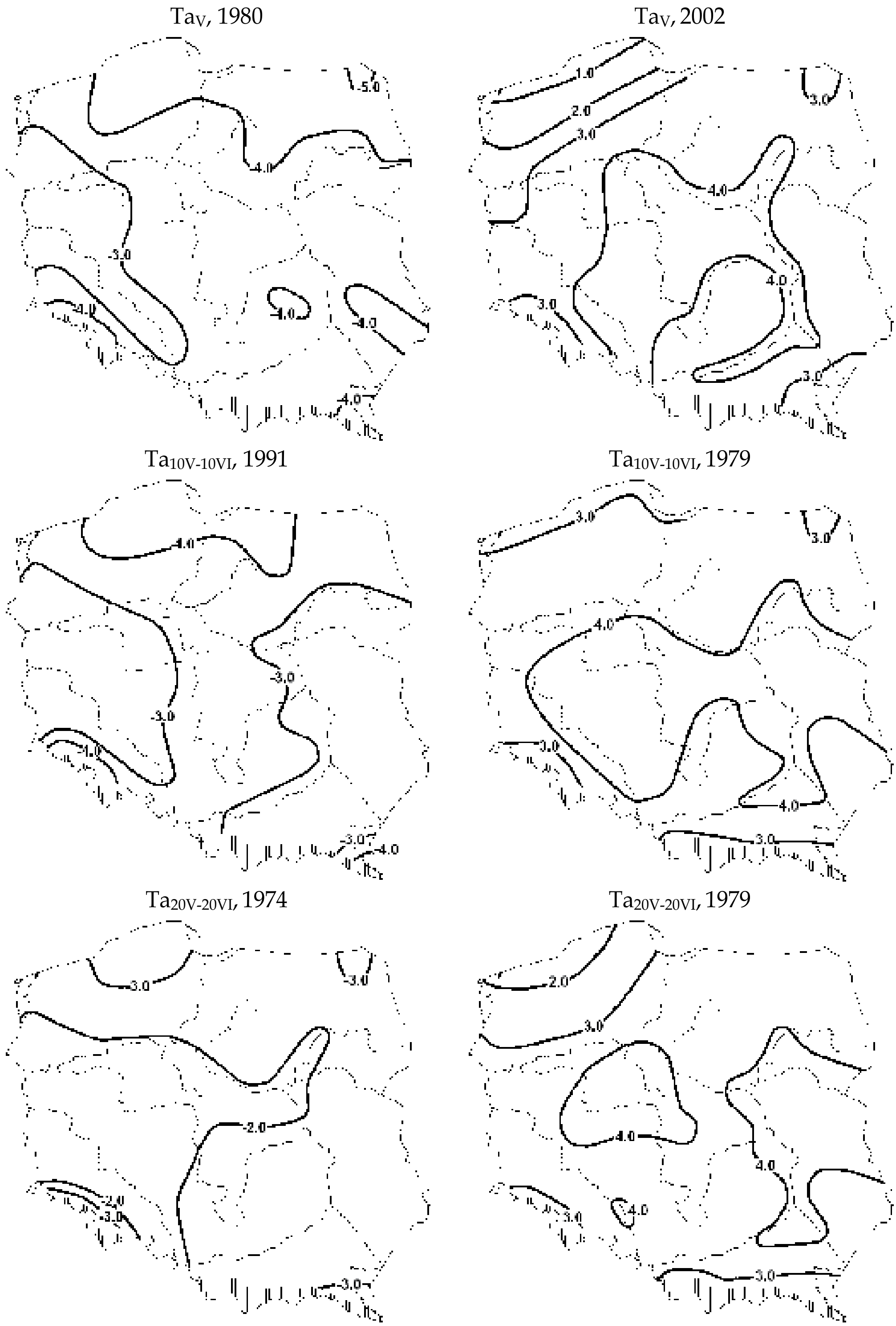
In 2002, the highest air temperature in May (Ta_V) was recorded, 3.3°C higher than the average (Fig. 9). In 2002, the date of the beginning of tomato flowering was earlier than the average in the years 1965-2004, by about 5 days. In the period from 10th May to 10th June ($Ta_{10V-10VI}$), air temperature was highest in 1979 (3.7°C higher than the average). Also in 1979, the air temperature was the highest (3.5°C higher than the average) in the period from 20th May to 20th June ($Ta_{20V-20VI}$). In the period 10th August to 10th September ($Ta_{10VIII-10IX}$), air temperature was highest in 2002 (3.2°C higher than the average), i.e. like in May. Air temperature in 1979 was higher than the average 1965-2004 air temperature. The higher 1979 air temperature contributed to acceleration of the dates of the beginning of fruit-setting and the beginning of harvesting, respectively by about 9 and 14 days compared to the average date. On the other hand, above-average temperatures in 2002 contributed to about an 8 days delay in the end of harvesting date.

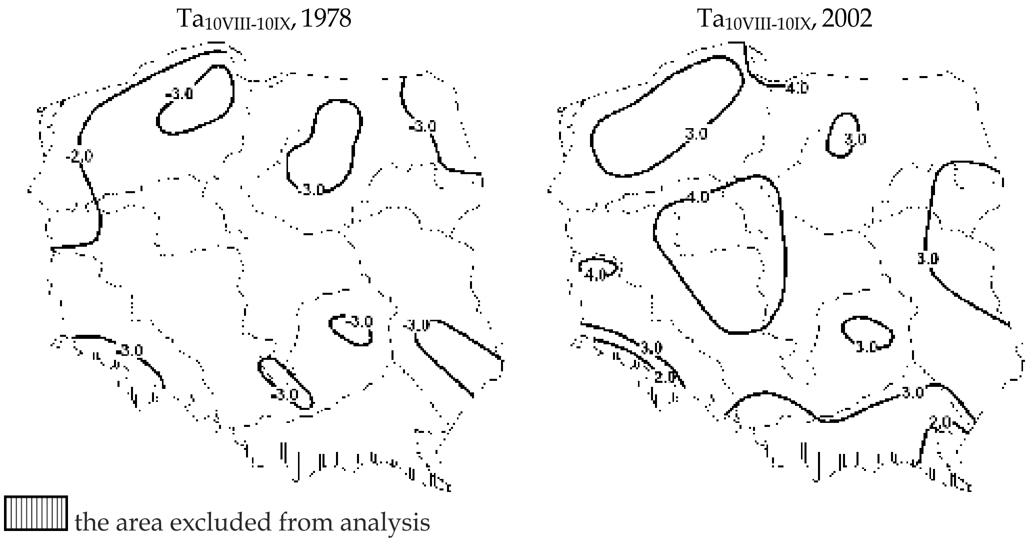
In May, in extreme years in terms of the course of thermal conditions of air, spatial distribution of air temperature was considerably different from the multi-annual structure in the years 1965-2004 (Fig. 10). In 1980 deviations from the norm of the analysed meteorological element, varied in most regions of Poland from -3.0 to -5.0°C, and in 2002 from 1.0 to 4.0°C. In 1980, it was coldest in the north-eastern part of the country and warmest in the central-west. In 2002, the lowest, positive air temperature which deviated from the average, were recorded in the north-west. The highest air temperatures which deviated from the average, were recorded mostly in central and southern Poland. In the periods from 10th May to 10th June in 1991 and 1979, the structures of air temperature deviating from the norm in Poland, were different than in May. In 1991 negative deviations oscillated from above -3.0°C in the central-western and central-eastern parts of the country to below -4.0°C in the northern, south-western and south-eastern parts. In 1979, as opposed to 1991, the highest deviations from the norm, amounting to above 4.0°C, were recorded in the central strip of Poland, stretching in latitude to the eastern border of the country. In the period from 20th May to 20th June, in the years of the highest deviations from the average, air temperature deviation oscillated from below -3.0°C in 1974 to above 4.0°C in 1979 (Fig. 9). In summer, in the period from 10th August to 10th September, the values of temperature deviations from the norm were similar to the earlier characterised periods and they oscillated generally from -3.0°C in 1978 to 4.0°C in 2002. In the summer of 1978, the air temperature was 3.0°C lower than the multi-annual average. This 3.0°C lower temperature occurred mainly in north and south-east Poland (Fig. 10). In the warmest period from 10th August to 10th September, which was recorded in 2002, in the central part of the country, on the Bay of Gdańsk and in the central-western part of Poland. This high 2002 temperature was 4.0°C higher than the average 1965-2004 temperature. In the tomato growing season, in the period from May to October, air temperature in the analysed years oscillated from 12.9 to 15.7°C, and at the stations of COBORU – as much as from 11.6 to 18.0°C. On the other hand, average air temperature during short periods, significantly influencing agrotechnical dates and the dates of phenological phases of tomato, oscillated from 13.0°C for Ta_V to 16.1°C for $Ta_{10VIII-10IX}$ (Table 5, Fig. 11). In May, the highest average air temperature amounted to 16.3°C, and was 1.7°C lower than the highest average $Ta_{10V-10VI}$, 2.2°C and 3.0°C lower, respectively, than the highest averages $Ta_{20V-20VI}$ and $Ta_{10VIII-10IX}$. The absolute maximum air temperature was from 8.0°C higher than the minimum one in the period from 10th August to 10th September, to 11.2°C in May. Average air temperature in Poland was marked by the highest variability in the period from 10th May to 10th June, which is confirmed by the value of standard deviation (S = 1.8°C). Temperature in the period from 10th August to 10th September was marked by the decidedly lowest variability. Temperature in the period from 10th August to 10th September had the lowest determined standard deviation (S = 1.1°C) and the smallest range (R = 5.8°C).



r – correlation coefficient, *** significant at $p \leq 0.01$.

Fig. 9. Left-hand side: relationship between agrotechnical dates (Bh, Eh) and phenological phases (Bf, Bfs) of tomato in Poland and average air temperature (Ta_V, $Ta_{10V\text{-}10VI}$, $Ta_{20V\text{-}20VI}$, $Ta_{10VIII\text{-}10IX}$). Right-hand side: deviations from the multi-annual average (1965-2004) in Poland of the dates (ΔBh, ΔEh) and phases (ΔBf, ΔBfs) of tomato and air temperature (ΔTa_V, $\Delta Ta_{10V\text{-}10VI}$, $\Delta Ta_{20V\text{-}20VI}$, $\Delta Ta_{10VIII\text{-}10IX}$) in the subsequent years of the analysed multi-annual period 1965-2004.


TaV, 1980
TaV, 2002
Ta10V-10VI, 1991
Ta10V-10VI, 1979
Ta20V-20VI, 1974
Ta20V-20VI, 1979



the area excluded from analysis

Fig. 10. Deviations from the multi-annual average (1965-2004) of air temperature in Poland: in May (Ta_V) – in 1980 and 2002, in the period 10th May-10th June ($Ta_{10V-10VI}$) – in 1979 and 1991, in the period 20th May-20th June ($Ta_{20V-20VI}$) – in 1974 and 1979 and in the period 10th August-10th September ($Ta_{10VIII-10IX}$) – in 1978 and 2002.

In the whole growing season of tomato, a significant increase in air temperature by 0.3°C /10 years ($p \leq 0.05$) was proved. Out of the four short analysed periods, there was a significant increase only in two air temperatures, most in May by 0.4°C/10 years ($p \leq 0.01$), and slightly less in the period from 10th August to 10th September by 0.3°C /10 years ($p \leq 0.01$). In Poland, air temperature increase was not uniform in all climatic regions (Fig. 12). The changes of agrotechnical dates and tomato development stages were also not uniform in all climatic regions (Fig. 2, Fig. 6). In May, a significant increase in air temperature, by more than 0.5°C /10 years, was recorded in the western part of Poland. The highest increase in air temperature was in the Kraków and Wrocław regions where air temperature increased by as much as 0.6°C /10 years. In summer, in the period from 10th August to 10th September a significant increase of more than 0.4°C /10 years, occurred in the south-west and locally in the central-west and the north. The highest increase of 0.5°C /10 years was in the Wrocław region.

4. Discussion

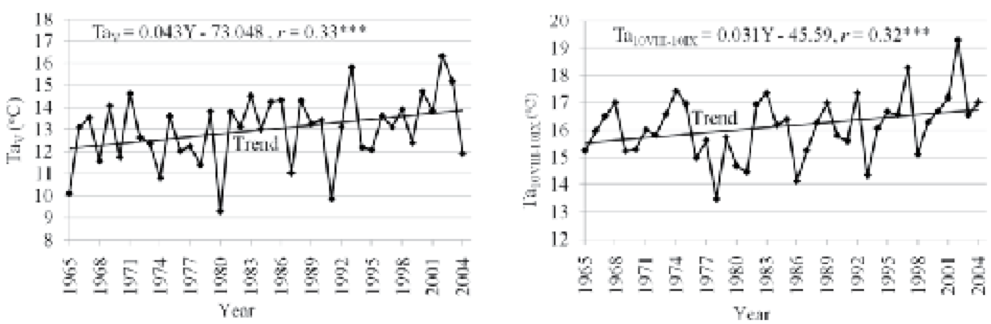
Since the second half of the 20th century in many places of Europe, changes of average phenological dates have been observed in both the world of wild-growing and crop plants (Ahas et al., 2002; Bonofiglio et al., 2009; Chmielewski et al., 2004; Menzel, 2000; Menzel & Estrella, 2001). The most frequently shown direction of change has been in the acceleration of phenological dates, especially in relation to spring and summer dates. The strongest acceleration of phenological dates has been observed since the end of the 1980s (Kalbarczyk, 2009a; Kalvāne et al., 2009; Schleip et al., 2009a). However, the size and direction of the changes of phenological dates is spatially diverse. In many research studies, acceleration of phenological dates has been confirmed mainly in the north-western part of the Europe, but

Period	Temperature (°C)						Absolute temperature (°C)	
	mean	highest	lowest	range[4]	S	trend (°C/10a)	max	min
May	13.0	16.3	9.3	7.0	1.5	0.4***	18.7	7.5
10th May-10th June	14.3	18.0	11.1	6.9	1.8	n.s.	19.7	9.2
20th May-20th June	15.0	18.5	12.7	5.8	1.4	n.s.	21.3	10.6
10th August-10th September	16.1	19.3	13.5	5.8	1.1	0.3***	20.5	12.5
May-October	14.3	15.7	12.9	2.8	0.7	0.3**	18.0	11.6

max – absolute maximum temperature, min – absolute minimum temperature, [4]between the highest and the lowest temperature. The remaining explanations see Tables 2 and 3.

Table 5. Statistical characteristics of the average air temperature in the growing season (May-October) of tomato, and in the periods significantly affecting agrotechnical dates and the dates of phenological phases in Poland, in the years 1965-2004.

also in Central Europe, in the Black Sea region, in the Baltic Sea region and around the Carpathians (Estrella et al., 2007; Kalvāne et al., 2009; Menzel & Estrella, 2001; Mozny et al., 2009). Delay of phenological dates according to Schleip et al. (2009a) has been observed in central Poland and in the Baltic Sea region. Delay of phenological dates, proved by research, mainly pertains to the autumn period, but in this case the direction of change is diverse, depending on the examined plant species (Gordo & Sanz, 2009).

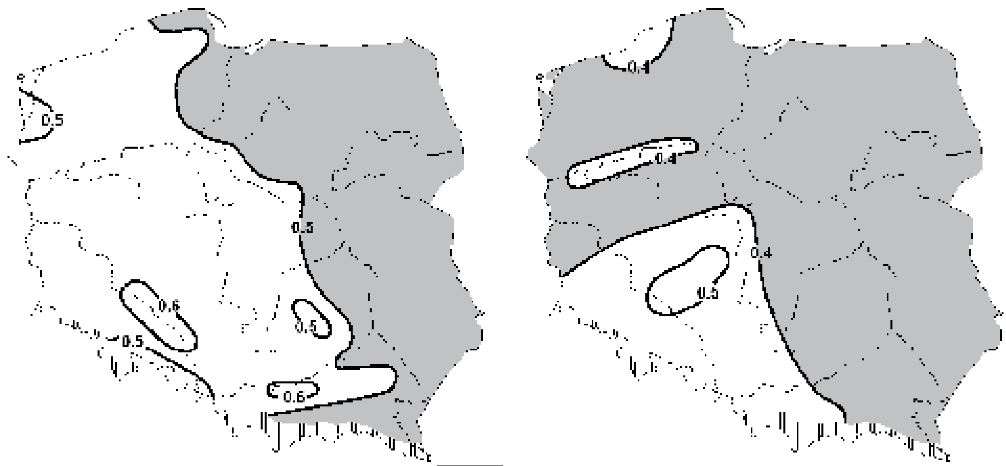


r – correlation coefficient, *** significant at $p \leq 0.01$.

Fig. 11. Temporal distribution of the average air temperature in May (Ta_V) and in the period 10th August-10th September ($Ta_{10VIII-10IX}$) in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

The observed changes most often oscillate from 1 to several days per 10 years, and less frequently – about a dozen days per 10 years (Fujisawa & Kobayashi, 2010; Tao et al., 2006). Acceleration of hop flowering observed in the Czech Republic amounted to -1.6 days/10 years (Mozny et al., 2009). In Germany changes of certain phenological dates of winter rye and fruit trees amounted to -2.0 to -2.9 days/10 years (Chmielewski et al., 2004). According to Estrella et al. (2007) in the multi-annual period 1951-2004, average acceleration of phenological dates of field plants and vegetables in Germany amounted to -1.1 to -1.3 days /10 years. In the Mediterranean region, changes of leaf unfolding, flowering and fruiting which had been measured since the mid-70s amounted to -3.2 to -5.9 days /10 years (Gordo & Sanz, 2009). A much bigger acceleration occurred in the case of wild-growing trees; in Lithuania and Latvia, European hazel flowering was accelerated by -1 to -11 days /10 years and alder bloomed earlier from -1 to -15 days /10 years (Kalvāne et al., 2009).

Ta_V $Ta_{10VIII\text{-}10IX}$



the area excluded from analysis, lack of significant influence at the level of $p \leq 0.05$

Fig. 12. Statistically significant, at least at the level of $p \leq 0.05$, linear regression coefficients for the trend of the average air temperature in May (Ta_V) and in the period 10th August-10th September ($Ta_{10VIII\text{-}10IX}$) in Poland, calculated for 10 years, in the years 1965-2004.

During the 40-year period of the present research, there was an acceleration of almost all phenological dates of tomato. This acceleration amounted to -0.6 to -3.5 days /10 years. The biggest acceleration concerned the dates occurring at the end of June and the beginning of July. Acceleration of dates of similar size was observed in Poland in relation to other vegetal and crop plants (Kalbarczyk, 2009a, 2009b). The results show that thermophilous vegetal plants cultivated in Poland are subjected to similar thermal conditions as plants cultivated in the western part of Europe. However, persistence of a negative trend for the tomato dates in June, over several years, can be evaluated as not very favourable. Cultivating tomatoes at too early a date is a risk because of the possibility of a late spring frost (Kalbarczyk, 2010b). In Poland the average date of occurrence of the last spring frost is marked by a negative trend (Koźmiński et al., 2010). However, such a trend was not confirmed for the absolute dates of frost occurrence. In Poland, the last spring frost may occur even at the end of June.

The above-mentioned possible delay of autumn phenological dates (Gordo & Sanz, 2009; Matsumoto, 2010), in the case of tomato cultivated in Poland, manifests itself by delay of the end of harvesting. In the examined multi-annual period, the end of harvesting was delayed by 2 days /10 years. The proved later course of some dates can be found in the research conducted in Spain, Japan and China (Gordo & Sanz, 2009; Matsumoto, 2010; Matsumoto et al., 2003; Tao et al., 2006). The degree of the observed delay was within a range of from 3.6 to as much as 21 days /10 years.

Changes of the phenological dates cause diverse duration of particular development stages of plants, and duration of the whole growing season (Liu et al., 2010; Moiseev et al., 2010; Mozny et al., 2009). According to research studies, the observed changes in duration of the growing period most frequently lead to lengthening, which can amount to about a dozen days (Kalvāne et al., 2009; Song et al., 2008). Lengthening of the growing period occurs in the case of an earlier beginning of spring and summer phenological dates and a later course of autumn phenophases. Lengthening of the growing season may even occur in the case of acceleration of all phenological dates. In the Baltic states, the growing season lengthened in spite of the recorded acceleration of both spring and autumn dates (Kalvāne et al., 2009). This lengthening was a consequence of a big dominance of spring acceleration over autumn acceleration. In the 31-year research period, the growing season of wild-growing trees in Lithuania and Latvia lengthened by 7 days (Kalvāne et al., 2009). Lengthening of the growing season by 8% (18 days) was also confirmed in the Mediterranean region (Gordo & Sanz, 2009). The cause of this lengthening was also mainly the acceleration of the spring phases.

The duration of the particular developmental stages of plants underwent more diverse changes. A year by year shortening in the duration of the spring and summer development stages is observed most frequently. However, extreme differences occur which depend on: development stage, kind of plant, and the area of its cultivation or occurrence. In Germany, significant shortening of the period from sowing to emergence of maize was found to be, on average 1.6 days/10 years (Chmielewski et al., 2004). However, duration of the remaining part of maize growth and development, i.e. from emergence to the beginning of harvesting, lengthened, on average, 2.1 days/10 years. Significant lengthening of development stages was also proved for the period from the beginning of stem elongation to the beginning of heading of winter rye, and the beginning of row closing to the beginning of harvest of sugar beet. The degree of lengthening amounted to 1.0 day/10 years for winter rye and 1.2 days/10 years for sugar beet (Chmielewski et al., 2004). In Poland, negative trends in the duration of some development stages were proved for, e.g., onion, medium-early potato and medium-late potato (Kalbarczyk, 2009b, Kalbarczyk E. & Kalbarczyk R., 2010). A significant shortening of duration for two onion periods was also proved. For the period from sowing to the end of emergence, shortening amounted to -1.7 day/10 years; for the period from the end of emergence to the beginning of leaf bending it amounted to -0.7 day/10 years. Similar results were obtained for potato. Medium-late potato cultivars were characterised by a shortening of the period from emergence to flowering by -1.7 days/10 years. For medium-early potato cultivars, shortening of the period from haulm drying to harvesting was -0.8 day/10 years. On the other hand, for both groups of potatoes, the period from flowering to haulm drying lengthened by about 2-3 days/10 years (Kalbarczyk E. & Kalbarczyk R., 2010). In the case of tomato, in the years 1965-2004, only the period Bfs-Bh became significantly shorter; on average by -1.4 days/10 years. However, an opposite tendency was seen in the case of the period from the beginning of harvesting to the end of harvesting of the plant. The period from the beginning of harvesting to the end of harvesting, on average, lengthened by as much as 5.6 days/10 years. Changes in the duration of particular tomato development stages caused the whole season, which lasts from planting up to the end of harvesting, to lengthen by 2.6 days/10 years. It seems that a longer period of tomato harvesting creates the possibility of achieving a bigger yield of the plant.

The conducted research confirmed that, in the case of tomato, like the majority of plants (Craufurd & Wheeler, 2009; Morin et al., 2010; Schliep et al., 2009b), changes in the course of tomato phenological dates and in duration of tomato development stages are significantly dependent on changes in air temperature. The relationship between tomato growth and

development and temperature was confirmed in the research by Bojacá et al. (2009) and van der Ploeg & Heuvelink (2005). All phenological and agrotechnical dates of tomato considered in the present study, were significantly dependent on air temperature. The first three dates: Bf, Bfs, Bh, were negatively correlated with air temperature, and the last considered date, Eh, was positively correlated with air temperature. The degree of change in the tomato phenological date, caused by a 1°C temperature change, amounted to 1.8 to 3.1 days. Similar reactions were observed in other crop plants in Poland and Germany (Chmielewski et al., 2004; Kalbarczyk E. & Kalbarczyk R., 2010). A statistically confirmed air temperature increase in May and in the period from 10th August to 10th September amounted to, respectively, 0.4°C/10 years and 0.3°C/10 years. In southern Poland, the temperature trend in May amounted to as much as 0.6°C/10 years. The obtained results are similar to those described in different parts of Europe (Bauer et al., 2009; Bonofiglio et al., 2009; Chmielewskiet et al., 2004; Kapur et al., 2007; Saue & Kadaja, 2010) and the world (Lobell et al., 2007; Song et al., 2008; Wang et al., 2008).
Air temperature may affect the quantity and quality of the yield directly and indirectly (Tshiala & Olwoch, 2010). Indirect influence of air temperature is seen through the proven effect on the rate of growth and development of plants. The present work confirms changes occurring in the course of tomato development in Poland. However, there are no clear observations corroborating an increase or decrease in tomato yield occurring from this cause.

5. Conclusions

An increase, by 0.3°C /10 years, in average air temperature in the growing season of tomato (May-October), contributed to the changes of not only the dates of phenological phases and development stages but also to the agrotechnical dates of the plant. In the years 1965-2004, important changes in temporal distribution of all the considered dates were noted, and of the period duration from planting up to the end of harvesting. In Poland, the growing season of field-cultivated tomato lengthened by 2.6 days /10 years, which resulted both from acceleration of the dates of: planting up (-0.6 day /10 years), flowering (-0.7 days /10 years), fruit-setting (-1.1 days /10 years), the beginning of harvesting (-3.5 days /10 years), and delay of the end of harvesting date (2.1 days /10 years). The biggest changes in the development of the tomato were recorded in the fruiting period - from the beginning to the end of harvesting, which for the whole country, on average, lengthened by 5.6 days / 10 years. However, in Poland this lengthening was not even, as it fluctuated from less than 1.5 days /10 years in the northern, north-eastern and central-eastern parts of the country, to above 2.5 days /10 years in the southern part.
An increase, by 1°C, in the average air temperature during the periods which significantly affect the dates of tomato caused acceleration of: the beginning of flowering by 1.8 days, the beginning of fruit-setting by 2.2 days, the beginning of harvesting by 3.1 days and delay of the end of harvesting by 2.1 days. During the 1965-2004, 40-year research period, deviations from the multi-annual average of the agrotechnical dates and duration of tomato development stages were discovered. These deviations were a result of the change in thermal air conditions. The date of the beginning of harvesting differed most from the average date in 1965, and the date of the end harvesting differed most from the average date, in the years: 1978, 1997 and 2002. Positive deviations from the norm of agrotechnical dates in Poland, oscillated from less than 4 to more than 8 days, in the years 1965 and 2002,

and from less than 2 to more than 6 days in 1997. Negative deviations from the norm of agrotechnical dates in Poland, oscillated from more than 6 to less than 8 days, in 1978. The length of the period from the beginning of harvesting to the end of harvesting differed most from the multi-annual average in 2002, and the length of the period from planting up to the end of harvesting in 1978 and 2002. The highest deviation from the norm, for the duration of the period from the beginning to the end of harvesting, amounted to more than 14 days, and occurred in the central-west and in the Warsaw region.

Changes in the course of tomato development found in the present work do not lead to evident changes in cropping of this plant. However many things indicate, that the occurring changes may improve the conditions of tomato field-cultivation in Poland, in the future. According to the IPCC report (2007), it is predicted that as a result of climate change the yield of crop plants in central Poland will decrease on average by 5%. On the other hand, there are forecasts of an increase in the yield in the north by 5% and by 30% in the submontaineous regions. The changes in the yield quantity will vary depending on a type of plants. The highest yield increase, by several dozen per cent, is predicted for thermophilous plants, which will result from increased thermal resources.

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16

Economic Impacts of Climate Change on Agriculture: Adaptation and Vulnerability

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1. Introduction

It is well known that agriculture is vulnerable to climate change because agricultural industries are strongly affected by climate conditions (see the summary treatment in Intergovernmental Panel on Climate Change [IPCC], WGI, 2007). Production conditions are directly influenced by temperature, precipitation, storms, and droughts along with the plant growth stimulating effects of carbon dioxide (CO_2). They are also indirectly affected by climate induced alterations in market prices, incidence of pests and diseases, forest fire, and invasive species plus water supply.

Agricultural impacts have been found to vary by region. For example, at higher latitudes, crop productivity tends to increase when temperature increases in the range of crop heat tolerance and away from ranges where cold depresses production; however, in lower latitudes, temperature increases often have a negative effect on crop productivity (IPCC, WGII, 2007). Alterations in climate will further affect livestock production since it alters fecundity and appetite plus the changes in crop yields and forage growth rates directly influence feed availability.

It is extremely likely, in fact virtually inevitable that agriculture will need to adapt to climate change (IPCC, WGIII, 2007; Rose & McCarl, 2008). The momentum that society exhibits in terms of greenhouse gas emissions largely arising from the interrelationships of economic activity and energy use coupled with the lack of real progress on reducing emissions makes it likely that a substantial degree of climate change will be realized before greenhouse gas concentrations peak and begin to drop as indicated by table 3.5 in Chapter 3 of IPCC, WGIII (2007).

Given these motivations, in this chapter we review knowledge on agricultural climate change vulnerability and potential means to reduce sector vulnerability through adaptation.

2. Nature of agricultural vulnerability

Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, WGII, 2007). In agriculture, vulnerability involves more than the biophysical impacts of altered temperature and precipitation. It also affects prices and markets for crops or livestock produced along with interregional comparative advantage and international trade patterns (Reilly et al., 2001; Wehbe et. al., 2005).

2.1 Production vulnerability

The production vulnerability of agriculture is related to a variety of interacting factors, including changes in temperature, rainfall regimes and water supply, frequency of occurrence of extreme weather events including droughts and storms, plant responses to CO_2 concentrations, climate induced changes in pest incidence, soil fertility, sea level induced inundation of lands, and adaptive adjustments in planting dates, crop mixes and other management factors. Some of these factors directly affect agricultural productivity, e.g., temperature, precipitation, droughts, rainfall and CO_2; while others influence the productivity indirectly, such as water supply, soil fertility and pests.

2.1.1 Factors causing vulnerability

The factors causing vulnerability as listed above are discussed in the subsections below.

2.1.1.1 Changing temperature

Changes in temperature can alter crop yields and water use. The effects vary across types of crops and locations. In general, rising temperature increases crop productivity at higher latitudes while the effect is negative at lower latitudes. In addition, some crops like cotton and sorghum are well adapted to warmer conditions and thus can gain in relative or absolute yield. This was found in the 2001 US national assessment (Reilly et al., 2001, 2002).

2.1.1.2 Precipitation and water supply

Agriculture is highly dependent on water. Irrigation uses an estimated 69% of global water with roughly 15-35% of irrigation withdrawals are unsustainable (World Business Council for Sustainable Development [WBCSD], 2009).

Climate change effects on water are projected to vary across the globe (IPCC, WGI, 2007). The IPCC shows a projection with a general mid-latitude drying coupled with a high-latitude wettening. Some countries, such as Africa, New Zealand, Australia, and Latin America, are expriencing reduced precipitation and increased evaporation raising water security problems. Changes in water seasonality are also expected where for example rising temperatures increase the proportion of winter precipitation received as rain and decrease the proportion arriving in the form of snow. This in turn decreases the amount of time that snow stores water and thus the hydrograph of runoff with less in the summer and more in winter/spring/fall (US Climate Change Science Program [USCCSP], 2008). The effect is regionally heterogenous where for example, Central and Eastern Europe will have a higher water stress because of the decrease of summer precipitation, while Asia might confront an increase flooding risk induced from glacier melt in the Himalayas (IPCC, WGII, 2007).

Water supply and in turn the availability of irrigation water for agriculture could be affected by climate change in the following ways:

- Altered precipitation alters water runoff into surface water and infiltration into groundwater, thus affecting water stored behind dams or in aquifers;
- Higher temperatures and altered precipitation influence consumption by vegetation in watersheds altering run-off;
- Heat waves increase water demand by crops increasing respiration and evapotranspiration and irrigation requirements (Adams et al., 1999; McCarl, 2006; Adams & Peck, 2008);
- Climate change may alter vegetative mix in water sheds further influencing run-off;
- Higher temperatures increase evaporation loss from lakes, rivers, and reservoirs;

- Altered seasonal water availability will cause shifts in crop timing and species;
- Diminished supplies will mean less dilution and in turn cause pollutants and salts emitted into rivers and streams to be a greater problem rendering water less suitable for agriculture and putting greater pressure on agricultural water use and runoff (Thompson, 2005; IPCC, WGII, 2007);
- Precipitation alteration may contribute to yield variability. Campbell et al. (1997) argue that it is the cause of 90% of the variance in primary production of grassland systems.

Precipitation patterns are likely to shift in intensity. IPCC, WGI (2007) presented data showing that between 2001 and 2005 we observed an ever greater proportion of precipitation coming from the wettest days of a month. In addition, significant heavy-precipitation events have increased over the past several decades, and most intense precipitation usually occurs in warm regions (Easterling et al., 2000). This indicates a shift in precipitation shares from gentle frontal rains to more intense events which is a condition that is less suitable for agriculture. Several studies project increasing heavy precipitation events in the future over most regions (USCCSP, 2008, as cited in Kharin & Zwiers, 2005). Shifts in extreme precipitation events happen across regions within countries. For example, the incidence of heavy precipitation events has increased in north-eastern and south-eastern Australia as well as decreased in south-western Australia (Suppiah & Hennessy, 1998).

2.1.1.3 Increased frequency of extreme weather events

Projections indicate that climate change will cause extreme weather events to become more frequent, more widespread and/or more intense (IPCC, WGI, 2007). Altered frequencies and intensities of events like floods, droughts, heat waves, cold waves, tropical storms, hurricanes, and storms, are likely to have wide-ranging impacts on agricultural productivity. Besides, the hydrologic cycles are projected to intensify such that floods and droughts will become more severe in low- to mid-latitude regions and further alter seasonal water availability and the need for impoundments (McCarl & Reilly, 1999).
Extermes have been observed, for example,

- Europe suffered from a heat waves in 2003 with an estimated 14,800 excess deaths occurring (Haines et al., 2006) while the world had the warmest August in this period (National Oceanic and Atmospheric Administration [NOAA], 2003).
- Murray-Darling Basin in southeastern Australia, which supports 41% of Australian agriculture activities and 85% of the irrigation, has suffered from harsh droughts in the 2000s while, since the end of 2010, there have been large flood disasters in Queensland and Victoria induced by possible climate change forces along with tropical cyclone Tasha and a La Niña year (National Aeronautics and Space Administration [NASA], 2011).

Projections for future changes in extremes are as reviewed in the US Climate Change Science Program report (2008):

- In North America, droughts, floods or extreme heat are likely to become more frequent or severe in some regions to human-caused climate change.
- The intensity and frequency of hurricanes/typhoons are projected to increase by 1 to 8% and 6 to 18%, respectively. Some existing studies have attributed part of the increase to climate change (Mann & Emanuel, 2006; Trenberth & Shea, 2006; Anthes et al., 2006;

USCCSP, 2008). Hurricanes depress crop yields and reduce the total net welfare (Chen & McCarl, 2009).

- More intense and frequent El Niño-Southern Oscillation (ENSO) events and other large-scale climate circulation patterns such as the Pacific Decadal Oscillation (PDO), and the Northern Annular Mode (NAM) have occurred since the late 1970s and appear to influence climate extremes. Timmermann et al. (1999) forecasted increased intensities and frequencies of the cold and hot ENSO phases which in turn would likely increase the intensity and frequency of extreme events.

More information about the impacts of climate change due to extreme events can be found in Table 1.

2.1.1.4 Changing CO_2 concentrations

Since the mid-20th century most of the observed increase in global average temperatures is very likely (>90%) owing to the observed increase in anthropogenic greenhouse gas (GHG) concentrations (IPCC, WGI, 2007). CO_2 is one of the most important anthropogenic GHGs. CO_2 concentrations are not only one of the drivers of climate change but also a growth simulating factor. Analyses in Adams et al. (1990) show that this is a key item to consider as ignoring it leads to impact estimates that are substantially more damaging.

2.1.1.5 Soil fertility and water holding

Soil fertility and soil water holding capacity is affected by climate change. Temperature increases combined with precipitation increases will likely reduce the water-holding capacity and organic matter content of soils, leading to erosion and consequently to an increase in the magnitude of soil nutrient losses and water stresses. Given a constant water supply increases in temperature decreases soil moisture at a nonlinear rate and would need to be offset by precipitation increases and/or expansions in irrigation. In addition, organic matter can be negatively affected as microbial decomposition is stimulated by warmer temperatures. In turn this lessens orgainc matter which is key to the ability of the soil to retain nutrients and moisture. Soil managment may in part overcome this as Luers et al. (2003) indicate better managed soils are less vulnerable to changing climate, irrespective of the soil type.

2.1.1.6 Pest incidence

Climate conditions are likely to exacerbate pest problems, such as expanding pest ranges and management costs (Chen & McCarl, 2001; Gan, 2004; IPCC, WGII, 2007). For instance, more than 1.2 Mha of pinyon pine mortality occurred due to extreme drought, coupled with a beetle outbreak in the southwest of US (Breshears et al., 2005). Chen and McCarl (2001) indicate that US pesticide use is projected to increase for most crops in most states under the climate scenarios although non chemical means such as host resistance, tillage, IPM and other items may increase as well and possibly substitute. Increased pesticide use could cause some substantial water quality and other environmental problems.

2.1.1.7 Animal and crop diseases

Animal and crop diseases are likely to increase with earlier springs and warmer winters, which create favorable conditions for higher survival rates of pathogens and parasites. Owing to climate change, previously rare diseases may become more prevalent. For example, Mu (2009) finds that spread of Avian Influenza, is positively correlated with increased temperatures while Egbendewe-Mondzozo et al. (2011) find that malaria spread is

Phenomenon and direction of trend (Likelihood of future trends)	Examples of major projected impacts by sector			
	Agriculture, forestry and ecosystems	Water resources	Human health	Industry, settlement and society
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights (Virtually certain)	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snow melt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increases over most land areas (Very likely)	Reduced yields in warmer regions due to heat stress; increased danger of wildfire	Increased water demand; water quality problems, e.g., algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially-isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor
Heavy precipitation events. Frequency increases over most areas (Very likely)	Damage to crops; soil erosion, inability to cultivate land due to water logging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases (Likely)	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases (Likely)	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers, potential for population migrations, loss of property
Increased incidence of extreme high sea level (excludes tsunamis) (Likely)	Salinisation of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

Note: Table based on IPCC, WGII, 2007, Table SPM-2. The descriptions of likelihood of future trend refer to a probabilistic assessment and the associated probability measures are listed as follows: virtually certain, greater than 99% chance; very likely, 90 to 99% chance; likely, 66 to 90% chance. More details in IPCC, WGII, 2007.

Table 1. Examples of possible impacts of climate change due to changes in extreme weather and climate events.

correlated with climate change. Another example is the expected rise in cattle ticks that carry blood pathogens to non–immune cattle. According to the final report by the Allen Consulting Group (2005), the estimated potential impact (without adaptation) of cattle ticks rise in Queensland and New South Wales (NSW) could range from between $18 million to $192 million, depending on the discount rate used. Also, plant disease pressure may also increase (USCCSP, 2008).

2.1.1.8 Fires

Disturbances from forest, grass and crop fires have important consequences for grassland production, timber production, species composition, infrastructure and public perception. Increased temperatures in spring and summer, earlier spring snowmelt, dieing vegetation and altered woodland growth have been found to be associated with increased fire risk (Westerling et al., 2006; Rapp, 2004). Since climate change will exacerbate forest fire on a regional basis, new fire and fuels management strategies may be needed to manage such fire risks (Brown et al., 2004).

2.1.1.9 Sea level induced inundation

Sea level rise and associated innundation of agricultural lands can be a serious threat. The rate of sea level rise has been accelerating with the 100 year average 1.8 mm per year and the 1993-2003 periods showing an average of 3.1 mm per year (Douglas, 1997; Church & White, 2006; Bindoff et al., 2007). Some predict yet larger rates for the future. For instance, Dasgupta et al. (2009) project 1 to 3 meters but also suggest as much as 5 meters is possible if the unexpected rapid breakup of the Greenland and West Antarctic ice sheet occurs while Hansen (2007) suggests up to a 5 meter rise is possible and Hansen and Sato (2011) argue for a nonlinear, rapid response later in the century.

The effect from sea level rise induces agriculture and the global food market vulnerable. Dasgupta et al. (2009) show substantial land loss in Southeast Asia, East Asia, South Asia, and the Southeast US. Chen et al. (2011) estimate the economic impacts of sea level rise in terms of rice production showing substantial regional effects on the rice market.

2.1.2 Productivity implications

The above forces have been shown or simulated to affect productivity of crops, livestock and forest. For the effects of climate drivers on crops, in general northern regions in US have positive yield changes, while southern regions increase less or even decline in some cases (Reilly et al., 2002; McCarl, 2006; Antle, 2009). Productivity of livestock is directly influenced through climate stress and indirectly impacted through pasture growth, forage production and grain availability (Seo & Mendelsohn, 2008a, 2008b). Besides, forest production is affected by the interaction of temperature, precipitation, nitrogen and CO_2.

2.1.2.1 Crop productivity

The effect of climate change on crop production is expected to vary by crops and regions owing to regional climate and resource conditions (Adams et al., 1998; Lewandrowski & Schimmelfennig, 1999; Reilly et al., 2001). At the national level, productivity of many major crops is likely to increase under the climate scenarios (National Assessment Synthesis Team [NAST], 2000). Although more frequent and/or severe extreme events, e.g., droughts and floods, cause agriculture to be more vulnerable with the increasing agricultural losses, concentrations of CO_2 tend to overcome much of the climate-altered yield dampening effects (Adams et al., 1995).

The crop productivity effects of changing climate, such as increasing temperature and possibly drier conditions has been extensively studied using crop simulation models and econometric methods. Both the mean and variance of crop yields in a crop specific fashion are expected to be modified by changes in climate (Chen et al., 2004; Kim & Pang, 2009). Moreover, the effects of CO_2 concentrations have been evaluated through FACE (Free-Air Concentration Enrichment) experiment and other experiments (Kimball et al., 2002) and then built into simulation models.

2.1.2.2 Livestock productivity

Hotter temperatures can alter animal mortality, feed conversion rates, rates of gain, milk production, conception rates and suppress appetite (Hahn, 1995, 2000; Mader et al., 2009; Adams, 1998) although again on a regional basis. Mader et al. (2009) review evidence that temperature increase will have negative effect on milk production in the central United States, while in northern areas swine producers may gain some benefit to climate effects and beef producers would need to feed cattle up to 16% longer with more common average increases of 4% to 5%. Extreme events are also important, for example, the heat waves of 1995 and 1999 caused severe documented cattle losses in individual states in US approaching 5,000 heads each year (Hahn et al., 1997, 2001).

Livestock will also be affected by climate influences on availability and quality of feed (Easterling et al., 1993; Ehleringer et al., 2002; Morgan et al., 2005). Swine and beef production are found to be affected most in the south-central and southeastern United States and dairy production is expected to be influenced the most in the mid-west and north-east regions (Frank et al., 2001). Forage production will be altered as climate alters grass growth (Reilly et al., 2002). Also higher concentrations of CO_2 could alter forage chemical content, nutritional value and digestability (The Allen Consulting Group, 2005; Adams et al., 1998).

2.1.2.3 Forest productivity

Climate change alters forest productivity. Increases in temperature, precipitation, nitrogen deposition and atmospheric CO_2 can raise forest growth and carbon storage (Irland et al., 2001). Sohngen et al. 2001 indicate climate change is predicted to increase global timber production. Producers in low-mid latitude forests react quickly with more productive short rotation plantations and drive down timber prices. Contrarily, because of long-rotation species, it is likely that producers in mid-high latitude forests are hurt by the lower prices, dieback, and slower productivity increases. On the other hand, carbon sequestration is an important characteristic of forests. Currently long-lived wood products offset about 20 percent of annual US fossil fuel carbon emissions (USCCSP, 2008). This carbon sequestration mitigates future climate change.

2.2 Economic vulnerability

Climate change potentially increases economic vulnerability of agriculture in a number of ways including altering the contribution of agriculture to the overall national economy, comparative advantage relative to other countries or regions, welfare distribution, and market prices (Fischer et al., 2002; McCarl et al., 2010).

In terms of extreme events, Chen et al. (2001) estimated the economic damages and the welfare change from Timmerman et al.'s projections of stronger and more frequent ENSO events. They found that the frequency shift caused the aggregate economic welfare loss while the frequency and strength shifts caused substantially larger damages.

2.2.1 Contribution of agriculture to the overall national economy

Since agricultural production is highly affected by climate, then countries with a higher proportion of agriculture in gross domestic product (GDP) have economies that are more likely to be vulnerable to climate change. This proportion in developing countries is about 13%, compared with 2% in developed countries (Fischer et al., 2002). Agriculture plays an important role in developing countries, such as Asian-Pacific region. For example, the share of agriculture in GDP in Thailand is 20%. Earning from exports of agricultural products occupies about 70% of the substantial foreign exchange earnings in Philippines (Luo & Lin, 1999). China produces the largest agriculture output in the world, but only about 15% of its total land area are arable, which causes the highly vulnerability of China's agriculture. In China meteorological disaster has become a major factor limiting the growth of grain production. During the period of 1996-2003, loss of grain production from meteorological disasters reached 50.9 million tons a year (Li & Lin, 2007). Another major agricultural producer, US, accounts for more than 25% of the total global trade in corn, soybeans, wheat, and cotton. The projection results show that the effect of climate change on agricultural production varies across the types of crops (NAST, 2000).

2.2.2 Comparative advantage shift

Changing climate is likely to alter agricultural production but on regionally specific bases. Regions near the equator where production is limited by heat may reduce production while higher latitude regions where production is limited by cold may gain. This will affect interregional agricultural production and trade patterns plus interregional comparative advantage, both within countries and internationally (Reilly et al., 1994; Darwin et al., 1995). Such shifts has been found in a number of settings. For example Adams et al. (1990) and Reilly et al. (2000) perform modeling studies that find such shifts in the US while Mendelsohn et al. (1994) show shifts in land values and Seo et al. (2010) show shifts in land use.

2.2.3 Welfare distribution

When assessing agricultural vulnerability, two major groups who are potentially vulnerable to changing climate are producers (e.g., farmers, retailers and people working in ancillary agro-industries) and consumers (e.g., who consume agricultural goods and/or agricultural services). Due to lower adaptive capacity, smaller farms are more vulnerable to climate change than larger farms. For instance, in Europe, more and more large farms grow at the cost of small farms. Consumers benefit from the process of fewer smaller farms since prices of agricultural products are lower than before (Adams et al., 1990; Berry, 2006).

A number of studies have conducted welfare assessments on the effects of climate change. In earlier studies, the total welfare change from climate change was found to be negative, but this effect has tended to be less and even beneficial over time, which is partly due to milder temperature and precipitation estimates emerging from the global circulation models, treatment of CO_2 fertilization effects, and inclusion of adaptation alternatives (Adams et al., 1990, 1995, 1999; McCarl, 1999, 2006; Reilly et al., 2001). Different from the results in Berry (2006) and Mendelsohn et al. (1994), US agricultural studies considering market price adjustments have found reductions in crop productivity induced by climate cause rising prices and turn out to be harmful for consumers and beneficial to producers.

2.2.4 Market price of agricultural commodities and inputs

Climate change affects agricultural production through the variability of commodity prices and input costs that determine one country's comparative advantage in international markets. Adams et al. (1995) present the importance of market-level changes using estimated wheat yield changes from the research by Rosenzweig et al. (1995) for the US. Market prices are likely to shift and stimulate production mix and other adjustments (McCarl, 2006). What's more, the interaction between climate change, CO_2 level, adaptation, and economic conditions such as relative output prices determines the relative and absolute measures of vulnerability (Antle et al., 2004).

2.3 Reallocation of land use

Climate change will cause alterations in land. Humans change their land use from crops to pasture because of adaptation of drought (Mu & McCarl, 2011). Droughts, and excessive grazing cause grassland degradation and desertification. Irrigated crop land expands substantially if water is available as irrigation allows adaptation to the hotter and drier climate (Adams et al., 1999).

Land competition is also induced by adaptation or mitigation policies against climate change. For example, alternative energy is proposed as a response to climate change. However, the excess demand of crops promotes the rising of global crop prices which induce the incentive to Brazilian agricultural producers to increase deforestation and expand the scope of tillage (Searchinger et. al., 2008).

3. Adaptation to climate change

As shown above agriculture is vulnerable to climate. However by its very nature agriculture has historically adapted to climate. There is also an inevitability of a substantial degree of climate change due to the energy emission development linkage plus the projected growth of population and income (Antle, 2009; IPCC, WGII, 2007; Rose & McCarl, 2008). Adaptation is the inveitable response to such developments. It seeks to maintain the current productivity even under climate change by using adaptation strategies such as change of planting dates, crop mix, and livestock feeding management, or migration strategies (Adams et al., 1999; Reilly et al., 2002, 2003).

3.1 Means of adaptation

A variety of adaptation options are available. They may be privately or publically implemented. Private or autonomous adaptation to climate change (IPCC, WGII, 2001; Smit et al., 2000) occurs by the people who produce agricultural goods, and manage the land, trees, waterborne transport, water facilities, and other capital resources related to the production. Those are able to select to alter their management practices, crop mix, and other strategies. These adaptation behaviors are referred to as "autonomous adaptation" in that most of them can be made without governmental intervention.

Planned or public adaptation is made by governmental interference. This adaptation is often addressed in the case unlikely met by autonomous actions because of the existence of externalities and/or the needs for large scale and resource requirements. Both of them are not mutually exclusive and the planned adaptation can increase the possibility of autonomous adaptation in the way of education, subsidies, and other regulations.

Both private and public actions to facilitate adaptation to changing climatic conditions can be pursued by different parties at different levels of operation and forms, the features of which have different investment needs. Some of the adaptation strategies would go further without demanding direct investment but several of them would need some mix of capital and research investments with information and technology dissemination. The degree of needs for agricultural adaptation depends on the level of mitigation, anticipated potential local climate change, capacity to adaption, and relative effects with other sectors (Rose & McCarl, 2008).

3.1.1 Means of private adaptation

Private, autonomous, or market adaptation decisions are made by individuals, households, and businesses. In managed systems, they react to the climate alterations through changing such things as planting and harvesting date, varieties, crops grown, species, etc. For instance, the private decision makers can adjust insurance premiums, and air-conditioning as human system adaptation against the altering climate (Klein et al., 1999). Other common strategies of private adaptation include altering the management or practice of crop, forage and tree varieties, livestock breeds and species, soil moisture, pest and disease, natural area, fire, and land use.

3.1.2 Means of planned adaptation

Planned adaptation including facilitation of autonomous ones, as carried out by governments, international organizations, and NGOs. Such actions can have a significant impact on the increased public related investments. A number of possible strategies can be pursued including the following as summarized from McCarl (2007).

3.1.2.1 Research and extension investment

Public investments on research and extension can provide and disseminate adaptation strategies that could be implemented by individual agricultural producers. Public investments would need to go into adaptation increasing technology and adaptation information dissemination designed to help private level implementations.

3.1.2.2 New infrastructure

Investment for the planned adaptations to climate change may need to address providing or altering transport and municipal infrastructure, developing new lands, improving of existing lands, constructing irrigation/water control structures, protecting coastal resources, incubating of new industries, and other possible facilities.

3.1.2.3 Adaptation adjustment assistance

Migration of facilities and land uses may be required to adapt to climate change. Needed would be the investments on supporting the new industries, creating job opportunities, assisting incomes, developing new institutions, relocating industry, improving market functions, developing insurance, and others.

3.1.2.4 Trade policy

Governments may facilitate adaptation by modifying trade policies to allow imports and exports to alleviate lost production and cope with surpluses by lowering the international trade barriers.

3.2 Limits to adaptation

IPCC, WGII (2001) identified six determinants that will influence the degree of adaptation: economic resources; technology availability; information and skills; infrastructure;

institutions; and equity. There are also relevant affecting factors: degree of realized climate change; the amount of public and private investment undertaken; asset obsolescence; generated research findings; information availability and producer flexibility. Furthermore, the change of the regulations may change the ability of adaptation in agriculture. For example, implementing the GHG cap and trade policy may allow agricultural industry to provide alternative energy sources as opportunities for improving income.

The availability of the affecting factors is very diverse across nations. For instance, differences in the agricultural technology research and investments would differ the degree of adaptation. A country might choose the other economic investments rather than the agricultural technology and hence linger the improvement of food production in spite of the large demands for food security (Pardey et al., 2006a; Pardey et al., 2006b; Roseboom, 2004).

3.3 Findings about effectiveness and extent of adaptation

Literatures on adaptation are now emerging and diverse but deal with merely partial issues. Moreover, they do not fully address the potential and the constraints of adaptation along with the costs since adaptation measures are often narrowly studied in small regions thanks to geographical and climate factors as well as institutional, political and financial constraints (IPCC, WGII, 2007). Here are some research findings of analyses of adaptation to climate alterations.

- Cropping system management adjustments can deal with projected climatic and atmospheric changes (R. M. Adams et al., 2003; Butt et al., 2005; Challinor et al., 2007; Easterling et al., 2003; Travasso et al., 2006).
- Tubiello et al. (2000) examine crop adaptation in Modena, Italy and find that currently there are adaptations of varieties and planting times that avoid drought and heat stress during the hotter and drier summer months. Furthermore they show that these adaptations have avoided significant negative impacts on sorghum (-48 to -58%) moderating them to be neutral to marginally positive ones (0 to +12%).
- IPCC, WGII (2007) provides evidence on the benefits of adaptations which alter crop productions on temperature changes across regions. It estimates approximately a 10% yield benefits from adaptation comparing to yield with no adaptation.
- Crimp et al. (2008) find that benefits of adaptation would be diminished by increasing temperature.
- Parry et al. (2009) provide an estimate that there will be a needed $8 billion in costs for adapting crop irrigation systems to climate change by 2030.
- McCarl (2007) assumes adaptation will require a 10% increase in research and extension funding and a 2% increase in capital infrastructure costs and develops global marginal estimates for additional funding for adaptation of the agricultural sector due to climate which are $12.6 billion and $11.3 billion – without and with mitigation, respectively, in the year 2030.
- Changes in tree harvesting rates, composition of species, pest control, and location of managed woodland could result from the adaptation of unmanaged forest (Parry et al., 2009).
- Adaptation in forest is a complementary strategy with mitigation of greenhouse gas emissions (Parry et al., 2009).
- Sohngen et al. (2001) find that producers in low-mid latitude forests can adapt with more productive short rotation plantations, driving down timber prices.

- Many studies have discussed the necessity of adaptation in water management system but they do not take account of the feasibility of adaptation options (Hayhoe et al., 2004; Hurd et al., 2004; Mote et al., 2003; Roy et al., 2001).
- Adaptive strategies to deal with climate change are beginning to be considered in conservation of ecosystems (Chopra et al., 2005; Lemieux & Scott, 2005), and have emphasized the importance of planning guided by future climate scenarios (IPCC, WGII, 2007).
- Competition among land use is a big issue in agricultural adaptation (Hertel et al., 2009). As one of the results from land use competition, Fischer et al. (2002) expect that globally there will be major benefits from agricultural land by 2080, specifically in Russian Federation (40-70%) and North America (20-50%), but losses of up to 9% in sub-Saharan Africa.
- Adaptation is regionally specific and capacity to adapt varies. Consequently equity and burden sharing are an issue. It is likely that highly vulnerable developing countries have lower adaptive capacity due to lower per capita incomes, weaker institutions, and less access to technology, credit and international markets (Burton et al., 2006; Green et al., 2010).
- Climate variability can play a significant role in changing the cropping system productivity (Porter & Gawith, 1999; Wheeler et al., 2000).

4. Concluding comments

As reviewed above agriculture is vulnerable to climate change. This will stimulate a wide array of climate change adaptations plus public efforts facilitating adaptations. The following list contains a few of the unresolved issues in need of further studies in agricultural adaptation.

- The distribution of positive and negative impacts from climate change is uneven depending on the regions. Parry et al. (2009) argue that the positive effects would happen in agriculture at the higher latitudes unlike the more immediate negative impacts at the lower latitudes. They emphasize the needs of studies on balancing different parts of the world and over a range of time projections in a complex environment.
- Adaptation and development costs will be dominated by other changes like population growth (McCarl, 2007). However, there are many intrinsic links between increases in productivity and resilience to climate (Parry et al., 2009).
- Producers and processers in agriculture will be required to adapt to altered variability in patterns of rainfall and temperature including alterations in extremes. Parry et al. (2009) argue that adapting to this altered variability is a significant challenge.
- Competition will occur between food, energy, adaptation and mitigation in terms of resources and funds.
- The optimal degrees of adaptation and practical levels of the extent to which climate change vulnerability can be addressed needs examination.
- Understanding of the process in which adaptation is taking place and the future limits plus needed institutional innovation is needed (IPCC, WGII, 2007);
- Further studies need to address means for adapting existing crops and livestock, moving varieties of heat tolerant crops and livestock breeds into regions, and altering management (Antle, 2009; McCarl, 2006).
- Examinations of the levels of investment required for adaptation are needed.

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Sensitivity of Mexico's Farmers: A Sub National Assessment of Vulnerability to Climate Change

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1. Introduction

In ecology and systems theory, sensitivity refers to the ability of an environmental system which deals with stress or disturbance´s. Sensitivity is the degree to which a system is affected, or its ability to respond to a stimulus, in this case, climate stimulus (Smit et al., 2009). Some concepts that have been applied to natural systems are stability, resilience and flexibility, which may well be applied to human systems. Stability refers to the ability of a system to remain fixed or unchanged when exposed to a disturbance. Resilience refers to the ability of the system to rebound from a disturbance that could be experienced. Flexibility is the degree of manoeuvrability that exists within the system. Despite their application in ecology, the boundaries in human systems between these concepts are not clear and kept on being discussed (Smithers and Smit, 2009). But what we can be certain of is that the terms described above have gained attention in recent years because they influence the internal definition of systems and their vulnerability to changes in climate systems (Klein and Nicholls, 1999).

The IPCC recognizes the vulnerability to climate change as "the degree to which systems are able or unable to address the negative impacts of climate change" (Parry et al., 2007), referring to geophysical, biological and socioeconomic systems. They point out that vulnerability may relate to the vulnerable system (a city, an agricultural activity), the impact on the system (flood) or the mechanism that drives it (melting). Cutter (1996) and the Third Assessment Report of the IPCC (McCarthy et al., 2001) identified three components that determine the vulnerability of a system or group of people: their exposure, sensitivity and adaptive capacity. In fact, since the second IPCC report (1996) it was recognized that "the most vulnerable systems are those more sensitive to climate change and with less adaptability." More information on the vulnerability analysis can be found in Berry et al., 2006; Bohle et al., 1994, Downing and Patwardham, 2006, Kelly and Adger, 2000; whereas in the present work the definition of IPCC on vulnerability is used and especially in this chapter on climate sensitivity, a component of vulnerability.

The sensitivity, according to the IPCC (2007), is "the degree to which a system is affected by a disturbance, either adversely or beneficially, by variability or climate change," and points out that the effects can be direct or indirect. Sensitivity refers to the extent such a system will respond to a change in climate. This measure determines the level at which the system will be affected by a particular stress, or how the system will be affected by climate change. O'Brien´s report (2004) indicates that human and environmental conditions are what would worsen or lessen the impacts of a given phenomenon.

The sensitivity analysis attempts to directly link future climate change scenarios with its potential effects or impacts (Downing and Patwardham, 2006). That is, the purpose is to understand the process by which future scenarios result in hazards or impacts on a particular group or system. An important aspect pointed out by the authors is that it is possible to identify points of intervention and response options.

The literature reveals few evaluations of climate sensitivity from the perspective of vulnerability and climate change. For example, O'Brien (2004) to measure the sensitivity under exposure to climate change built a climate sensitivity index, which measured the soil aridity and the dependence on monsoon in India. Besides, a sensitivity evaluation to climate stimuli at national and municipal level is not known in Mexico. Thus, the objective of this study was to contribute to the analysis of climate sensitivity in Mexico, by evaluating the sensitivity of the municipalities in the country to the stimulus of climate change. Another objective was to apply indicators to assess the current state of the agricultural sector (in infrastructure and land production capacity), and by using scenarios of future climate change the possible impacts on agriculture, livestock and forestry in the country, as sensitive components to climate change.

2. Methods

The method used in this paper was organized into three components: (I) selection of indicators to assess the sensitivity to climate change, (II) obtaining an index of sensitivity to climate change and (III) mapping of the sensitivity to climate change in the municipalities of Mexico. The aim of the first component was to obtain indicators to assess both the existing capacity to address climate change and the potential impact on agricultural activity (agriculture, livestock and forests) that is expected to occur in the municipalities. It was in this way how the current sensitivity to future climate change was represented. Indicators were selected into three groups; the first one was about existing infrastructure, the second one about land capacity and the last one about the impacts of climate change on natural and productive resources (agriculture, livestock and forests). The main source of data was the Agriculture, Livestock and Forestry Census by the National Institute of Statistics and Geography (INEGI, 2009), as well as the results for agriculture (Monterroso et al., 2011a), livestock (Monterroso et al., 2011b) and forests (Gómez et al., 2011) obtained for Mexico at national level. The information was processed geographically in ArcGIS (version 9.3) and statistically in SPSS (version 18). The sensitivity index was built and then we proceeded to develop it´s mapping, as detailed in the following paragraphs.

2.1 Selection of indicators

The selected indicators to evaluate the sensitivity of the municipalities were grouped into: a) indicators of existing infrastructure b) indicators of land capacity and c) indicators of climate change impacts on natural and productive resources. The first two groups establish the current conditions and therefore the ability (or inability) to cope with climate change. The third group is the translation of possible future scenarios of climate change and its impacts on farming, livestock and forestry in Mexico. Table 1 presents information about the indicators applied.

Existing infrastructure indicators include the total number of greenhouses and/or nurseries in the municipality, the total existing irrigation systems, percentage of production units that reported insufficient infrastructure in the municipality and all machinery in the municipality. The information for the infrastructure indicators was obtained from the Agriculture, Livestock and Forestry Census (INEGI, 2009) and corresponds to that reported for each production unit within the municipalities. The indicator referring to the total number of greenhouses and/or nurseries in the municipality represents the total amount reported by the production units within the same municipality. The selection of this indicator was based on that the larger the number of greenhouses or nurseries within the same municipality, the greater the production capacity, presenting even better quality than the production dependent only on rain irrigated. Thus, the larger existing capacity in greenhouses and/or nurseries, the lower the sensitivity of the municipality. This allowed us to identify the most sensitive municipalities, given its low amount of actual existing infrastructure. In regards to the total irrigation systems, they represent the sum of all existing systems within the municipal production units, regardless of the present type of irrigation. The central hypothesis for the selection of this indicator is that the smaller the number of irrigation systems existing in a municipality the lower its capacity to cope with climatic variations, therefore, the greater its sensitivity to change. The third indicator was the total reported machinery, and is the sum of those reported by each production unit within a municipality. The selection as an indicator was considered because the total amount of machinery in a municipality makes reference to the capacity to do work in agriculture in less time, which means higher production efficiency. If machinery for work is available at the municipalities, it is hoped that they will be more able to adapt to climate change conditions, for example, and will be therefore less sensitive. The last indicator, insufficient infrastructure, includes the percentage of total production units within the same municipality which reported failure in infrastructure for agricultural, forestry or livestock production. The selection of the indicator was based on the fact that the greater the percentage of insufficient reported infrastructure within a municipality the greater the sensitivity to changes is considered, thus presenting greater vulnerability. The four indicators above were considered enough to evaluate the degree of sensitivity of the municipalities, in regards to existing infrastructure, since a system with infrastructure will be less sensitive to changes to any climatic variable.

To evaluate the land capacity we include the assessment of its current state in terms of production capacity, because if there is any land degradation, agricultural production will be more difficult to be carried out, making it possible to identify the municipalities with these characteristics as more sensitive, compared with those that do not have this problem. The selected indicators in this group were five: total hectares reported with loss of soil fertility, total hectares with presence of salts, total hectares with presence of some degree of erosion, total surface area without vegetation and finally total hectares with presence of some degree of contamination. The information was also obtained from the Agriculture, Livestock and Forestry Census (INEGI, 2009) and corresponds to that reported for each production unit within the municipalities. The loss of soil fertility includes the total reported hectares per production unit within a municipality that reported this feature. The indicator presence of salts comes from the total number of hectares reported by the production units with problems of salinization of soils in each municipality. Similarly, the erosion indicator refers to the total hectares per production unit that have reported the presence of some degree of erosion of their soil within a municipality. The total surface area indicator without

apparent vegetation refers to the total sum of hectares reported by the production units within a municipality. Finally, the pollution indicator includes the total hectares reported with pollution problems per production unit within a municipality.
Indicators of climate change impacts on natural resources were considered as sensitive elements of the production system, since a negative change in them will means a reduction in the land productive capacity. They include the changes suggested by climate change on agricultural suitability, as exemplified by the production of rainfed maize in Mexico. As the authors point out (Monterroso et al., 2011a), the suitability for cultivation was classified into four classes: very suitable, suitable, marginally suitable and unsuitable, thus forming the baseline scenario. The climate change scenarios used were Echam and Hadgem, according to the A2 group by 2050. The new outputs for agricultural potential for the cultivation of maize were also classified in the same number of classes. Modelled changes are also included both in the livestock capacity and forest suitability; the first by analysing the change in the stocking rate and the second by the shift in suitability for some forest species. The livestock suitability (Monterroso et al., 2011b) refers to the stocking rate needed to sustain one animal unit, expressed as the number of hectares needed per animal unit per year (ha/AU/year). Six classes were defined for livestock suitability: 0-1, 1-5, 6-10, 11-50, 51-100 and +100, all in ha/AU/year. Climate change scenarios were the same as those used in the agricultural suitability and their application were also ordered in the same number of classes. In regard to forests, forest species were selected representing the groups of tropical vegetation, temperate and semi-arid, as is mentioned in Gómez (2011). The defined classes were also four, both for the base scenario and climate change scenarios: suitable, moderately suitable, marginally suitable and unsuitable.

2.2 Sensitivity Index to climate change

Sensitivity to climate change is the degree to which a system is affected, or its response to climate change. To represent the ability to cope with changes in the municipalities of Mexico four infrastructure indicators were proposed and five for land capacity. To include the future impact on the evaluation of the sensitivity on the agricultural sector, the outputs of climate change scenarios were included and their corresponding result in the agricultural, livestock and forest suitability by 2050.
This research considered that the sensitivity in the municipalities of Mexico is based on existing infrastructure, the productive land capacity and the change in agriculture, livestock and forest potential to climate change, as shown in the following formula:

Sensitivity = f (existing infrastructure, productive land capacity, natural resources) (1)

According to the four selected indicators who represent the existing infrastructure with information at municipal level, the variable can be represented as:

Infrastructure = f (total greenhouses, total irrigation systems, total machinery, percentage of insufficient infrastructure) (2)

To estimate the sensitivity of the current production capacity of the land, five indicators were considered about the current state, represented as:

Land Capacity = f (percentage of fertility loss, total hectares with salinity, total hectares without vegetation, total contaminated hectares) (3)

Natural resources, as the sensitive elements of the system, were included as the future potential aptitude change in agricultural, livestock and forest suitability caused by climate change, and can be represented in the following formula:

Natural resources = f (percentage of area used by primary sector, current agricultural suitability, Δ future agricultural suitability, current livestock suitability, Δ future livestock suitability, current forest suitability, Δ future forest suitability) (4)

Table 1 presents information on units of measurement of the original indicators, the minimum and maximum values and the standard deviation of each indicator.

Indicator	**Code**	**Min**	**Max**	**Average**	**Standard Deviation**	**Variance**
Greenhouses	S1	0	1857	6.8	43.8	1921.6
Irrigation systems	S2	0	11403	288.0	661.1	437116.8
Sufficient infrastructure	S3	0	89	9.1	12.0	144.0
Reported machinery	S4	0	3484	33.4	120.1	14427.1
Fertility losses	S5	0	100	22.8	20.1	407.0
Salt-affected soils	S6	0	22222	56.7	723.8	523957.6
Soil erosion	S7	0	11648	47.0	494.7	244809.6
Hectares without vegetation (ha)	S8	0	197878	865.3	6692.6	44791159.9
Contaminated hectares	S9	0	2263	4.3	63.9	4087.1
Primary activities	S10	0	100	65.7	21.4	458.2
Base agriculture	S11	0	4	2.0	1.3	1.9
Base livestock	S12	1	10	3.6	1.2	1.5
Base forests	S13	1	4	3.6	0.6	0.4
Echam Agriculture	S14	0	4	2.1	1.4	1.9
Hadgem Agriculture	S15	0	4	2.1	1.3	1.9
Echam livestock	S16	1	10	3.5	1.2	1.5
Hadgem livestock	S17	1	10	3.3	1.3	1.8
Echam Forests	S18	1	4	2.8	1.1	1.2
Hadgem Forests	S19	1	4	3.0	1.0	1.0

Table 1. Statistical values of sensitivity indicators.

All values (s1 ... s19) were standardized (z) to eliminate the measurement units and consider all the variables implicitly equivalent in terms of the collected information. In future scenarios of agriculture, livestock and forest suitability, probabilities and future risks were not considered for being out of the context in the index.

Once the indicators had been standardized the sub-indexes were constructed to represent the partial value of the evaluated subcomponent (sensitivity). Thus, the formula (2) of existing infrastructure was expressed as:

$$\text{Infrastructure} = (S1 + S2 + S3 + S4) / 4 \quad (5)$$

Following this idea, the formulas (3) and (4) are represented as:

$$\text{Land capacity} = (S5 + S6 + S7 + S8 + S9) / 5 \quad (6)$$

$$\text{Natural Resources} = (S10 + S11 + S12 + S13) / 4 \quad (7)$$

With the information of the sub-indexes (5), (6) and (7) the baseline sensitivity scenario was constructed defined here as the current scenario of sensitivity. The formula (8) then represents the current sensitivity of the municipalities in Mexico. This is defined as the sum of the production capacity of the land plus the capacity of natural resources (which together denote the productivity potential) minus the existing infrastructure, (denoting a greater potential to address a harmful climatic stimulus), represented as:

$$\text{Current Sensitivity} = (\text{Land capacity} + \text{Natural Resources}) - \text{existing Infrastructure} \quad (8)$$

Or specifically, the current sensitivity index is given by:

$$Current\ Sensitivity = \left(\frac{S5 + S6 + S7 + S8 + S9}{5} + \frac{S10 + S11 + S12 + S13}{4} + (1 - \frac{S1 + S2 + S3 + S4}{4})\right)/3 \quad (9)$$

Since the subcomponent of natural resources is the one that assesses the climate change scenarios and their potential impacts, a sub-index for each of the two applied scenarios was built. As shown in formula (9), to build the base scenario, variables were used without climate change scenarios (S1 ... S13). To estimate the change in current sensitivity when considering climate change scenarios the same formula was used (9) but including the expected changes on natural resources, as shown below:

$$Future\ Sensitivity_{\ Echam} = \left(\frac{S5 + S6 + S7 + S8 + S9}{5} + \frac{S10 + S14 + S16 + S18}{4} + (1 - \frac{S1 + S2 + S3 + S4}{4})\right)/3 \quad (10)$$

$$Future\ Sensitivity_{\ Hadgem} = \left(\frac{S5 + S6 + S7 + S8 + S9}{5} + \frac{S10 + S15 + S17 + S19}{4} + (1 - \frac{S1 + S2 + S3 + S4}{4})\right)/3 \quad (11)$$

From the above it was possible to compare the current sensitivity (9) with the one estimated by climate change scenarios (10) and (11). The results are presented below.

2.3 Mapping sensitivity to climate change in Mexico

Once the sub-index of sensitivity was built, the value obtained was assigned to each municipality, allowing the hierarchization of the municipal level of sensitivity in the country. The values were divided into quintiles and assigned a qualitative indicator of sensitivity (Table 2):

Sensitivity index	0-20	21-40	41-60	61-80	81-100
Severity of sensitivity	Very low	Low	Moderate	High	Very high

Table 2. Criteria applied for sensitivity in the municipalities of Mexico

Finally, with the information obtained the sub-index and the severity of the sensitivity could be drawn on maps at municipal level.

3. Results and discussion

In this study, the sensitivity was defined as a function of the existing infrastructure, land capacity and natural resources. Sensitivity to climate change is the degree to which the municipalities of Mexico will be affected, or their ability to cope with climate change. The results are presented in that order, the current sensitivity and future sensitivity which included climate change scenarios.

3.1 Current sensitivity

The infrastructure sub-index reflects the total amount of production equipment, in terms of the total number of greenhouses, irrigation systems, machinery and producers viewpoint as to whether the infrastructure is enough, for each municipality. The five municipalities with less infrastructure reported are: Xocchel and Opichén (Yucatán), San Gabriel Mixtepec and Santa Catarina Tayata (Oaxaca) and Sochiapa (Veracruz). All of them did not report having greenhouses and have only one machine or none for the entire municipality. The existing irrigation systems are less than twenty or even none in Sochiapa. It is reported that in more than 80% of the production units there is insufficient infrastructure. This shows the lack of infrastructure facilities and therefore a greater sensitivity to climate phenomena. On the other hand, the five municipalities that reported better infrastructure´s are Villa Guerrero, Ixtlahuaca (Mexico), Nuevo Ideal (Durango), Cuauhtémoc (Chihuahua) and Mexicali (Baja California). The first two are those who reported more greenhouses and irrigation systems. The amount of machinery for agricultural work is more than a thousand units per municipality, only in Ixtlahuaca was reported less than 100. Table 3 summarizes the main results for each component of the index.

Land capacity assesses the current condition of the land, as to whether or not this presents some degree of degradation, such as salinity, erosion, pollution, loss of fertility or if vegetation is absent on its surface. The five municipalities with further degradation in their land are: Ensenada (Baja California), Ocampo (Coahuila), Camargo (Chihuahua) and Ahome and Navolato (Sinaloa). Although these municipalities did not report having significant losses due to lack of fertility, they reported problems of salinity and erosion. In the case of Ensenada, for example, is the one that reports the largest surface without vegetation and with pollution problems on their land. On the other hand, the five municipalities that did not report problems on their land are Chicxulub (Yucatan) and San Juan Atepec, Santa Catarina Zapoquila, Santa Maria Ixcatlán and Santos Reyes Pápalo in Oaxaca.

The natural resources group represents the degree of suitability of land production (agriculture, livestock and forestry) and the percentage of municipal area devoted to these primary economic activities. The municipalities that have greater sensitivity are Pocitlán (Jalisco), San Agustin de las Juntas and San Francisco del Mar in Oaxaca as well as Ixmatlahuacán (Veracruz), since almost its entire surface are devoted to primary activities (municipalities of Oaxaca with a 97%) mainly agriculture. On the contrary, the municipalities with less sensitivity because of their natural resources productivity potential are: Cuajimalpa (DF), Empalme (Sonora), Telchac Puerto (Yucatan), Ciudad Madero (Tamaulipas) and Zoquitlan (Puebla). This happens because these municipalities do not rely solely on farming and do not have some degree of suitability for farming, livestock or forestry.

The current sensitivity index was obtained by integrating the results of the three previous subindexes in formula (9). Figure 1 shows the behaviour of the three components and their participation in this index. It is possible to observe how two subindixes reflect the behaviour of the current sensitivity in the municipalities. In the infrastructure variable, the greater the amount of existing infrastructure the lower the sensitivity; on the contrary, the fewer infrastructure the greater the result of its sensitivity. With regard to the natural resources variable, the lower (or absence) the agricultural suitability, the lower sensitivity, and the greater the suitability the greater the sensitivity obtained.

STATE	**MUNICIPALITY**	**S1**	**S2**	**S3**	**S4**		**Infraestructure Index**	
Yucatán	Xocchel	0	8	11	0		2.88	Less existing infrastructure, more sensitive
Oaxaca	San Gabriel Mixtepec	0	11	11	1		2.87	
Veracruz	Sochiapa	0	0	13	0		2.84	
Oaxaca	Santa Catarina Tayata	0	16	17	1		2.75	
Yucatán	Opichén	0	18	20	1		2.68	
Baja California	Mexicali	12	4847	97	929		-2.75	More existing infrastructure, less sensitive
México	Ixtlahuaca	103	11403	94	65		-3.88	
Chihuahua	Cuauhtémoc	27	1182	82	2356		-4.10	
Durango	Nuevo Ideal	5	788	89	3484		-6.32	
México	Villa Guerrero	1857	3288	82	1022		-12.56	
		S5	S6	S7	S8	S9	Land capacity Index	
Baja California	Ensenada	9	3280	2093	197879	2263	14.54	Less land capacity, more sensitive
Coahuila	Ocampo	5	6314	11649	40216	0	7.40	
Chihuahua	Camargo	7	34	11194	69037	0	6.37	
Sinaloa	Ahome	11	22223	310	84	2	6.08	
Sinaloa	Navolato	23	20922	468	15627	1	6.37	
Oaxaca	San Juan Atepec	0	0	0	0	0	-0.30	Greater land capacity, less sensitive
Oaxaca	Santa Catarina Zapoquila	0	0	0	0	0	-0.30	
Oaxaca	Santa María Ixcatlán	0	0	0	0	0	-0.30	
Oaxaca	Santos Reyes Pápalo	0	0	0	0	0	-0.30	
Yucatán	Chicxulub Pueblo	0	0	0	0	0	-0.30	
		S10	S11	S12	S13		Natural Resources Index	
Veracruz	Ixmatlahuacan	62	4	10	4		1.72	Greater dependence and greater agricultural suitability, more sensitive
Jalisco	Poncitlán	74	4	9	4		1.66	
Oaxaca	San Francisco del Mar	97	4	10	2		1.37	
Oaxaca	San Agustín de las Juntas	97	4	6	4		1.33	
Distrito Federal	Cuajimalpa de Morelos	44	1	2	2		-1.39	Less dependence and less agricultural suitability, less sensitive
Sonora	Empalme	41	1	4	1		-1.40	
Yucatán	Telchac Puerto	20	0	4	2		-1.45	
Tamaulipas	Ciudad Madero	0	4	3	1		-1.54	
Puebla	Zoquitlán	26	1	4	1		-1.58	

Table 3. Municipalities of Mexico with greater sensitivity according to sub-index of infrastructure, land capacity and natural resources

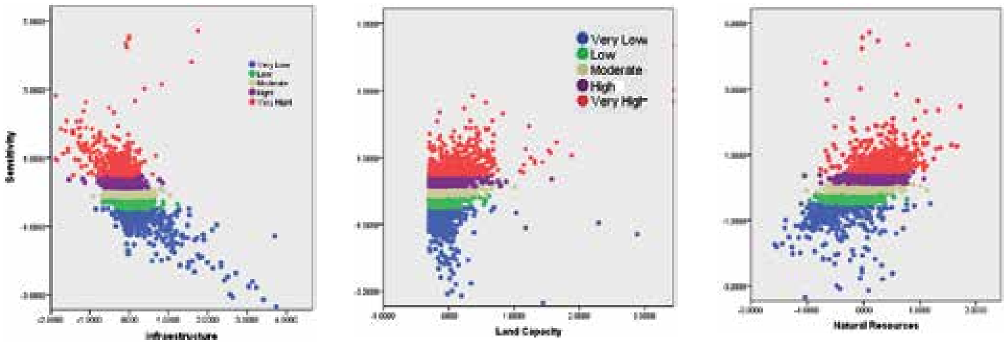

Fig. 1. Distribution of the participation of infrastructure, land capacity and natural resources in the current sensitivity index.

The index then represents the sensitivity observed in the municipalities and was classified into five groups according to their severity: very high, high, moderate, low and very low sensitivity. The obtained results for the sensitivity index present a minimum value of -4.19 (very low sensitivity) and a maximum of 4.6 (very high sensitivity) with a separation range of 8.78. The index distribution is shown in Figure 2 and their spatial distribution for the country in Figure 3.

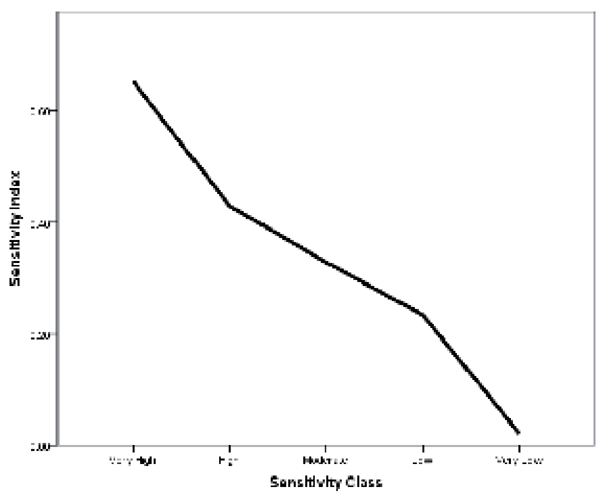

Fig. 2. Current sensitivity index and class grouping.

The municipalities with the highest sensitivity index, or those more sensitive, are concentrated in the northern part of the country and are Ensenada (Baja California), Ocampo (Coahuila), San Nicolas Tolentino (San Luis Potosi), Camargo (Chihuahua), Navolato (Sinaloa), Manuel Benavides (Chihuahua), Sahuaripa and Divisadero (Sonora). The municipality identified as the most sensitive of the country is Ensenada (with an index value of 4.6), in Baja California. Although the agricultural production units in the municipality report that there are greenhouses (80), irrigation systems (1137) and machinery (191), problems of soil degradation were also reported, with over 3000 hectares with salinity problems, 2000 hectares with erosion and the same number of hectares contaminated, besides reporting more than 190 000 hectares without apparent vegetation. The problem of soil degradation is what best explains the sensitivity of the municipality, since existing infrastructure and some degree of suitability was found for agricultural productivity. In addition, the municipality uses over 30% of its surface to primary economic activities, being a municipality that is not solely dependent on the agricultural sector.

On the other hand, municipalities with the lowest sensitivity index, or those less sensitive are Tenancingo (Mexico), Guerrero (Chihuahua), Durango (Durango), Fresnillo (Zacatecas), Mexicali (Baja California), Ixtlahuaca (Mexico), Cuauhtemoc (Chihuahua), Nuevo Ideal (Durango) and Villa Guerrero (Mexico). The municipality found as the least sensitive of the country is Villa Guerrero (with an index value of -4.19) in the state of Mexico. This municipality is characterized for having insufficient existing infrastructure and very little degradation of soils, which explains the behaviour of being the least sensitive. Natural resources are productive and well suitable for agriculture but only 44% of its area is devoted to primary economic activities.

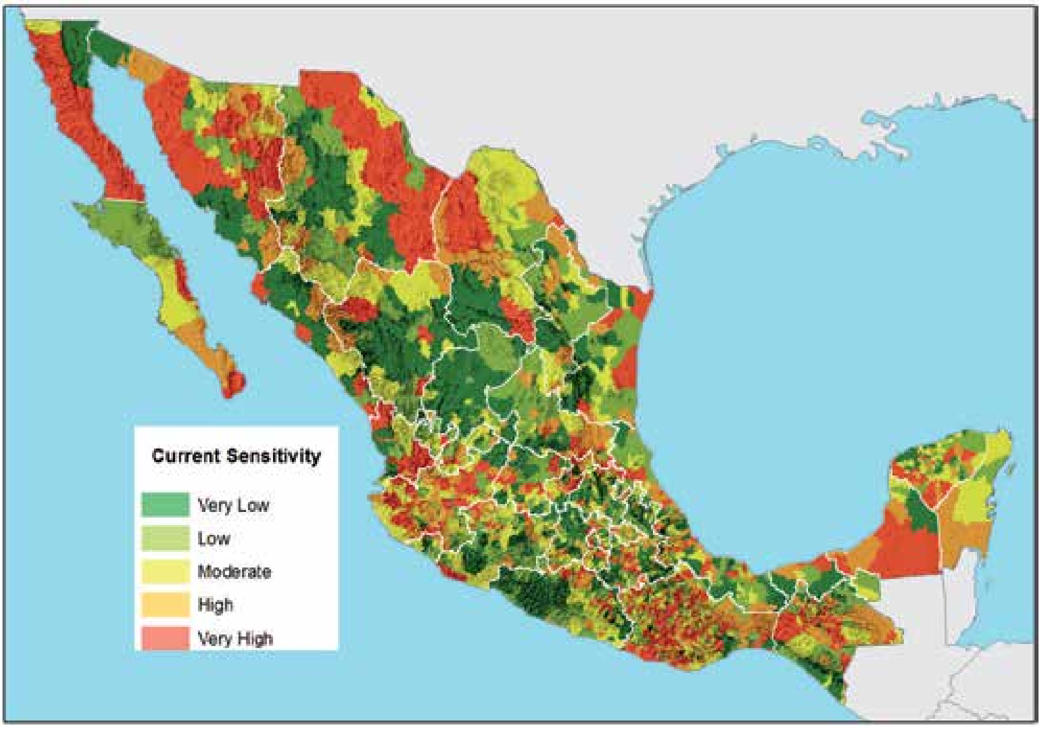

Fig. 3. Current spatial distribution of the sensitivity index in Mexico.

3.2 Sensitivity to climate change

To assess the future sensitivity under climate change scenarios only the possible impacts on the agricultural, livestock and forestry suitability in the country were used, within the natural resources group. Existing infrastructure and land capacity were not modelled with climate change scenarios. So that formulas (10) and (11) described above were applied to obtain the same number of sensitivity indexes to climate change.

Table 4 and Table 5 show the obtained results for the sensitivity index as reported by the scenarios Hadgem and Echam. It was found that according to both models the five most sensitive municipalities continue to be Ensenada, Ocampo, San Nicolas Tolentino, Camargo and Sahuaripa. However, the severity of the sensitivity will be higher when presenting higher values in future indexes. This can be explained by analyzing the potential of change in land suitability. Land suitability was assessed by the authors for agricultural activities (Monterroso et al., 2011a), livestock (Monterroso et al., 2011b) and forests (Gómez et al., 2011). Land suitability refers to the climate and soils potential to develop a productive activity, in this case, agriculture, livestock and /or forestry. When the outputs of these climate change scenarios are incorporated they indicate that, in general for the country, temperature will increase, and precipitation will increase in some areas and will decrease in others. This behavior of the climatic variables will modify the future capacity of the land, so in those places where temperature is expected to raise and rainfall to lower they will be more limited to produce food, therefore, are more sensitive.

State	Municipality	Infraes-tructure (current)	Land Capacity (current)	Natural Resources (current)	Natural Resources (Echam)	Current Sensitivity Index	Future Sensitivity Index (Echam)
More sensitivity:							
Baja California	Ensenada	-0.05	14.54	-0.73	-0.30	4.59	4.73
Coahuila	Ocampo	1.22	7.40	-0.19	-0.14	2.81	2.83
San Luis Potosí	San Nicolás Tolentino	0.99	5.39	0.40	0.51	2.26	2.30
Chihuahua	Camargo	0.31	6.37	-0.04	0.03	2.21	2.23
Sonora	Sahuaripa	1.02	4.20	0.26	0.52	1.82	1.91
Less sensitivity:							
Nayarit	Santiago Ixcuintla	-2.14	0.01	0.52	-0.22	-0.54	-0.78
Mexico	Ixtlahuaca	-3.88	0.01	0.24	0.93	-1.21	-0.98
Chihuahua	Cuauhtemoc	-4.10	0.23	-0.65	-0.02	-1.51	-1.30
Durango	Nuevo Ideal	-6.32	-0.06	0.23	0.34	-2.05	-2.01
Mexico	Villa Guerrero	-12.56	0.04	-0.05	0.26	-4.19	-4.09

Table 4. Municipalities of Mexico with future major and minor sensitivity to climate change according to the Echam model.

However, although the most sensitive municipalities in the current scenario will remain the same in the future, the vast majority of municipalities will see a change in their sensitivity. To show the above, Table 6 is presented in which the current sensitivity scenario is compared with the two future sensitivity indexes applied. In the columns is the current sensitivity index, while in the rows are the kinds of sensitivity for each model. In the main diagonal and in italics is the total number of municipalities that will not change their sensitivity when incorporating climate change scenarios is shown. Below the main diagonal are all the municipalities that increase their sensitivity when including climate change scenarios. Above the diagonal are all the municipalities that reduce their sensitivity.

In the current scenario, moderate class municipalities to very low add up 1473 from a total of 2454 municipalities reported for Mexico, which means 60%. 981 municipalities are sensitive under current conditions, in other words, 40% of the municipalities in Mexico are in the high and very high classes. According to the model Echam, a total of 1100 municipalities (44%) will remain with the current sensitivity level, 686 will observe an increase (29%) and 668 (27%) will decrease its sensitivity. What the model Hadgem indicates is a very similar behavior, since 1054 municipalities (43%) will remain under current conditions, 707 (29%) will increase and 693 (28%) will decrease its sensitivity. The spatial distribution of the indexes under future conditions of climate change is presented in Figure 4.

State	**Municipality**	**Infraes-tructure (current)**	**Land Capacity (current)**	**Natural Resources (current)**	**Natural Resources (Hadgem)**	**Current Sensitivity Index**	**Future Sensi-tivity Index (Hadgem)**
More sensitivity:							
Baja California	Ensenada	-0.05	14.54	-0.73	-0.37	4.59	4.70
Coahuila	Ocampo	1.22	7.40	-0.19	0.17	2.81	2.93
San Luis Potosi	San Nicolas Tolentino	0.99	5.39	0.40	0.52	2.26	2.30
Chihuahua	Camargo	0.31	6.37	-0.04	0.19	2.21	2.29
Sonora	Sahuaripa	1.02	4.20	0.26	0.75	1.82	1.99
Less sensitivity:							
Mexico	Tenancingo	-2.23	0.11	0.34	-0.12	-0.60	-0.75
Mexico	Ixtlahuaca	-3.88	0.01	0.24	0.16	-1.21	-1.24
Chihuahua	Cuauhtemoc	-4.10	0.23	-0.65	-0.64	-1.51	-1.50
Durango	Nuevo Ideal	-6.32	-0.06	0.23	0.34	-2.05	-2.01
Mexico	Villa Guerrero	-12.56	0.04	-0.05	-0.30	-4.19	-4.27

Table 5. Municipalities of Mexico with future major and minor sensitivity to climate change according to the Hadgem model.

Future Sensitivity		Current Sensitivity*				
		Very Low	Low	Moderate	High	Very High
Echam	Very Low	277 (56)	120 (24)	63 (13)	23 (5)	8 (2)
	Low	131 (27)	175 (36)	109 (22)	54 (11)	22 (5)
	Moderate	53 (11)	130 (26)	154 (32)	111 (23)	43 (9)
	High	18 (4)	53 (11)	113 (23)	192 (39)	115 (24)
	Very High	11 (2)	14 (3)	52 (11)	111 (23)	302 (61)
Hadgem	Very Low	279 (57)	115 (23)	67 (14)	24 (5)	6 (1)
	Low	129 (26)	165 (33)	123 (25)	53 (10)	21 (4)
	Moderate	60 (12)	126 (25)	126 (25)	130 (26)	48 (10)
	High	13 (3)	67 (14)	131 (26)	175 (35)	106 (21)
	Very High	9 (2)	19 (4)	44 (9)	109 (22)	309 (63)

* In parentheses the percentage that represents the total of the municipalities within each class is shown.

Table 6. Total municipalities by sensitivity class compared with future scenarios.

The existing infrastructure is an indicator that lowers the final weight of the sensitivity. The greater the amount of existing infrastructure for the agricultural activity, the lower its sensitivity. In an early analysis, this would suggest increasing the infrastructure with the aim of reducing future sensitivity to climate change. However, this would be wrong since other variables should be also considered. According to the results found, the infrastructure variable is not the biggest problem of sensitivity in Mexico, but it helps to reduce climatic stress. Figure 4 presents a simulation where the three variables are maximized hypothetically: infrastructure, land capacity and natural resources. If all the municipalities in the country would have the highest infrastructure reported, the sensitivity index would drop to the low sensitivity class (red line). This shows how important the infrastructure is in our sensitivity index.

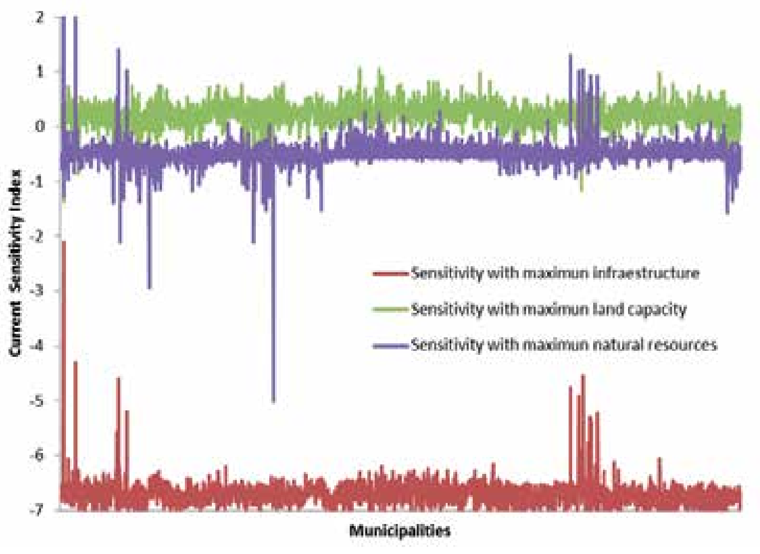

Fig. 4. Sensitivity index with hypothetical maximum data.

However, under these hypothetical conditions, some municipalities in the country continue to show sensitivity, shown as peaks in Figure 4. So it is worth analysing the other two variables. Land capacity variable represents higher values in the index (green line) and therefore determines to a large extent the current and future sensitivity, this is the variable that integrates the degree of degradation of soils, or the amount of problems in the agricultural production units. Even under hypothetical conditions this variable always remains positive. The third variable, natural resources (blue line) were the elements assessed under climate change scenarios and are those that show some degree of future impact of climate change. Municipalities that increase their sensitivity can be observed, while others lower it, under the assumption of presenting the best values of agricultural potential and natural resources.

Sensitivity in this work evaluates the degree of stress in the system. A system close to its sensitive limits will suffer more damage for climate change. In this case, the municipalities of Mexico are sensitive to climate change impacts on natural resources. The possible changes on temperature and precipitation suppose that the future suitability for agriculture will be affected. The production capacity of the land in Mexico has been diminished already, mainly by soil degradation. This is seen in our index, which for the current scenario presented values that increased sensitivity. In summary, currently the country's municipalities are already sensitive and this sensitivity increases by incorporating climate change scenarios.

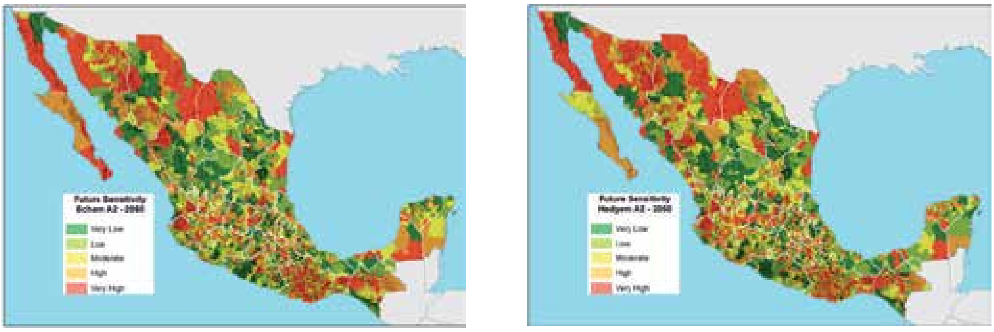

Fig. 5. Spatial distribution of sensitivity under future climate change scenarios.

The magnitude of the sensitivity, as the extent to which a system is affected in its current form, by climate change or variability is manifested in the municipalities of Mexico differently. Some regions are more sensitive than others. This can be attributed to several factors, among which the dependence of municipalities to primary activities stand out (agricultural production, livestock and forestry). Of all the municipalities, 1528 (62%) dedicate over 60% of their surface to such activities, and 16% (411 municipalities) dedicates over 90% of their surface to the primary sector. If the amount of existing irrigation systems is added to the 60% of the municipalities of Mexico the result will be 100 irrigation systems or less. This reflects that the primary activity keeps being very important in Mexico and that it is also dependent on the natural climatic conditions to take place. Hence, this is a sensitive group to any future changes in climate.

The sensitivity is a component of vulnerability, it is the internal element that allows its characterization. The sensitivity, together with the exposure, determines the potential impact of climate change, without considering adaptation. Therefore it is important to continue studies in Mexico on vulnerability, but which includes exposure and adaptive capacity. Moreover, it is also important to work with the uncertainty of working with models of future climate change. Currently, only 817 municipalities (33%) have some degree of suitability for agricultural production, the rest (67%) carries out agricultural activities but under marginal conditions, requiring higher production inputs. From the climate change scenarios, Echam model suggests there will be 811 (33%) and the Hadgem model 766 (31%) municipalities that will show some degree of future suitability to continue doing agriculture. This uncertainty in the models should also be considered when making decisions.

This study shows the kind of sensitivity and where this sensitivity takes place. However, further more detailed studies at local level must be carried out to promote adaptation measures. Decision makers in the country must decide where to apply economic resources and implement actions, so that a practical use of this work is to assist in making decisions using criteria that consider climate change.

4. Conclusion

This study contributes to the sensitivity analysis, an element of vulnerability, in Mexico. Much of the literature reports this type of studies within a broader context of vulnerability analysis, but rarely is this studied independently. In Mexico, studies on vulnerability have come into existence only recently, but none has been addressed at a national and municipal level.

The sensitivity of the municipalities of Mexico was evaluated under current conditions and considering climate change scenarios. For this purpose, a current sensitivity index was built and two more that show future scenarios of climate change. To calculate the indexes a simple linear formula was used, so it was possible to combine the variables studied. By applying the indexes, it was possible to characterize the current and future sensitivity of the municipalities of Mexico, based on indicators that assessed the potential impact of climate change, including the potential change in the agricultural, livestock and forestry suitability in the country.

The results showed that the municipalities in Mexico are sensitive even without considering climate change. When climate change scenarios are included the future sensitivity increases. Contrary to what was expected, the existing infrastructure is not the variable that better explains the current and future sensitivity. According to the results, it would be inappropriate to suggest the extension of agricultural buildings in order to decrease the sensitivity of the municipalities. The production capacity of the land is the variable that best helps explain the current and future sensitivity. However, the level of current land degradation presents high values and determines to a greater extent the agricultural potential of the municipalities of Mexico. Therefore, it is essential to promote soil improvement and conservation activities, to reduce to some degree the future sensitivity to climate change. Currently the most sensitive regions are the northern states, and under conditions of climate change are expected to remain so. This let us propose that the region must be addressed immediately to be in a better position to face the challenges that climate change poses.

One disadvantage observed is the weight that the infrastructure represents in the model, for which in the future it is recommended to consider more variables in the study of sensitivity in the country.

Considering the previous thing, we believe that it is possible to apply the methodology in other places of the world. It will have to pay attention to the chosen variables and consider the local information as a principal source of information. As we have written it, more indicators of land capacity will allow obtaining better results in a sensitivity analysis. Also, climate change scenarios will have to be according to the targets of the study and preferable downscaled.

It is difficult to assure if the mexican farmers are more or less sensitive that other farmers in the world. First, because in accordance with the results the north zone of the country is more sensitive to climate change that the south region. In this context, the most sensitive region is comparable with the results presented by O'Brien (2004), where the authors evaluated soil aridity and dependence of the monsoon, both related to land capacity. From the agronomic point view, the north region of the country will be more sensitive to climate change. But at the other side, from the economic point view, maybe the south region of the country will be a land of opportunity.

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18

Global Warming and Livestock in Dry Areas: Expected Impacts, Adaptation and Mitigation

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1. Introduction

In most developing countries livestock is the key asset for rural people providing multiple economic, social and risk management functions. Rangelands contribute to the livelihoods of over 800 million people including poor smallholders. The arid area of the globe is home for extensive livestock production mainly based on small ruminants (Ben Salem & Smith, 2008). The most important sheared characteristic of such zones, despite the high variety of biotopes, is aridity with a very erratic pattern of rainfall and extended periods of high temperatures. These two factors together with a higher frequency of extreme climatic events will be amplified under the perspective of global warming thus affecting negatively food availability through the seasons of the year. The impacts that climate change will bring about are expected to exacerbate the vulnerability of livestock systems and to reinforce existing factors that are simultaneously affecting livestock production systems such as rapid population and economic growth, increased demand for food and products, and increased conflicts over scarce resources (e.g. land tenure, water, and feed). There is an urgent need for detailed assessment of climate change impacts in each production system and for identifying appropriate options that can help livestock keepers adapt to climate change. This chapter summarizes current knowledge on global warming, discusses its impacts on the different components of the production systems and reports technical options to overcome negative effects of climate change on the livestock productivity and health and sustainability of livestock-based production systems. The approach recommended to transfer and adopt these options is also discussed.

2. Common knowledge on global warming

Human activity is changing climate on earth and many of these changes are now admitted to be inevitable. The main question raised today is on the magnitude of such changes and on their links with human activity. Even though certainties related to details of these changes are lacking, most available scenarios on climate change converge towards a global warming together with a reduction in average rainfall and in increase in climatic variability both in terms of frequency and the limits reached by extremes.

During the last century, the globe temperature has increased by 0.7°C. The variation of rainfall in time and in space has undergone wide changes and the level of sea water rose by approximately 25 cm. The increase in temperature has already affected the biological systems on earth. Changes have been observed in species distribution, the size of populations, seasons of reproduction and migration of animals and a higher occurrence of parasites and diseases in the forest system (Watson, 2008). Several examples can be given, however the authors have chosen to report on predictions from their country of origin where, average temperature, as a result of global warming, is expected to rise by 2.1°C in 2050 with a sharp decline of rainfall and an increase of climate variability (GTZ, 2007). The south will be exposed to the highest increases of average temperature and will undergo more frequent successions of dry years. Water availability will decline by 28% in 2030 and agricultural yields generated by dry farming will decline by 50% in 2050. Beef, sheep and goat production will be greatly affected particularly in the centre and the south and losses up to 80% can be recorded during drought years.

Globally, most of the available scenarios on climate change and their relationship with agriculture are pessimistic and predict a negative effect of global warming on production outputs. From another point of view, there is a consensus as to the difficulties to pinpoint the impact that can be attributed to global warming. Levels of agricultural production including livestock produces, are subject to important interactions between factors such as the use of inputs, the market forces and agricultural policies mainly subsidies and incentives. In addition, inter annual climatic variability is a major determinant of agricultural yields and this will not allow easy isolation of the effect attributed to global warming. Therefore, a large body of the available literature is based on prediction models and several trends remain very conceptual.

3. World consumption trends of livestock products

Livestock production including poultry has a significant contribution to human nutrition, agriculture and rural economy. Products and services provided by the livestock sector include meat, milk, eggs, fiber, traction animals, organic manure and fuel.

Livestock production represents 40% of the world agricultural production and contributes to the livelihoods and the food security of nearly one billion people around the world. At the global level, livestock contribute with 15% of total food energy and 25% of dietary protein (FAO, 2009a). Products from livestock provide essential micronutrients that are not easily obtained from plant based foods.

In agricultural economics, livestock has the fastest growth rate as a result of an increase in incomes and technological and structural evolutions. This is particularly true in developing countries of many areas of the globe. The sustained improvement of incomes and rapid urbanization during the last three decades in parallel to a population growth have prompted a higher demand on meat and other animal products particularly in developing countries (FAO, 2009a). These trends and the challenges they entail were identified a decade ago by Delgado et al. (1999), who launched the term “livestock revolution” to describe the process that is transforming the sector. In this respect and to meet the increased demand on livestock products, the World Bank has estimated that meat production should increase by 80% between 2000 and 2030. For this, available animal resources should be used more efficiently while it is essential to preserve natural resources and to prevent pollution of the environment.

In many developing countries, livestock keeping is a multifunctional activity. Beyond its direct role in generating food and income, livestock is a valuable asset, serving as a store of wealth, for credit and a safe survival mechanism during times of crisis.

Consumption of livestock products has increased rapidly in developing countries over the past decades, particularly from the 1980s onwards. Growth in consumption of livestock products per capita has markedly exceeded growth in consumption of other major food commodity groups. Since the early 1960s, consumption of milk per capita in the developing countries has almost doubled, meat consumption more than tripled and egg consumption increased by a factor of five (FAO, 2009b).

4. Relationship between global warming and livestock

Climate change represents a special "feedback loop", in which livestock production both contributes to the problem and suffers from the consequences.

The possible effects of climate change on food production are not limited to crops and agricultural production. Climate change will have tremendous consequences for dairy, meat and wool production, mainly arising from its impact on grassland and rangeland productivity. Heat distress suffered by animals will reduce the rate of animal feed intake and result in poor growth performance (Rowlinson, 2008). Lack of water and increased frequency of drought in certain countries will lead to a loss of resources. Consequently, as exemplified by many African countries, existing food insecurity and conflict over scarce resources will be exacerbated. Such effects will be moderate in extensive systems where animal resources are often local breeds tolerating environment stressors such as increased temperature and extreme climate variability.

In areas threatened by global warming such as the Middle East and North Africa, a higher incidence of transboundary diseases is feared. Some diseases with a major economic impact in particular those transmitted by ticks will have a wider spread.

The agriculture sector is the world's largest user of natural resources and, like any productive activity; livestock production has an environmental cost. The livestock sector is also often associated with policy distortions and market failures, and therefore places burdens on the environment that are often out of proportion to its economic importance. For example, livestock contribute less than 2% of global gross domestic product but produce 18% of global greenhouse gas emissions (Steinfeld et al., 2006). There is thus an urgent need to improve the resource use efficiency of livestock production and to reduce the negative environmental fallouts produced by the sector.

Livestock is therefore perceived as a contributor to global warming and public policies across the world should be designed in a way where increased and more intensive animal production should not exacerbate the environment by reducing contribution to global warming and by ensuring a sustainable use of the natural resources.

Climate change may also alter the integrity of the rural populations exposing men and women to other constraints and pushing them to make other choices like migration of men for work. Other categories of the society (women and young persons) may therefore be in a more vulnerable situation.

The Intergovernmental Panel on Climate Change (IPCC, 2007) concluded that anthropogenic greenhouse gases, including carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and halocarbons have been responsible for most of the observed temperature increase since the middle of the twentieth century. Agriculture, particularly livestock, is increasingly being recognized as both a contributor to the process of global warming and a potential victim of it. In the following, we will attempt to separate both sides of the interaction between global warming and livestock: the impact of livestock production on global warming and the effects of global warming on livestock production.

4.1 Impact of livestock on climate change

Livestock contribute to climate change by emitting greenhouse gases, either directly (e.g. from enteric fermentation) or indirectly (e.g. from feed-production activities, deforestation, overgrazing, etc.). Greenhouse gas emissions can emanate from all the main steps of the livestock production cycle. Emissions from feed-crop production and pastures are linked to the wide use of chemical fertilizers and pesticides, to soil organic-matter losses and to transport (use of fossil fuels). When forest is cleared for pasture and feed crops, large amounts of carbon stored in vegetation and soil are also released into the atmosphere. In contrast, when good management practices are implemented on degraded land, pasture and cropland can turn into net carbon stores, sequestering carbon from the atmosphere. Contributions of livestock activities to carbon cycle may therefore have an important impact on the process of global warming. At the farm level, CH4 and N2O are emitted from enteric fermentation and manure. In ruminant species, CH4 is exhaled as a by-product of the process of fermentation of fibrous feedstuffs in the rumen. Nitrous oxide is released from manure during storage and spreading, and CH4 is also generated when manure is stored in anaerobic and warm conditions.

4.2 Impact of climate change on livestock

Some of the greatest impacts of global warming will be visible in grazing systems in arid and semi-arid areas (Hoffman & Vogel, 2008). Increasing temperatures and decreasing rainfall reduce yields of rangelands and contribute to their degradation. Higher temperatures tend to reduce animal feed intake and lower feed conversion rates (Rowlinson, 2008). There is also evidence that growing seasons may become shorter in many grazing lands, particularly in sub-Saharan Africa. The probability of extreme weather events (droughts, floods) is likely to increase. In the non-grazing systems, which are characterized by the confinement of animals (often in climate-controlled buildings), the direct impacts of climate change can be expected to be limited and mostly indirect resulting from reduction of yields and increased prices of the main feed used in animal production (OECD–FAO, 2008). The development of energy-saving programs (biocarburants) may also result in increased energy prices. A warmer climate may also increase the costs of keeping animals cool by the building of adapted housing and the use of cooling devices. With higher temperatures, all countries are likely to be subject to increased animal-disease incidence but poor countries are more vulnerable to emerging diseases because of inappropriate veterinary services.

Despite all the expected negative impacts of global warming on livestock, some positive effects can be addressed. For example, higher winter temperature can reduce the cold stress experienced by livestock raised outside. Furthermore, warmer winter weather may reduce the maintenance energy requirements of animals and reduce the need for heating in animal housing (FAO, 2009a).

5. Effect of global warming on the main components of the livestock environment

5.1 Grazing land

Livestock is the world's largest user of land resources, with grazing land and cropland dedicated to the production of feed representing almost 80% of all agricultural land. The sector uses 3.4 billion hectares for grazing and 0.5 billion hectares for feed crops (Steinfeld et al., 2006); the latter figure corresponds to one-third of total cropland.

In arid and semi-arid rangelands, animal pressure is increasing because of low productivity, conflict over this resource and an arbitrary common use. As a consequence, the expansion of land used for livestock development can contribute to deforestation in some countries, while intensification of livestock production through maximization of the number of grazing animals can cause overgrazing in others.

Approximately 20% of the grazing lands and rangelands of the planet are degraded and this percentage is expected to rise until 73% in dry areas (UNEP, 2004). Degradation of rangeland has tremendous consequences on the environment mainly, soil erosion, degradation of the vegetation cover, emission of carbon, loss of biodiversity and alteration of the water cycle. Global warming is expected to further contribute to this degradation process and according to Thornton et al. (2006), large areas of the African continent will have a reduction of the length of the growing period of the vegetation by 20% in 2050. Regions gaining 5% or more in length of the growing period occupy considerably less than 1% and examples are limited to the North African coast and to a small area to the south of the Great Rift Valley in Ethiopia. Furthermore, under forest grazing systems, global warming is expected to increase the incidence of fires and this will reduce even further the available grazing land.

5.2 Soil

Any trend for climate change will have an impact on soils. Most scenarios of climate change predict a small variation of average rainfall but large variation of extreme meteorological events. Such trend will increase the risk of floods as well as the the frequency and the succession of dry years. Droughts and floods will cause a more important degradation of the soils and therefore a loss of the production potential for grazing and cropping. In many parts of the world, the impact of climate change will be an additional pressure on soils already undergoing advanced degradation processes. Erratic and reduced rainfall resulting from climate change will accentuate salinization of soil and water. While at the lower levels of salinity (<15dS/m) both legumes and grasses with moderate salt tolerance are capable of producing 5-10 tons of edible dry matter/ha/year, however at high salt concentrations (> 25 dS/m) production levels drop and plant options decrease significantly. However, even at these high salinities there are a range of halophytic grasses and shrubs that will produce 0.5 and 5 tons of edible dry matter/ha/year, respectively (Masters et al., 2007). Many plants growing in saline environments accumulate a range of secondary compounds. For example, most of halophytes which grow easily in saline soils (e.g. *Atriplex nummularia* L.) contain high levels of oxalic acid (Ben Salem et al., 2010).

Twice of the quantity of carbon in the atmosphere is stored in the soil. The manipulation of carbon sequestration into soils might offer a potentially useful contribution to climate change mitigation. Rangeland practices have a relevant potential to sequester carbon. These practices include management of stocking rate, rotational or adaptive grazing and enclosure grassland from livestock grazing. Reduced grazing intensity would result in increased soil carbon stocks. However, it seems that the relationship between grazing and soil carbon sequestration is a complex phenomenon involving environmental, social and economic issues. Grazing management affects soil carbon stocks by influencing the balance between inputs and outputs from the soil.

5.3 Water

Coupled with population growth and economic development, climate change impacts will have substantial effects on global water availability in the future. Changes in rainfall patterns and other water balance components like potential evapo-transpiration resulting from the increase of temperature will contribute substantially to water scarcity. The drier conditions expected in some areas like Mediterranean basin or South Africa will cancel the positive potential impact of higher CO2. Water competition between different strands of human activity will be one of the defining issues. The global demand for non-irrigation water will increase by two-thirds by 2025 (Rosegrant et al., 2005). But due to the restricted availability and the price of water the agricultural demand for water will increase slowly. Therefore, a decline of crop production and an increased competition for the outputs of arable agriculture are expected. Developing water harvesting techniques, appropriate water management and the integrated involvement of research and development to improve water-use efficiencies are laudable and necessary objectives to achieve. Strategic feed sourcing, conserving of water and enhancing animal productivity provide multiple options for increased livestock water productivity (LWP, i.e. the ratio of the net beneficial animal products and services produced in an agricultural production system to the amount of water depleted as a cost of producing them). Increasing LWP through better management of livestock-water interactions holds promise for sustainably improving livelihoods of rural people and making more fresh water available for other human needs (Oweis & Peden, 2008).

5.4 Plant

In general, animals are less sensitive to climate change than crops because they can move to seek for consumable vegetation and can access to feed. Changes in the primary productivity of crops, forages and rangelands could be observed in areas affected by climate change. Increased temperatures coupled with water scarcity and irregular rainfall patterns would affect the optimal growth rates of many forage and range species. The substitution of some crops that used to be cropped for fodder production (e.g. Maize) by others (e.g. Sorghum and millet) more suited to drier environments should be emphasized. Probabilities of germination and establishment decreased with a decrease in precipitation and increased with an increase in precipitation (Peters et al., 2010). These authors observed reductions in recruitment (73-80%) for all vegetation types with 50% less rainfall. However, reductions in rainfall below 25% of current amounts would reduce recruitment to low levels (<0.03). A small decrease in rainfall coupled with fewer but more intense storms may result in an increase in establishment. Peters et al. (2010) concluded that in addition to plant-soil feedbacks that favor shrub growth, soil water availability effects on the germination and establishment of grass seedling is another important constraint. As temperature and the level of CO2 change the competition dynamics of plant species and the floristic composition of rangelands will be exacerbated. The increase of CO_2 level will result in increased growth and a dominance of woody vegetation (i.e. fodder shrubs and trees) at the expense of herbaceous vegetation. Climate change may impact negatively on the nutritive value of consumable biomass through increased lignification of plant tissues and accelerated synthesis of specific secondary compounds. These compounds have different mechanisms of action, for example tannins form insoluble complexes with proteins rendering them unavailable to rumen microflora and the host animal. However, oxalates precipitate calcium and magnesium, thus limit their use in metabolic and digestive patterns occurring in the animal body. The direct and indirect impacts of climate change on space distribution of plants and their growth and quality justify the need to develop appropriate strategies for better use of fodder vegetation in the livestock-based production systems.

5.5 Pathogens and their hosts

In dry areas global warming is expected to increase the extent and intensity of aridity leading to a complex situation marked by changing patterns of interaction between hosts, pathogens and men within their environment. The potential impact of global warming on livestock health will be reviewed in the context of dry areas focusing on pathogens and their transmission and the hosts and their exposure and susceptibility to pathogens.

5.5.1 Pathogens and their transmission

The climatic changes induced by global warming exert a selection pressure that will modify the biodiversity of pathogens (Lovejoy, 2008), their biomass and the epidemiology of the infections they cause. Pathogens that are able to maintain and disseminate better in drought conditions would be expected to become dominant in areas where aridity would be increased under the influence of global warming. In general, it could be expected that pathogens having the lowest basic reproductive ratio or Ro (number of secondary cases produced in a population of naïve hosts after the introduction of one primary infected host, Morand & Guégan, 2008) would be the most vulnerable to the changes induced by global warming.

Among all pathogens, macroparasites are certainly those which development is the most highly conditioned by the variation of abiotic factors driven by climate changes (Morgan & Wall, 2009). Livestock species living in dry areas are exposed to different parasites, agents of specific diseases, or vectors of other pathogens. Ticks are widespread parasites in dry areas, for example in Tunisia up to 15 species infesting livestock have been identified (Bouattour et al., 1999). In the context of global warming that drives aridity northward in Tunisia, and more generally in North Africa, the most thermophilic tick species with low host selectivity like *Hyalomma dromedarii* could be expected to increase their distribution area. This tick species is usually found in arid and hyper-arid regions closely associated to the presence of camel. The tropism of this tick species is a strong biological advantage for emergence as its immature and adult stages could feed on different ungulates in addition to camels (Walker et al., 2003). *H. dromedarii* could establish and reproduce in other regions of Tunisia as observed after introduction of infested camels for instance for tourism activities. In Mauritania *Hyalomma dromedarii* has been identified, in conditions of cohabitation of cattle and camels, as an emerging natural vector of tropical theileriosis (d'Oliveira et al., 1997), a severe cattle disease due to the protozoan *Theileria annulata*. This emergence could be reproduced elsewhere particularly if camels will move to traditional regions for cattle rearing in North Africa. The potential emergence of a new natural vector of tropical theileriosis will modify drastically the epidemiology of this disease particularly in term of periods and context of transmission. In endemic regions these changes might lead to emerging new epidemiological profiles for tropical theileriosis to which animal health decision makers and farmers should adapt in terms of control strategies. This emergence of epidemiological patterns for already endemic pathogens should be clearly taken into account when assessing potential effects of global warming in term of animal and even public health.

Fasciolasis due to *Fasciola hepatica* is a helminthiasis of which the geographical distribution and local impact are highly influenced by climatic factors (Mas Coma et al., 2008). Fasciolasis is emerging or re-emerging in several regions of Latin America, Africa, Asia and Europe (Mas Coma et al., 2008). In Tunisia, the endemic zones for fasciolasis have been usually limited to the humid and sub-humid zones of the North West (Akkari et al., 2011) and to some oases of the South West of the country (Ayadi et al., 1993). In recent years, the severity of fasciolasis has been reported to increase according to several field observations. Furthermore, new foci of disease have been recorded in different regions of the semiarid and arid zones of Tunisia (unpublished data). This trend is probably resulting from the interaction between several factors directly or indirectly linked to global warming: i) Extension of irrigated areas and dams in the country, especially in the arid regions, ii) mobilisation of water resources from the humid regions of the North West, the usual habitat zone of the lymneid snail *Galba truncatula* the intermediate hosts of *F. hepatica*, to other regions, iii) occurrence, in the last 10 years, of repeated episodes of severe floods particularly in the North of the country, iv) longer suitable periods for the reproduction of the intermediate hosts with subsequent increased abundance of infective stages of *F. hepatica* on vegetation cover, due to retraction of the length of the cold (winter) season. In addition to rendering more frequent the application of control measures, increased number of parasites generations will increase the risk of occurrence of acquired resistance to anti-parasite molecules.

However, it must be emphasised that macroparasites populations, due to their longer generation time, expand slowly and need more time to become detected by the animal owner. However, these changes could be already initiated in several dry areas under the influence of both of global warming and human activities, as emphasised with the two examples developed above.

Vector borne pathogens are amongst the disease agents that are expected to get through important changes under the effect of global warming and particularly those having a wide spectrum of hosts including men and a high spreading potential. Arboviruses are probably the group showing the highest potential for emergence under the effect of global warming. The bluetongue invasion in North Africa and Europe is a good example of the risk of extension of an arbovirus far away of its usual distribution zones. The capacity of this virus to spread has been amplified by several factors reviewed by Purse et al. (2008), in particular: i) a host preference for a wide range of ruminants probably continuously distributed across agro-ecosystems, ii) wide range of susceptible vectors (Culicoides) with different ecology, iii) vectorial capacity influenced by temperature, iv) presence of silent infected animals sources of transmission to vectors, and v) over-wintering ability of the virus in the vector and eventually in the ruminant host. The occurrence of bluetongue virus epidemics in Tunisia since 1998 is emphasising the risks of introduction of pathogens from sub-Saharan Africa, most certainly with animal transboundary movements. Furthermore, extension of irrigated zones has certainly increased, across the country, the availability of habitat zones suitable for the development of *Culicoides*. The same mechanisms that are underlying the spread of bluetongue virus across the Mediterranean region could globally apply to other arboviruses and in particular the Rift Valley Fever virus (RVF), a pathogen transmitted by vector mosquitoes of the genera *Aedes* and *Culex* which are common in North Africa and the Middle East. Epidemics of RVF were initially described in semi arid and humid zones of East Africa, endemic or epidemic foci were therafter reported in semi arid areas of northern Senegal, Saudi Arabia and in irrigated zones in Egypt and Yemen (Martin et al., 2008). Changes directly or indirectly induced by global warming could enhance risks for RVF epidemics and in particular, heavy rainfall, building of dams and water storage structures for irrigation purposes, and extreme variation in rainfalls with combination of periods of drought and very heavy rainfall (Van den Bossche & Coetzer, 2008). Endemic vector transmitted diseases might be affected by global warming although on a lesser scale than with arboviruses agent of transboundary diseases. For instance, the epidemiology of piroplasmoses (infection due to piroplasmids of the genus *Babesia* and *Theileria)* could experience important changes in particular in regions where the vector tick species are hibernating during the cold season. This phenomenon of hibernation contributes in the regulation of pathogen biomass due to increased mortality in the vectors and probably also in the pathogen itself. It could be expected, as described with other parasites (Morgan and Wall, 2009), that any reduction or even alleviation of this overwintering process in response to extension of the warm periods of the year, will result in enhancing tick biomass as well as piroplasmid infection rates and intensities within the tick. Consequently, the risks and severity of piroplasmid infections in target hosts could increase above usual during the transmission season. In the case of tropical theileriosis this phenomenon could explain the higher tick infection rates and intensities recorded in regions where the vector ticks are active the year round in contrast to regions where theses vectors are going through a hibernation process (Darghouth et al., 2010).

The effect of global warming has been poorly assessed on several pathogens such as telluric helminths and protozoa, and non vector borne viruses and bacteria agents of epizootic or enzootic infections. As global warming is expected to increase ambient temperature and reduce soil and air moisture in dry areas ,pathogens that are known to be more susceptible to these changes would be expected to become less prevalent. However, it is important to remind that these stressing conditions could be moderated by particularities regarding the biology and the transmission of the pathogen itself as for instance, high contagious transmission (example of Foot and Mouth Disease virus), presence of terrestrial intermediate hosts (example of Anoplocephalid cestodes), intrinsic resistance of the exogenous forms of pathogens, presence of long lasting adults forms of macroparasites or infection state in the ruminant hosts, hypobiotic larvae in the case of helminths, and finally survival of pathogens/vectors in suitable microenvironment from where they could pass to their hosts. Based on the above discussion on pathogens it is rather difficult to draw general considerations, each relevant pathogen should be analysed in the context of global warming taking into account its vulnerability to the expected changes.

5.5.2 Host susceptibility and exposure to pathogens in dry areas

In addition to its direct effect on pathogens and their transmission, global warming will also influence the host susceptibility to pathogens and the factors of exposure to these agents. Host susceptibility is likely to play an important role in changes affecting animal health under the influence of global warming. Global warming will directly affect the wellbeing of livestock due to increased ambient temperature (Van den Bossche & Coetzer, 2008), furthermore more frequent episodes of severe drought will affect the availability of food and eventually the quality of water particularly in dry areas. These environmental stresses are likely to affect the capacity of innate and acquired immunity of livestock to pathogens (Sheldon & Verhulst, 1996). In the hyper-arid zones of the extreme south east of Tunisia, subnormal concentrations of globulins were recorded in 40% ewes during the lactation season in a severe drought episode, although the body conditions of animals remained acceptable. Consequently, the antibody response of the ewes to pathogens (or vaccination) might be harmed leading to risks of reduced immuno-competence against a range of pathogens and to less effective colostral transfer of immunity to lambs (Darghouth & Gharbi, in press). The question of host susceptibility should be also considered in case of emergence of new pathogens to which livestock has not co-adapted. The role of high host susceptibility has been considered in the rapid spreading of bluetongue virus serotypes within the European sheep flock (Purse et al., 2008). A similar phenomenon could also apply for the bluetongue epidemics recently recorded in Tunisia. High host susceptibility could also deeply influence the epidemiology of enzootic diseases as for example with tropical theileriosis. In this last case, it was observed in a Tunisian cattle herd exposed to the infection that disease incidence surveyed over 8 years increased dramatically, from 7.7 to 52% following progressive replacement of local cattle by Friesian phenotype in the herd. This evolution was recorded in the absence of any change in the enzootic state of tropical theileriosis (Darghouth & Gharbi, in press).

Exposure to pathogens is governed by different factors, for simplification we will consider in this part only those regarding the hosts and their management system.

Extensive loss in biodiversity has already been largely initiated under the influence of human activities in several regions of the world. In dry areas, global warming could be accounted as an additional factor worsening this loss at an extended scale. Pathogens intensity and spread are inversely related to host species diversity as spread of host specific pathogens is increased within the remaining species (Morand & Guégan, 2008). This loss in diversity might also represent an important force of selection for new trophic behaviours particularly for tick and insect vectors. The potential consequences of this "trophic shift" in term of pathogen transmission have been already outlined above with the example of the tick species *Hyalomma dromedarii*.

Global warming is expected to introduce important changes in animal management practices, which at their turn could increase the risks of emergence or re-emergence of pathogens and epidemiological profiles for diseases. The occurrence of extreme drought episodes in dry areas could enhance important migrations of livestock toward less affected zones. When occurring these migrations represent important risk factors for the spread of pathogens particularly those more prevalent in dry areas, such as for instance in the case of Tunisia, *Brucella mellitensis* infection which is by far more frequent in the arid regions of Tunisia by comparison to the North of the country (Hdia et al., 2009). Furthermore, the increased livestock density that could occur in the hosting regions might represent an additional factor enhancing the spread of specific pathogens particularly those highly transmissible or contagious. The challenges that farmers will face in dry areas under the effect of global warming, will most probably re-orientate the priorities of stockowners toward the mobilisation of resources and means for animal food, particularly at the light of recent increases of the international prices of crops. As a consequence there is a strong risk of marginalisation of animal health expenses given to the herds and subsequently an increased vulnerability to various pathogens. This question of vulnerability should be also addressed at the level of livestock production systems, for instance in Tunisia it is anticipated that cattle farms of small size will have a better resilience to global warming than will do big intensive modern units. By itself, this change, if occurring, will modify the epidemiology of major cattle diseases in Tunisia since the disease/exposure risk factors associated to small cattle units are not qualitatively and quantitatively similar to those prevailing in large cattle units as observed for instance with tropical theileriosis in Tunisia (Darghouth et al., 2010).

6. Livestock response to environmental factors affected by global warming

Global warming may strongly affect production and reproduction performances of farm animals and impact worldwide on livestock production (Nardone et al., 2010).

6.1 Heat stress

High ambient temperatures compromise reproductive efficiency of farm animals in both sexes and hence affect milk and meat production. There is a range of thermal conditions under which animals are able to maintain a relatively stable body temperature through behavioural and physiological mechanisms (Bucklin et al., 1992). Heat stress includes not only temperature and solar radiation, but also humidity and wind speed. Adjustments for humidity can be made using the temperature-humidity index (NOAA, 1976; Hubbard et al., 1999) which has been adapted for use in the livestock safety index (Livestock Conservation Institute, 1970). McDowell et al. (1976) suggested that the temperature–humidity index (be used as an indicator of thermal climatic conditions. This index is calculated from the relative humidity and the air temperature of a particular day according to the equation defined by Kadzere et al. (2002): $THI=0.72\ (W+D)\ +40.6$

where W is wet bulb and D is dry bulb temperature in °C. Adjustments for solar radiation and wind speed have been also developed and should be considered when predicting heat stress (Mader et al, 2006).

6.1.1 Effect on milk production

There is a particular temperature zone in which lactating dairy cows feel comfort and produce at an optimal level. Lactating dairy cows prefer ambient temperatures ranging from 5°C and 25°C, the ‘thermoneutral’ zone (TNZ) (Roenfeldt, 1998). When environmental temperatures move out of the thermoneutral zone (or comfort zone) dairy cattle begin to experience either heat stress or cold stress.

In dairy cows, studies have considered two critical THI thresholds (Davison et al., 1996): Milk production starts to decline at THI above 72 for cows which have no access to shade, but important declines occur at THI above 78 for cows having access to shade and a sprinkler system (Jones & Hennessy, 2000). High productive animals having high endogenous heat production, exhibit tolerance to heat. Holstein dairy cow is the primary target of heat stress relief, followed by feedlot cattle (Berman, 2005).

The stage of lactation is an important factor affecting dairy cows' responses to heat. Johnson et al. (1988) observed that the mid-lactating dairy cows were the most heat sensitive compared to their early and late lactating counterparts while Sharma et al. (1983) concluded that after 60 days of parturition (early lactation), climatic conditions affect cow performances and decreased its capacity to cope with heat stress.

Lactating dairy cows feel heat stress, when the rectal temperature is above 39.4°C. To cope with heat stress the cow should allocate more energy to maintain the body temperature at the expense of the amount of energy needed for milk production. Reducing dry matter intake, and therefore heat generated during ruminal fermentation and body metabolism, help maintain heat balance. Decreased feed intake has been recognized as one of the main reasons for reduced milk yield (Beede & Collier, 1986).

The reduction in milk production caused by heat stress could be the result of decreased nutrient intake and nutrient uptake by the portal drained viscera of the cow. Blood flow shifts to peripheral tissues for cooling purposes, alter nutrient metabolism and contribute to lower milk yield. The decrease in energy intake results in a negative energy balance, and partially explains why cows lose significant amounts of body weight and body score when subjected to heat stress (Lacetera et al., 1996; Rhoads et al., 2009).

During late pregnancy and the early post partum period, hot environment negatively affects milk quality, leads to lower colostrum net energy fat and protein content. In addition, the analysis of protein fractions showed a reduction in percentages of casein, lactoalbumin, IgG and IgA (Nardone *et al.*, 1997, 2006).

Due to the reproductive seasonality of sheep in the middle latitudes of the northern hemisphere, physiological drop in milk yield which occurs during late lactation in summer often hides the negative impact of high temperature on milk production. Ambient temperatures in late spring and summer often exceed the thermal neutral zone (5°C to 25°C) of sheep (Curtis, 1983; Costa et al., 1992). Hot climate induces a marked increase in rectal temperature, and respiration rate, which increases energy requirements for maintenance by 7 to 25% (NRC, 1981). This may result in respiratory alkalosis due to reduction in blood CO2 (Habeeb et al., 1992). Feed intake decreases in heat-stressed sheep (Abdalla et al., 1993), due to both the effort of reducing heat production (Yousef, 1987; West, 1994) and the slower feed transit throughout the digestive tract (Christopherson, 1985). Under these conditions, body reserves of fat and nitrogen are used to supply energy through gluconeogenesis at the expense of the mammary gland, especially in early lactating animals (Jones et al., 1990; Amaral-Phillips et al., 1993).

Also, high temperatures decrease milk production in goats and affect its composition (Olsson & Dahlborn, 1989).

6.1.2 Effect on growth performances

Birth weight and survival of neonatal lambs was improved when shade was provided during late pregnancy (Hopkins *et al*., 1980). This suggests that heat stress has an effect on the uterine environment, substantially reduces the total embryo cell number and placentome size resulting in smaller size of lambs. They would also be more susceptible to dehydration during the early stages of life. Temperatures ranging between 15°C and 29°C do not seem to have any effect on growth performance. The effects of high ambient temperature on growth performance are induced by the decrease of the anabolic activity and the increase in tissue catabolism (Marai et al., 2007). This decrease in anabolism is essentially caused by a decrease in voluntary feed intake of main nutrients. The increase in tissue catabolism occurs mainly in fat depots and/or lean body mass. Lamb production is deleteriously affected by exposure to heat stress and this causes an economic loss.

6.1.3 Effect on reproduction performances

High ambient temperatures compromise reproductive efficiency of farm female and male animals. Cattle's fertility is reduced from around 50% in winter to less than 15% in summer A drop can occur in summer of about a 20–27% (Thatcher & Collier, 1986; Chebel et al., 2004). In practice, dry pregnant cows are not protected from heat stress because they are not lactating, and it is incorrectly assumed that they are less prone to heat stress. The dry period is particularly crucial since it involves mammary gland involution and can affect endocrine responses that may increase foetal abortions, shorten the gestation length, lower calf birth weight, and reduce follicle and oocyte maturation associated with the postpartum reproductive cycle (Bilby et al., 2008).

The somatic cells within the follicles (theca and granulosa cells) could be damaged by heat stress. Heat stress affects ovarian follicles and induces a decrease in estradiol synthesis (Wilson et al., 1998). It compromises oocyte growth in cows by altering progesterone, luteinizing hormone, and follicle-stimulating hormone secretions during the oestrus cycle (Ronchi *et al.*, 2001). Rensis & Scaramuzzi (2003) hypothesised that the dominant follicle develops in a low LH environment resulting in reduced estradiol secretion inducing poor expression of oestrus by reducing its length and intensity. High temperature can reduce the drive for sexual behaviour, leading to "silent oestrus" in 35% of ewes (Sawyer et al., 1979).

Once ovulation occurs, the damaged oocyte has reduced chances of fertilizing and developing into a viable embryo. The ability of zygotes to develop blastocyst was reduced during summer (Al-Katanani et al., 2002). Heat stress can also affect the early developing embryo. When heat was applied from day 1 to day 7 after estrus, there was a reduction in embryo quality and stage from embryos flushed from the reproductive tract on day 7 after estrus (Putney et al., 1989). During pregnancy and prepartum heat stress could decrease thyroid hormones and placental estrogen levels, while increasing non-esterified fatty acid concentrations in blood; all of which can alter growth of the udder and placenta, nutrients delivered to the unborn calf, and subsequent milk production (Collier et al., 1982a).

In male, semen quality (concentration, number of spermatozoa and motile cells per ejaculate) is lower in summer than in winter and spring (Mathevon *et al.*, 1998). Heat stress reduces libido of rams and causes sperm damage, reducing fertility which will affect flock production.

Buffaloes' ovarian activity decreases in hot summer and increases during winter and spring; the lowest sexual activity occurred in summer season (Zeidan, 1989). Oestrous cycle is suppressed (Williamson & Payne, 1971). Anoestrus occurred in heat stressed animals (Bond *et al.*, 1960). Despite the evidence of some intrinsic hormonal constraints (Madan 1987), the problem of long intercalving periods seems to be due to environmental factors, and can be controlled by the farmer (Sastry & Tripathi 1988). Buffaloes protected from high ambient temperature and direct solar radiation, and adequately fed exhibit higher reproductive performance (Acharya & Bhat 1989). Management practices involving provision of shade and application of water to the skin surface reduces the adverse effects of a hot environment and improves oestrous expressivity and thus reduces breeding seasonality.

6.2 Drinking water

Water has several important functions in the animal body such as regulation of body temperature, elimination of waste products from the body via urine, feces, and respiration;

transport of nutrients and other compounds into and out of cells; electrolyte balance in the body; and as a fluid environment for the developing foetus. Water is needed to make saliva for swallowing feed and for chewing. In addition a milking cow needs water for milk production. Domesticated animals can live about sixty days without food but only about seven days without water. Livestock should be given all the water they can drink because animals that do not drink enough water may suffer stress or dehydration. The total requirements of water to produce world-wide animal products per year is approximately 2800 km3 of water, which represent 7.8% of the net precipitation on land masses of the globe (36,000 km^3=107,000 km3 total precipitation−71,000 km^3 evapo-transpiration) (Nardone et al., 2010).

Lactation and high environmental temperatures are major elements that drain body water and consequently increase the demand for water by animals. The amount of water a dairy cattle will drink is influenced by the quantity of dry matter ingested. Milking dairy cows consume 4 to 5 kilograms of water per kilogram of milk they produce. Of this amount, drinking water provides 80 to 90% of these needs, with the remainder coming from moisture found in feeds. Dairy cows are able to cope with a sustained restriction of total water intake to almost 50%.

Intake of water is intermittent, while the loss of water is continuous. During the dry season, intermittent watering had a negative effect on the growth rate of sheep. Live weight loss associated with water deficit could be ascribed to a reduction in feed and water intakes, together with loss in the body water.

The reproductive performance of the pregnant ewes is also adversely affected by water deprivation, since the rates of abortion and stillbirths, as well as the lamb mortality rate, rise as the ewes are deprived from drinking-water.

Goats are considered highly suitable animals for rearing in such areas, as they were the first domesticated in hot and arid regions of the world. Desert goats seem to be the most efficient among ruminants in regard to their ability to withstand dehydration (abioja et al., 2010). During periods of water shortage, goats activate several water saving mechanisms that would result in minimizing their water losses and therefore increasing their capacity to withstand water deficit (Silanikove, 2000b).

Water intake in buffaloes increases with increasing environmental temperature, exposure to direct solar radiation and the ratio of water intake/food consumption also increase.

Total dissolved solids (TDS), total soluble salts (TSS), and salinity (S) are physiochemical properties of water used to assess water quality. Saline is one of the more common causes of high TDS water, but the effect on water intake and animal performance is likely to be less than when the same TDS level is a result of high sulfate combined with magnesium and/or sodium. When TDS levels in water are less than 3,000 ppm, there is little to no effect on cattle, although at first introduction there may temporarily be a mild case of diarrhea. Between 3,000 and 5,000 ppm TDS, the effects on milk production and animal performance are variable; however, high TDS water is more likely to decrease milk production during summer months (Jaster et al., 1978; Challis et al., 1987; Sanchez et al., 1994; Solomon et al., 1995). The TDS guidelines suggest that water containing less than 5,000 ppm TDS may be offered to lactating cattle, but water containing more than 7,000 ppm is unacceptable for all cattle (NRC, 2001). High salts reduce water intake, in turn will reduce feed intake, which reduces overall performance.

7. Adaptation of livestock to potential stressors from global warming

7.1 Animal breeding

In an attempt to match animal genetic resources with production systems to achieve livestock development objectives, a substantial body of information will need to be sought out, collated and scrutinized. This will include information on government policies and legal instruments that affect livestock production (including how they promote or inhibit development strategies); the country's major production systems (human development objectives that need to be addressed, the capacity and motivation of farmers to participate in development strategies and the environmental sustainability of the production systems); and historical and predicted future trends for each production system (i.e. social, market and environmental trends – including the predicted effects of climate change) (FAO, 2010).

To further stress the environmental dimension in livestock production, we report the policies and legal instruments related to some environmental issues that need to be considered when developing livestock development and breeding strategies (FAO, 2010):

- Soil erosion associated with grazing systems;
- Depletion of soil nutrients;
- Disposal of animal waste;
- Water availability and management;
- Water pollution;
- Gaseous emissions associated with climate change;
- Forest conservation and management; and
- The integration of livestock management with the management of wild flora and fauna.

Animal genetic resources can be used in various ways to achieve livestock development objectives. Strategies may be based on the use of locally available breeds, introduced breeds, or both. The breeds chosen may provide the basis for straight- or cross-breeding schemes. It is essential to ensure that the animal genetic resources used are well matched to the production systems in which they will be kept, taking account of the development objectives and planned development strategies for these systems. Evidence gathered in the last 10 to 15 years has yielded ample evidence that in many cases local breeds provide a good fit to these needs; in such cases a decision to use a locally available breed will be appropriate (FAO, 2010). In extensive production systems, locally thriving breeds show great adaptation to the prevailing environment including the occurrence of extreme climatic events (droughts, temperature rise, water scarcity, etc.).

Ruminants are a major source of green house gas emission especially methane (Wall & Simm, 2008) hence contributing to global warming. In many parts of the world, livestock development programs are no longer based on the increase of livestock population and several developed countries are now adopting adjustment policies to stop growth of livestock population. Such strategies should also be implemented by developing countries or regions that are threatened by overgrazing and that are facing large disproportions between livestock population and the size of the grazing space. For these countries, under the most pessimistic scenarios of global warming and the reduction of the grazing space, strategies to develop livestock must target a substantial improvement of the productivity through genetic improvement of traits that are economically important. Basically, the same levels of production can be achieved while keeping less animals hence protecting the environment and reducing negative effect on global warming. If these objectives are to be reached by the introduction of exotic animals, additional cost investments are needed to provide adequate housing and cooling facilities. In the long term, such investments might hamper the profitability of livestock breeders.

7.2 Adaptation mechanisms to global warming

Climate change will accentuate water and food scarcity and alter their quality. This situation is acute mainly in dry areas where most of small ruminants, buffaloes and camels are raised. In absence of farmer intervention, these animals will be exposed to underfeeding and or to water deprivation or restriction. They may also face other environmental stresses like high temperatures. To cope with these nutritional and environmental stresses farm animals developed some adaptation mechanisms allowing them to survive and even to produce and reproduce when raised under these harsh conditions. Some of these mechanisms are reported below.

7.2.1 Behavioural, digestive and metabolic mechanisms

Metabolic and hormonal mechanisms and behavioural regulations could be involved to help the animal cope with different stressors resulting from climate change. We report here few examples of adaptive mechanisms:

- Severe underfeeding is associated with body reserve mobilisation and the establishment of mechanisms for saving limiting metabolites (glucose and amino acids) and a reduction in the basic metabolic and energy expenditure through reduced movement and walking by the animal (Blanc et al., 2006). Body reserves appear to play a fundamental role in restoring the energy balance. Fat-tailed sheep like the Barbarine breed cope with underfeeding better than thin-tailed sheep (Ben Salem et al., 2010). Fat-tailed sheep have a capacity to deposit and mobilise body reserves from the tail (fat) and the rest of the body.
- The capacity of the kidney to concentrate urine and its ability to reduce water loss during dehydration is directly related with the relative kidney medullary thickness (RTM). The greater the RTM, the greater the ability of the kidney to reabsorb water. Sustained water restriction resulted in the activation of water saving mechanisms. Plasma vasopressin concentration increases with the extend length of dehydration in lactating goats. This will reduce the renal secretion which contributes to the water saving mechanism. Short period of water deprivation is rather beneficial to range lambs and kids; it improves diet digestibility and nitrogen retention. The passage of ingesta through the digestive tract will slow down allowing more time for micro-organisms to digest available feed. Concentration of protozoa in the rumen increases because of dehydration which leads to more efficient utilization of nutrients and the rate of fermentation increases.
- To the question how they can cope with salty water, sheep and goats excrete more urine and increase the filtration rate to reduce the high salt load resulting from their high consumption of saline water. Exposure to saline water results in an induction of enzymes in the ileum, liver and kidney. The main enzyme is NaK ATPase that increases the pumping of sodium out of cells and potassium return to the intracellular space. The induction of this enzyme is a powerful adaptive mechanism.

7.2.2 Physiological mechanisms

Substantial progress has been made in the last quarter-century in delineating the mechanisms by which thermal stress influences performance of animals. Heat-stress sensitivity and tolerance influences all the reproductive features, from estrus behavior to seminal characteristics and embryonic survival (Silanikove, 2000a,b; Kadzere et al., 2002; West, 2003; Roth, 2008; Hansen, 2009; Nienaber and Hahn, 2009). These deleterious effects of heat stress are the result of either the hyperthermia associated with heat stress or the physiological adjustments made by the heat-stressed animal to regulate body temperature. Many effects of elevated temperature on gametes and the early embryo involve increased production of reactive oxygen species. Genetic adaptation to heat stress is possible both with respect to regulation of body temperature and cellular resistance to elevated temperature. The adaptive capabilities of animals and livestock production systems are key elements when an animal faces different environmental insults. Acclimation to thermal stress is now identified as a homeorhetic process under endocrine control. The process of acclimatization occurs in 2 phases (acute and chronic) and involves changes in secretion rate of hormones, as well as in amount of receptors in target tissues. The time required to complete both phases is weeks rather than days. In addition, biometeorology has a definitive role when implementing a rational management to meet the challenges of thermal environments. Under heat stress, either reductions of heat load or increase of heat loss are the primary management tools. Actions to mitigate environmental heat insults may be based on risk management, by considering perceived thermal challenges, assessing the potential consequences and acting accordingly. Appropriate actions include: shadow, sprinkling, air movement, or active cooling.

The ability of ruminants to adapt to marginal production systems is partially determined by their capacity to develop appropriate compensatory responses to counteract different environmental stressors (Silanikove, 2000b; Smith & Dobson, 2002). Despite the fact that most of small ruminants in the world are raised in the dry and humid tropics, limited information is available on the effect of thermal stress on reproduction of this species. Traditional goat production systems under arid and semiarid conditions have been developed under restricted conditions of both water and food supply besides high temperatures (Nagy, 1994; Silanikove, 2000a,b). Under this scenario, goats have exerted metabolic and renal compensatory responses throughout some neuroendrocrine controls related to an efficient use of both metabolic and water reserves (Silanikove, 2000a,b).

When facing stress, goats activate two response mechanisms:

- a short-term activation of the hypothalamic-hypophyseal-adrenal axis with the concurrent increase in cortisol release.
- a middle-term adaptation response to stress, which is characterized by a decrease of cortisol to basal levels (Minton, 1994).

8. Strategies to mitigate climate change

Research and development options should be emphasized to help mitigate negative impacts of climate change. Cost-effective and feasible options at the farm level should be considered while developing short or long-term mitigation strategies. Obviously, these strategies are not universally applicable but are specific to each production system and location.

8.1 Reducing enteric methane production

A set of nutritional strategies proved efficient in reducing methane emissions in ruminants. We report in this section some of these options depicted from the reviews by O'Mara et al. (2008) and Martin et al. (2010).

- Replacing roughages with concentrates results in increased proportion of propionate in the rumen, thus less hydrogen available for CH4 production.
- Feeding legume forages results in less emission of CH4 than grass-based diets.
- Feeding ensiled forages reduces methanogenesis.
- Improving pasture management is associated with decreased CH4 emissions due to improved livestock productivity and a reduction of dietary fibre.
- Administering plant extracts (condensed tannins, saponins, essential oils) reduces CH4 emissions. Tannins have a direct effect on methanogenesis and indirect effect on hydrogen production due to lower feed degradation. Saponins, glycosides available in many plants, have direct effect on rumen microbes. They decrease protein degradation and favour at the same time microbial protein and biomass synthesis. Saponins induce protozoa suppression. Essential oils contain many biologically active molecules which have antimicrobial properties. Some compounds in essential oils are toxic to methanogens.
- Supplementing ruminants with lipid sources (fat or oils) impacts negatively on methanogenesis by toxicity to methanogens, causes defaunation thus suppresses protozoa associated methanogens and decreases fibre digestion.
- Administering ionophores like monensin in the diet results in a shift of bacterial population from gram positive to gram negative organisms with a concurrent shift in the fermentation from acetate to propionate (Moss et al., 2000).

8.2 Carbon sequestration

The success of strategies of greenhouse gas mitigation depends on the use of appropriate tools to reduce carbon losses and to increase carbon sequestration. Soussana et al. (2010) reviewed a set of management practices that help achieve these objectives. We report below some of these practices that refer to grassland carbon sequestration:

- avoiding soil tillage,
- moderately intensifying nutrient-poor permanent grasslands,
- avoid heavy grazing,
- grass-legumes association rather than grass only.

8.3 Livestock health control

Although of being essential in facing the changes induced by global warming in animal health, the preparedness of veterinary authorities and stockowners to this important issue remains questionable in several countries located within dry areas. Taking into account the presence of important interregional differences in animal productions systems, pathogens background and risk factors for pathogens transmission and disease occurrence, it seems more appropriate to draw up realistic guidelines for livestock health strategies combating the impact of global warming in dry areas.

Maintaining immuno-competant animals in dry environment evolving gradually toward increased aridity will represent the first priority regarding animal health, this is not only important in regard to animal response to pathogens but also for an optimal efficacy of vaccinations and most particularly those targeting transboundary diseases. Non-sustainable systems based on subsidised feed complements are likely to be the first to collapse in dry areas under the effect of global warming, particularly with the current international market prices of their intrans. This collapse might generate additional risks of occurrence/

emergence and propagation of diseases, as it may be an indirect cause of stress impacting the health conditions of livestock. Species and production systems that are resilient to aridity should specifically be privileged. Camel is probably one of the species that should be considered as an alternative to ruminants in arid areas of Africa and Asia for the production of meat, in this context it is worth to envisage appropriate strategies for encouraging the extension of this species toward dry areas located outside of its usual distribution zones. In Tunisia for instance, camels grazed on rangelands of the hyper-arid region of the South East of Tunisia were shown to present much less biochemical disorders related to a diet deficient in proteins and misbalanced in minerals than do sheep. Local knowledge contributing to increase sustainability of livestock productions systems must also be valorised, for instance stockowners of the Tunisian south select their rams and ewes on resilience to drought conditions during the most difficult feeding period of the year. In arid and semi-arid regions of eastern and southern Africa pastoralist communities have developed autonomous adaptation strategies based on optimised management of resources including transhumance, diversification of economic strategies, use of different livestock species in the same herd, and intensification of resources use (Vand den Bossche & Coetzer, 2008). Similar strategies were also developed by agro-pastoral communities in hyper-arid zones of North Africa.

Any comprehensive mitigation strategy targeting the effect of global warming on livestock health should specifically be based on risk assessment of the probabilities of emergence and re-emergence of pathogens as well as of epidemiological profiles for already established diseases. A multidisciplinary approach was adopted in France for this purpose; 20 diseases, the incidence and distribution of which are prone to global warming effects, have been identified. These diseases were assessed further for their potential animal health, human health and economic impacts and their probability of occurrence. This approach has resulted in identifying a final list of 6 pathogens, the most likely to emerge or re-emerge, and also in recommending practical measures for monitoring risks of their occurrence. In practice, this approach will afford an objective basis for carrying out epidemio-surveillance operations and recommending appropriate prevention programmes specifically focusing on the expected impact of global warming on livestock health and even human health if zoonotic pathogens are at risks of emergence or re-emergence. It is important to emphasise, in the context of dry areas that this approach may also concern diseases that are absent in a considered dry zone but present in other bioclimatic zones of the same country, as for instance the case *F. hepatica* that spread out to arid zones of central Tunisia. The opposite situation needs also to be considered, as some pathogens could be more prevalent in dry zones of a specific country; any massive migration or transfer of livestock out of this zone, under the effect of extreme drought, could be an important factor of re-emergence of the pathogen in the rest of the country as outlined above with the example of small ruminants brucellosis in the arid and hyper-arid zones of Tunisia. Implementing epidemio-surveillance operation in the context of global warming raise also the question of preparedness of institutions and particularly of local diagnostic laboratories and the staff involved in identifying emerging pathogens.

The success of field implementation of epidemio-surveillance programs will greatly depend on the presence of enough skilled personnel and also on participation of stockowners. Stockowners must be even be involved in preparation phases of strategies coping with the effect of global warming on livestock health, emphasising the needs for a reliable stockowners representativeness through professional bodies totally independent of governmental administrations. This will ensure that specific field requirements necessary for an optimal monitoring of the risks of disease are properly understood and subsequently accepted by the end users. For instance, the issue of animal or herds identification is essential for any epidemio-surveillance system; its acceptance by stockowners could only be guarantied on the basis of a participatory approach.

In addition to the above mentioned technical options, recommended development solutions to mitigate GHG include:

- Participatory approach involving all concerned stakeholders (farms, herders, technicians, scientists, etc.) for sustainable management of natural resources.
- Involvement of target communities in the whole process of identifying, transferring and adopting appropriate solutions.
- Regulations and incentives for better management of natural resources and improvement of livestock production systems are keys to support livestock keepers better cope with climate change risks.
- Settlement of appropriate risk management mechanisms and preparedness measures.
- Awareness efforts should be made to share knowledge on climate change with target communities to anticipate negative impacts and to enable development organisms to assist livestock keepers.
- Development and research organisms should agree on methodological tools targeting reforestation, rehabilitation of degraded rangelands, livestock manure management, and improved feeding management.
- Local knowledge should be valorised while establishing strategies to adapt to climate change and to mitigate GHG emissions.

9. Conclusions

The growing human population and its increasing affluence will increase the global demand for livestock products. But the expected big changes in the climate globally will affect directly or indirectly the natural resource base, the animal productivity and health and the sustainability of livestock-based production systems. Global warming is expected to introduce an additional level of pressure for livestock production systems in dry areas, the challenge that it will cause might, hopefully, result in the emergence of novel sustainable models for livestock productions and for disease prevention opening the way forward to sustain this challenge. A battery of technical and environmentally friendly options have been recommended by scientists to help livestock keepers cope with climate change and to protect ecosystems against negative impacts of global warming (e.g. green house gas emissions, carbon sequestration, etc.). In addition to the technical options, communities based participatory approach involving all stakeholders should be considered for successful transfer and sustainable adoption of recommended technical packages in areas exposed to global warming. Additional efforts are needed to develop methodological tools for communities' development under the climate change context. We should remind that farmers already have a wealth of indigenous knowledge on how to deal with climate variability and risk, but well-targeted capacity building efforts are needed to help farmers deal with changes in their systems that go beyond what they experienced in the past.

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Regional Climate Change and Impact Assessment for the Federal State Hesse, Germany, and Implications of the Global 2 °C Climate Target

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1. Introduction

1.1 Background

While climate change is a global problem, the impacts as well as mitigation and adaptation measures are local and require local and regional stakeholders to act accordingly. Thus, there is an ever increasing demand to provide climate change information with high resolution for impact assessment and regionally tailored mitigation and adaptation actions. The environmental agency of the federal state of Hesse, Germany, is tasked to provide the scientific background for regional governmental bodies, local economy and the general public. The most recent development on the political agenda regarding climate change is the global political target of limiting climate change to not more than 2 °C above the pre-industrial level. In December 2010 the United Nations Framework Convention on Climate Change (UNFCCC) agreed on this goal at the 16th Conference of the Parties (COP16) to avoid the most dangerous and possibly irreversible impacts of climate change (UNFCCC, 2011). In the meantime, countries are preparing for adaptation to the expected impacts of climate change. For example, Germany has decided its Adaptation Strategy in December 2008 (Bundesregierung, 2008). Now it is the responsibility of the federal states to put this strategy into adaptation measures and into concrete action.

While the feasibility of the 2 °C climate target is quite uncertain and will require a concerted and ambitious mitigation policy from all states, the climate change and associated impacts that are projected under the 2 °C target can be considered the un-avoidable changes society has to face. For political and economic decisions that account for climate impacts a thorough assessment of the regional implications of the global 2 °C target is necessary. Here, we will present the climate change in Hesse that would occur under the global 2 °C target using two different analysis methods, i.e., dynamical downscaling and empirical statistical downscaling. We will compare their results to the regional climate change that would occur under the IPCC

Special Report on Emission Scenarios (SRES; Nakićenović et al., 2000) A1B scenario, which more or less resembles the current emissions. From this comparison we assess the regional climate change that can be avoided if the necessary mitigation actions were realized to shift from the current emission path to a low-emission path for keeping the 2 °C target.
In the EU FP6 Project ENSEMBLES a scenario, known as E1, was developed that follows an emission path which eventually leads to a CO_2-equivalent concentration of 450 ppm, a level which is considered to provide a more than 50% chance of limiting global warming to 2 °C (Johns et al., 2011). Therefore we will present results from an assessment for the climate change under the 2 °C target and compare it with the projected changes under the A1B scenario.

1.2 The global 2 °C target

At the COP16 of the UNFCCC held 2010 in Cancun, Mexico, it was agreed "*... to hold the increase in global average temperature below 2 °C above pre-industrial levels ...*" (UNFCCC, 2011). As pointed out by Randalls (2010), who traced the origins and the development of the 2 °C target, this was a milestone in a process of growing awareness that there is a "*... maximum allowable warming to avoid dangerous anthropogenic interference in the climate.*"
Whereas in the 1970s and 1980s the prevailing approach was to consider carbon emissions merely as a pollutant, publications such as Bach (1980) underlined the necessity that climate policy should be based on an assessment of the risks of climate change. There was dispute over the magnitude of tolerable change, whether it should be constrained to a temperature rise of 0.1 °C per decade or to a stabilization of the global temperature on a higher level. Rijsberman & Swart (1990) introduced the notion of a temperature rise that should not surpass a mark of 2 °C above the pre-industrial level. The German Advisory Council on Global Change (WBGU, 1995) performed important groundwork concerning aspects such as the identification of a tolerable window for the temperature development which is corroborated by the climate fluctuations of the present geological epoch as well as addressing the question of adaptation costs.
Basically, the 2 °C target is designed to avoid the most dangerous climate impacts. WBGU (1995) states the "preservation of creation" and "prevention of excessive costs" as the boundary conditions for which this target was developed. While even at a global warming below 2 °C impacts of climate change on ecosystems and society cannot be excluded, it is believed that below the 2 °C threshold some dangerous climate change can be avoided. In the third assessment report of the IPCC, a diagram summarizes the "reasons for concern" with respect to different levels of global mean temperature change relative to the 1990 level (IPCC, 2001, Fig 19-7). The figure was updated by Smith et al. (2009), showing even greater reasons for concern.
Previous simulations aiming at keeping the 2 °C target have either used stabilization scenarios (e.g., May, 2008) or were started from the SRES B2 scenario (Meinshausen et al., 2006; van Vuuren et al., 2007). Since current atmospheric CO_2 concentrations are clearly above the SRES B2 path (Le Quéré et al., 2009), both approaches seem questionable. In the framework of the EU-funded project ENSEMBLES (van der Linden & Mitchell, 2009) a mitigation scenario was developed that provides a plausible socio-economic path towards keeping the 2 °C target. The scenario starts from the SRES A1B scenario and aims at stabilizing atmospheric CO_2-equivalent concentrations at 450 ppm, while allowing a slight overshoot over this level around the middle of the current century. This scenario is called E1 (Lowe et al., 2009). A more detailed description of the scenario construction and global mean results for temperature, precipitation, and the carbon cycle feedbacks can be found in Johns et al. (2011).

For the planning of mitigation and adaptation measures, it is relevant to know how much of the projected climate change might be avoided due to mitigation actions and which part of climate change might occur even under the 2 °C target and therefore calls for adaptation. Because the goal refers to a global mean temperature increase, it is necessary to deduce what the impacts would be regionally.

It should be mentioned that there is debate in the scientific community on the feasibility of the 2 °C target. Randalls (2010) points out that (i) it is established in the context of large uncertainties about climate sensitivity, (ii) there is insufficient clarity on the damage costs and (iii) researchers interested in science-policy dynamics have critiqued it for forcing a rather tenuous policy debate that has detracted from the process of reducing emissions.

However, the 2 °C target can serve as a focus point to assess the possible gains (in terms of avoided impacts) of ambitious mitigation actions. For governmental and economic bodies this is a central argument on whether or not mitigation actions are put into place. Moreover, it has been consented to on a broad international basis and will be a major factor in climate change negotiations.

1.3 Climate change assessments in the federal state Hesse

As a typical regional stakeholder, the federal state Hesse in central Germany has instigated regional climate change assessments and climate impact research on the issues relevant for the regional economy and ecology since the year 2004. In two frameworks ("INKLIM2012" and "INKLIM2012 Baustein II plus") several projects were realized.

Already detectable climate change in Hesse shows that the annual mean warming from 1951 to 2000 was 0.9 °C (Schönwiese et al., 2005), thus larger than the global average for this period of about 0.7 °C (IPCC, 2007). This is accompanied by an increasing number of heat days (daily maximum temperature $\geq$ 30 °C) in the summer months, particularly in August, and a decrease of frost (daily minimum temperature $<$ 0 °C) and ice days (daily maximum temperature $<$ 0 °C) in winter and spring (Schönwiese et al., 2006). Furthermore there is already a detectable tendency in Hesse for dryer summers and wetter winters (Schönwiese et al., 2005), with an increase in the number and duration of dry spells in summer (Schönwiese et al., 2006).

These tendencies are also projected for future climate change in central Europe (IPCC, 2007). Furthermore there are results for the state of Hesse from an analysis of high resolution regional climate model projections for several SRES-Scenarios (Nakićenović et al., 2000) using both, empirical statistical (ESD) and dynamical (RCM) methods (Federal State of Hesse, 2011). An assessment of likely future temperature change for Hesse in conjunction with the 2 °C target can be found in Kreienkamp & Spekat (2009).

The analyzed future climate impacts for water management (groundwater and its use for irrigation and household demand as well as flood and low-flow conditions in rivers) show an increasing demand for irrigation water during the growing period (Berthold & Hug, 2008), combined with increasing flood risks during winter and increasing low-flow situations during summer (Brahmer et al., 2008) in the analyzed parts of Hesse.

The projected changes in temperature and precipitation have consequences for agriculture, forestry, fruits, vine, and natural ecosystems. In all these sectors the vulnerabilities of the respective systems are assessed, highlighting possible impacts. The goal of the impact research projects is to assess the risks and to develop possible adaptation strategies for each sector. A further focus of research projects is on the impacts of climate change on the health sector.

1.4 Goals of this chapter

The goals of this chapter are to:

(a) Assess the magnitude of regional climate change impacts in Hesse under a global 2 °C target from time slices of higher emission scenarios (IPCC SRES A1B, A2 and B1), for the time frame when the global 2 °C target is breached, using one GCM and two RCMs and one ESD.

(b) Assess the regional results for Hesse for the end of the century in one ENSEMBLES E1 simulation.

(c) Provide an estimate of avoidable regional climate change in Hesse from comparison of results for a higher emission scenario (A1B) to the results for the 2 °C target.

The methodologies are in principle applicable in any region of the world. Since RCM and ESD simulations are not available in all regions, some useful hints for the interpretation of the global results can be gained from the analyses shown in this chapter.
In Section 2 we present the data and methods used. Section 3 presents the results from different types of analyses. The first step is to determine what the local or regional temperature increase would be, if the global temperature would rise by 2 °C (Subsections 3.1 to 3.4). In Subsection 3.5, the E1 scenario (Lowe et al., 2009) is analyzed for the region of Hesse, which aims at keeping the 2 °C target for the end of the current century. Avoidable climate change for this time frame is assessed from the difference between results from the E1 scenario and a higher emission scenario (SRES A1B) in Subsection 3.6. A summary of the presented findings and some conclusions form the final Section 4.

2. Data and methods

The data used for this study encompass one global climate model (GCM), two dynamical regional climate models (RCM) and one empirical statistical downscaling (ESD) method. All are briefly featured below.
Global climate model ECHAM5: The global mean pre-industrial temperature level is derived from three historical runs of ECHAM5/MPI-OM (Roeckner et al., 2003; 2004), henceforth abbreviated as ECHAM5. Future temperature levels are determined by ECHAM5 runs, forced by SRES emission scenarios A1B, A2 and B1. Furthermore, global climate model results are used to force the RCMs COSMO-CLM and REMO as well as the ESD method WETTREG (all described further below) in order to obtain regional climate projections and to assess regional climate signals, as presented in Subsection 3.4. For the assessment of climate change in conjunction with the 2 °C target (Subsection 3.5) results of a GCM forced with the E1 scenario are analyzed. Since there are no ECHAM5 E1 runs, the E1 runs of the derived model version ECHAM5C (which includes a carbon-cycle sub-model) is used for this purpose, employing WETTREG to obtain a regional climate projection for Hesse. In Subsection 3.6 the analysis is then extended to ECHAM5C forced by E1 and the SRES scenario A1B, downscaled again by WETTREG, to enable an intercomparison of climate signals as they are derived by an identical GCM-downscaling cascade.
Regional dynamic climate model COSMO-CLM: Initially known as CLM, the Consortium for Small Scale Modelling (COSMO) model CCLM is nested into a global climate model (Böhm et al., 2006; Rockel et al., 2008). CCLM is a non-hydrostatic model. For Subsection 3.4 of this study the initializing and the boundary conditions are prescribed by ECHAM5 and it is applied to obtain regional climate information for the state of Hesse at the period when the global temperature increase has reached 2 °C. The so-called consortium runs, data stream 3,

of CCLM with 0.22° resolution are used (at a latitude of 55N this resolution amounts to about 22.2 km in meridional direction and 12.7 km in zonal direction).

Regional dynamic climate model REMO: The Regional Model (REMO) is a further high resolution climate model that is nested into a global climate model (Jacob et al., 2008; Jacob & Podzun, 1997). REMO is a hydrostatic model. For Subsection 3.4 of this study the initializing and the boundary conditions are as well prescribed by ECHAM5 and it is applied to obtain regional climate information for the state of Hesse at the period when the global temperature increase has reached 2 °C. The so-called UBA runs of REMO (Jacob et al., 2008) with 10 km resolution are used.

Empirical statistical downscaling method WETTREG: The ESD method WETTREG (German: Wetterlagen-basiertes Regionalisierungsverfahren. English: Weather pattern-based regionalization method) relies on the ability of global models to reproduce the circulation regime well and statistically derives a transfer function which links regional and large-scale climate (Enke et al., 2005a;b; Spekat et al., 2010). In order to develop the transfer functions, WETTREG requires surface climatological data (for this study, climate measurements from stations in and around the State of Hesse are used, provided by the German Weather service DWD), upper air climatological data (here, reanalyses from NCEP/NCAR are used, cf. Kalnay et al., 1996), re-simulations of the current climate and projections of a future climate which are provided by the GCMs ECHAM5 and ECHAM5C. WETTREG produces a set of ten equally valid, stochastically derived, climate projections. The analyses in Subsection 3.4 are based on WETTREG2006 (Spekat et al., 2007) which is available for runs forced by ECHAM5 A1B, A2 and B1 scenarios. The analyses in Subsections 3.5 and 3.6 are based on the updated method WETTREG2010 (Kreienkamp et al., 2010) which is available for runs forced by ECHAM5 A1B, ECHAM5C A1B and ECHAM5C E1.

As described in Subsection 3.1 the first task is to determine the pre-industrial temperature level from three historical runs of ECHAM5. Then, as shown in Subsection 3.2, for each of the ECHAM5 projections that are forced by SRES emission scenarios, the time is determined in which a global mean temperature rise of 2 °C above this level occurs and a period of 30 years around it is defined. The next step, documented in Subsection 3.3, uses global model projections to address the question which continental-scale temperature increase is occurring at the time frame when the global temperature rise amounts to 2 °C. The applied procedure to assess this temperature increase was developed on behalf of the Hessian Agency for Environment and Geology by the company Climate and Environment Consulting (CEC) Potsdam GmbH. It is straightforward, easy to apply, and computationally inexpensive. This analysis is followed by a dynamical and statistical downscaling study, described in Subsection 3.4, carried out to determine, which regional temperature rise will occur in the State of Hesse during the time of a global 2 °C increase. The ensuing Subsection 3.5 includes an analysis of the regional temperature signal that occurs in conjunction with the E1 scenario, forcing the GCM ECHAM5C, for the end of the 21st century. Finally, in Subsection 3.6, a comparison between results obtained by applying the ESD method WETTREG to ECHAM5C forced by A1B or E1 for the end of the 21st century is carried out.

Please note that results from the RCMs and the ESD in the subsequent subsections are displayed as changes relative to the time period 1971–2000. Since there are no pre-industrial simulations, an assessment of the temperature changes relative to the pre-industrial time needs to take an offset of 0.5 °C into account for the warming that was realized between 1860–1889 (pre-industrial time) and the reference period 1971–2000 (see Subsection 3.1).

Global simulations used in this study are freely available for research purposes at the German Climate Data Centre (www.mad.zmaw.de/projects-at-md/ensembles/).

3. Results and discussion

3.1 Determining the global pre-industrial temperature level

For the time 1860–2000, the global annual mean temperature is determined for the three historical runs of ECHAM5. The temperature development is shown in Fig. 1 which also includes curves of 30-year moving averages.

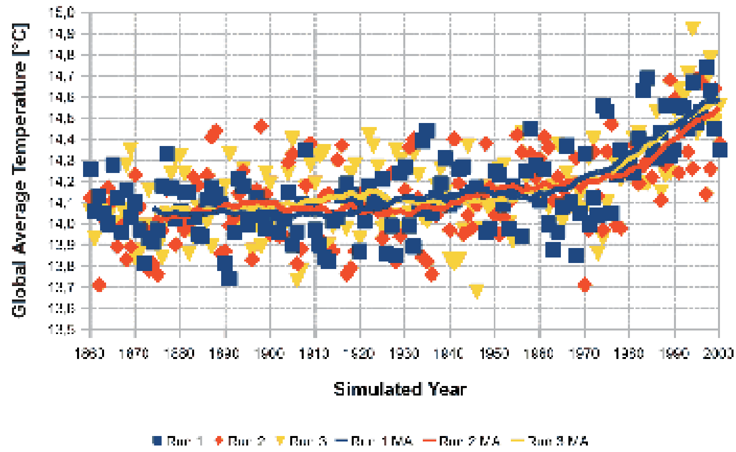


Fig. 1. Global annual mean temperature from three historical runs of the GCM ECHAM5 from 1860 to 2000 (triangles and squares). Lines show 30-year moving averages (MA).

From this analysis global temperature levels between 14.03 °C and 14.07 °C are found for the period 1860–1889 in the three ECHAM5 historical runs, which is assumed to be indicative of the pre-industrial time. The two-digit precision of the above temperature values is a by-product of the averaging over a set of 30 values and should not be mistaken for the accuracy with which global average temperature values can be assessed. In subsequent stages of the analysis an interval between 14.0 and 14.1 °C is used for the pre-industrial global average temperature.

Moreover, differences between the periods 1860–1889 and 1971–2000 can be inferred. These are between 0.27 °C and 0.37 °C, depending on the individual historical runs of ECHAM5. This is in broad accordance with Trenberth et al. (2007) who give an assessment of the temperature increase on the order of 0.5 °C for the respective time frame.

This means that about half a degree Celsius (in ECHAM5 0.3–0.4 °C) of the increase specified in the 2 °C target has already occurred from the pre-industrial time to the end of the 20th century which means that a global increase of less than 1.5 °C over the 21st century would be necessary to keep the 2 °C target.

3.2 Determining the time horizon of a global 2 °C increase

To begin with, the global average temperature for each year from 2001 to 2100 is computed from ECHAM5 projections forced with SRES emission scenarios A1B (two runs), A2 (one run) and B1 (two runs), as shown in Fig. 2.

Clearly, projections forced by scenarios A1B and A2 exhibit a higher temperature response compared to the ECHAM5 projections that are forced by the B1 scenario.

Fig. 3 zooms in on the period 2040–2080, i.e., the vicinity of the time frame when a global mean increase of 2 °C above the pre-industrial level (cf. Subsection 3.1) is expected in the GCM simulations. The temperature interval 16.0 to 16.1 °C is indicated by the grey band –

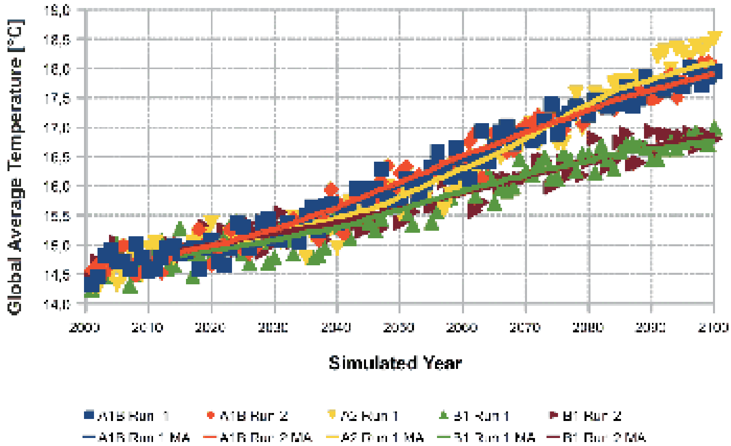


Fig. 2. Global annual mean temperature from five SRES scenario runs for A1B (2 runs), A2 (1 run) and B1 (2 runs) of the GCM ECHAM5 for the years 2001–2100 (triangles and squares). Lines show a 30-year moving average (MA).

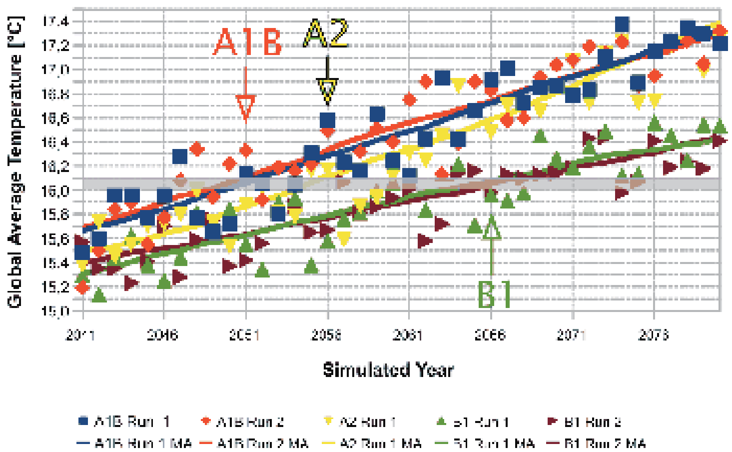


Fig. 3. As in Fig. 2, but zooming in on the time interval 2041–2080. The grey bar indicates the level of 2 °C temperature increase above pre-industrial time, arrows show time, when this level is breached by the simulations for different scenarios.

marking the level of 2 °C above the pre-industrial temperature of 14.0 to 14.1 °C, as assessed in Subsection 3.1 and defined in the 2 °C target.

The following time frames can be associated with a global mean temperature increase of 2 °C compared to pre-industrial times according to the ECHAM5 projections.

Forced by SRES scenario A1B: Around the year 2050, which leads to a representative 30-year period of 2036–2065.

Forced by SRES scenario A2: Around the year 2055, which leads to a representative 30-year period of 2041–2070.

Forced by SRES scenario B1: Around the year 2065, which leads to a representative 30-year period of 2051–2080.

3.3 Temperature increase on the global vs. the continental scale

After having determined the time of the breach of the 2 °C threshold on the global level (Subsection 3.2) we now focus on Central Europe. At this stage all comparisons are still being made on the basis of the global model ECHAM5 projections forced by the three SRES emission scenarios A1B, A2 and B1. We focus on the European continent by extracting data at 12 ECHAM5 grid-points in Central Europe and computing the temperature increase for this area. For the grid resolution of the global model ECHAM5 of approximately $2^o \times 2^o$ in mid-latitudes these 12 grid-points cover the area of 49.43N to 53.15N and 7.50E to 13.13E (in decimal degrees). The positions of these grid-points are indicated by yellow crosses in Fig. 6 (a).

In order to establish a reference value for Central Europe the procedure described in Subsection 3.1 is applied to the sub-set of these 12 grid-points. Fig. 4 displays the development of the annual temperature for the time 1860–2000 for Central Europe.

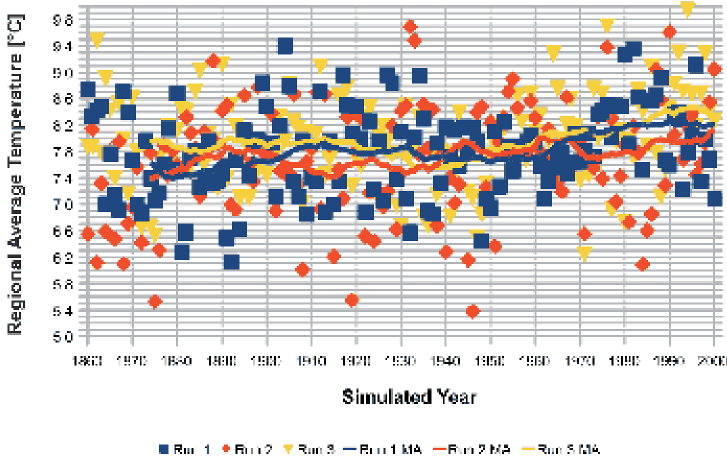


Fig. 4. As Fig. 1, only limited to the 12 grid-points covering Central Europe.

According to the three historical runs an increase of 0.32 °C to 0.56 °C for Central European temperature can be inferred from Fig. 4. Two conclusions can be drawn from this analysis:

(i) It is striking that in the three historical runs there is more variability between the Central European temperature trends than between the global mean temperature changes (cf. Fig. 1). This reflects the fact that averaging over larger areas tends to reduce variability.

(ii) The temperature increases for Central Europe of 0.32 °C to 0.56 °C tend to be of a larger magnitude compared to the global average of 0.27 °C to 0.37 °C (cf. Fig. 1). This can be attributed to the fact that over land surfaces the warming is generally stronger than over the oceans, since the land has a lower heat capacity than water.

Similar to the method applied in Subsection 3.1 for the global average temperature, Fig. 5 shows a zoom on the time period 2041–2080 of the temperature change for the 12 Central European grid-points. Using the 30 year periods determined from Fig. 3 we can assess the simulation-specific Central European temperature increases for the respective 30-year periods. Tab. 1 summarizes the Central European temperature levels for the pre-industrial period (1860–1889) and the present-day climate (1971–2000) as well as the temperature levels for the time periods when the global average temperature crosses the 2 °C threshold in the different scenarios. Additionally, temperature increases are given for the 12 grid-points covering Central Europe in the ECHAM5 model with respect to the pre-industrial time

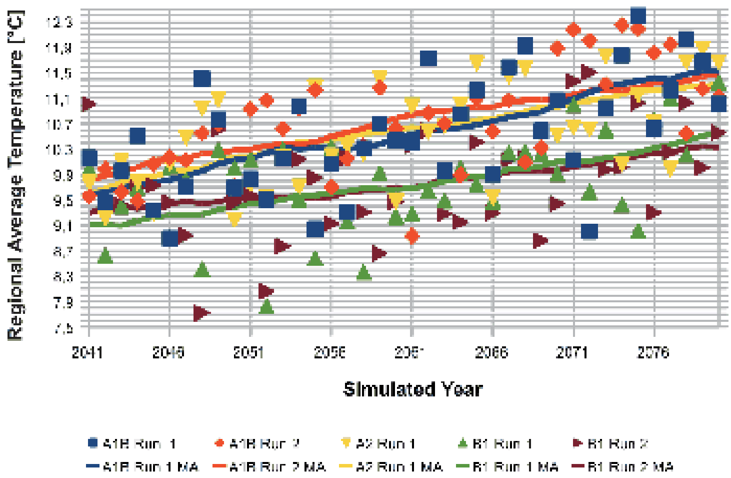


Fig. 5. As Fig. 3, only limited to the 12 grid-points covering Central Europe.

(Δ 1860–1889) and with respect to the present-day climate (Δ 1971–2000). The latter value is used to determine the warming that has already occurred from pre-industrial times until the reference period for present-day climate (1971–2000), yielding a value of 0.5 °C. Since for the regional climate simulations no pre-industrial time is available, we will add the difference of 0.5 °C to the climate signal calculated with respect to the present-day climate, to approximate the temperature change relative to pre-industrial times.

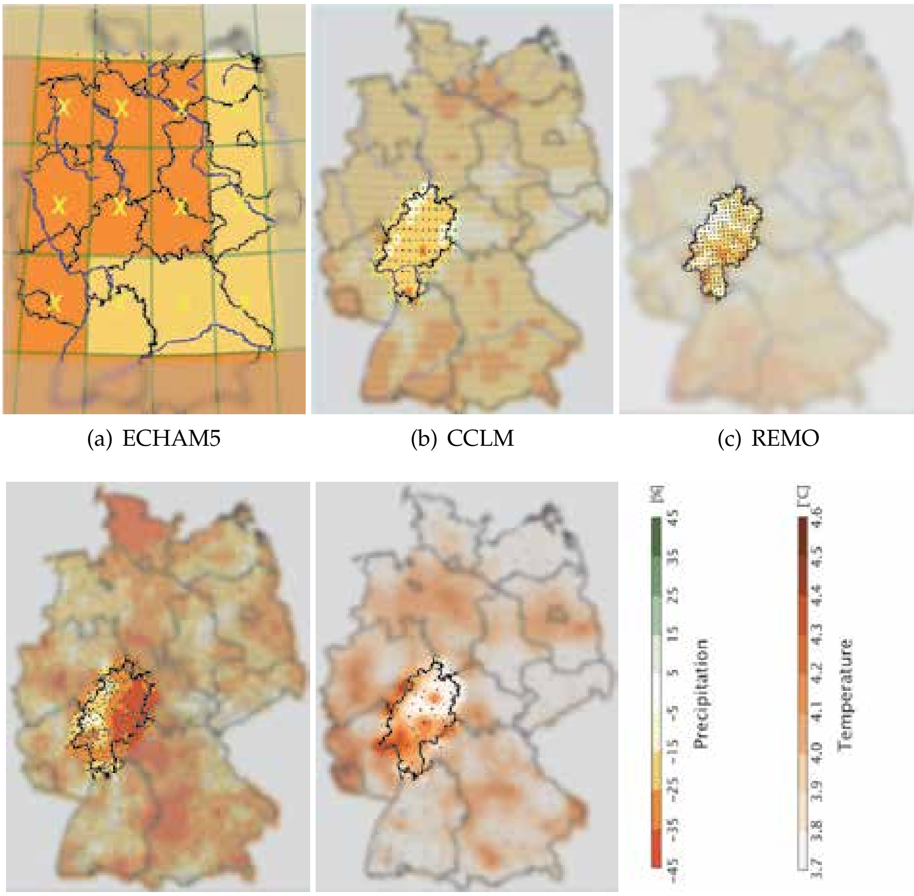
Period	*A1B Run 1*	*A1B Run 2*	*A2 Run 1*	*B1 Run 1*	*B1 Run 2*
1860–1889	7.62	7.36	7.62	7.62	7.36
1971–2000	8.19	7.85	8.19	8.19	7.85
A1B 2036–2065	10.13	10.29	–	–	–
A2 2041–2070	–	–	10.42	–	–
B1 2051–2080	–	–	–	9.88	9.86
Δ 1860–1889	2.51	2.93	2.80	2.26	2.50
Δ 1971–2000	1.94	2.44	2.23	1.69	2.01

Table 1. Annual mean temperature, computed from 12 grid-points of ECHAM5 covering Central Europe for the pre-industrial period (1860–1889), the present-day reference period (1971–2000) and for the scenario-specific periods (according to Subsection 3.1, i.e., the time of the breach of the global 2 °C threshold). The change signals with respect to the pre-industrial and to the present-day temperature are also given.

It can be concluded that the temperature increases as determined at 12 Central European grid-points of ECHAM5 are slightly higher (2.3 to 2.9 °C) compared to the global average warming of 2 °C at these times.

3.4 Approximating the 2 °C target for Hesse from downscaled SRES emission scenarios

In the next step, climate change signals are obtained from RCMs (CCLM and REMO) and from the ESD WETTREG (cf. Section 2), forced by output data from the global climate model ECHAM5. In this Subsection results are displayed only for the interior of the federal state of Hesse in Central Germany [see highlighted areas in Fig. 6 (b)–(e) where, in addition, the different models' resolutions are shown].



(a) ECHAM5 (b) CCLM (c) REMO

(d) WETTREG prec. (e) WETTREG temp. (f) Legends

Fig. 6. Resolutions of the models and method used. Subfigures (a)–(d) display the summer precipitation signal between 1971–2000 and 2071–2100 (scenario A1B). Subfigure (e) displays the respective signal of the daily mean temperature. The grid points evaluated for ECHAM5 are marked by yellow crosses in (a) and the shape of State of Hesse is indicated by the in-focus area in (b)–(e). The left-hand legend in (f) corresponds to Subfigures (a)–(d) and the right-hand legend in (f) is associated with (e). Grid points of CCLM and REMO as well as the positions of stations used in WETTREG are indicated by black dots.

In the downscaling results for the area of Hesse a slightly lower annual mean warming of 1.4 to 2.0 °C relative to 1971–2000 is projected (Tab. 2) compared to the temperature signal obtained for the 12 Central European grid-points from the global model (1.7 to 2.4 °C, cf. Tab. 1). Taking into account the already realized warming of 0.5 °C from pre-industrial to present-day conditions, this implies a warming of 1.9 to 2.5 °C relative to the pre-industrial time in Hesse.
Besides annual mean temperature, some further parameters are analyzed from the regional climate model simulations.

Model	*A1B Run 1*	*A1B Run 2*	*A2 Run 1*	*B1 Run 1*	*B1 Run 2*
CCLM	1.65	1.98	–	1.41	1.61
REMO	1.65	–	1.85	1.38	–
WETTREG	1.34	–	1.64	1.37	–

Table 2. Increase of the annual temperature on the regional scale (reference region: State of Hesse) based on the regional models CCLM, REMO and WETTREG. The temperature change signal is determined using the reference period 1971–2000 and the scenario-specific periods, i.e., 2036–2065 for A1B, 2041–2070 for A2 and 2051–2080 for B1.

When analyzing the number of heat days (daily $T_{max} \geq 30$ °C) per year, an increase by about 6 to 10 days per year compared to the present-day period is found, indicating a doubling to tripling of current occurrence frequencies.

When analyzing precipitation changes, a seasonal shift of rainfall from the summer season into the winter season is found for the analyzed periods. Thus, even under conditions of keeping the 2 °C target summer rainfall is projected to decrease between –16% and 0% in the area of the federal state of Hesse. Even though precipitation changes below 10% are considered not significant, the fact that all models show the same direction of trend gives a fairly clear picture of a drying trend in summer. In winter all regional model simulations show an increase of precipitation between 0% and +29% for the area. Here, differences between the different downscaling methods (or models) are quite large: While particularly the model CCLM shows very small to no signals, the WETTREG method produces the strongest signals. However, again all models show the same general tendency, thus giving confidence in the projected trend.

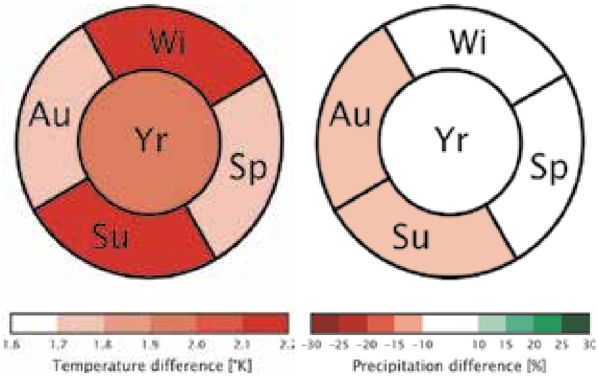
The precipitation reductions in summer coincide with slightly reduced relative humidity, while for winter projected changes in atmospheric humidity are not significant. In concord with the changes in atmospheric humidity, the regional climate projections reveal slight reductions in summer cloud cover and increase in sunshine duration, but mixed results or non-significant signals in winter.

Summing up, when determining regional climate change signals from regional simulations for a time interval when the global 2 °C target is breached in SRES emission scenarios, we find the temperature increase simulated by the regional models slightly below those simulated for Central Europe by the forcing GCM ECHAM5. Precipitation shifts from summer to winter can be detected and some small changes in atmospheric humidity, cloudiness and sunshine duration can be detected from the simulation results.

3.5 Downscaling the E1 scenario for Hesse

In this Subsection we analyze the regional climate change signals from the GCM ECHAM5C (cf. Section 2) projections forced by the E1 scenario, i.e., an emission scenario that aims at keeping global mean warming below 2 °C (Johns et al., 2011; Lowe et al., 2009). The global simulation results are downscaled using the ESD method WETTREG. Thus, in contrast to the previous Subsections, where the time in which the global 2 °C threshold was breached was defining the periods for the analysis, we now look at the 30-year time slice at the end of the current century (2071–2100). Such an approach is independent of the temperature level, i.e., whether for this time slice the global average temperature is lower or higher than 2 °C above the pre-industrial temperature.

The so-called ring diagram in Fig. 7 (a) shows the temperature signal for the Hesse area as the result of the ECHAM5C/E1-WETTREG downscaling. Displayed is the magnitude of the temperature increase between the E1 projection for the seasonal and yearly temperature averages 2071–2100 and those for the historical simulation for 1971–2000.



(a) (b)

Fig. 7. Ring diagram of the increases between 2071–2100 and 1971–2000 from an average over ten WETTREG regionalizations forced by ECHAM5C/E1. The outer ring segments indicate the seasonal temperature signals [Wi: Winter (Dec.–Feb.); Sp: Spring (Mar.–May); Su: Summer (Jun.–Aug.); Au: Autumn (Sep.–Nov.)] and the center denotes the annual value. (a): Temperature results derived from the mean of simulated series at climate stations in and around Hesse [cf. Fig. 6 (e)]. (b): Precipitation results (percentual change) derived from the mean of simulated series at precipitation stations in and around Hesse [cf. Fig. 6 (f)].

Comparing the results for the time slices in the SRES scenarios (Subsections 3.3 and 3.4) to the first results from the downscaled E1 scenario (using the statistical method WETTREG) we find that the climate signals for the period 2071–2100 relative to the reference period 1971–2000 are in the same order of magnitude for both investigations. Yet WETTREG regionalizations of the E1 scenario yield a slightly higher temperature signal which amounts to more than 1.9 °C for the annual mean temperature and between 1.7 and 2.2 °C for seasonal average temperature values. As stated in the previous Subsection, these values require an additional 0.5 °C correction to compensate for warming that occurred since the pre-industrial period.
As the ring diagram in Fig. 7 (b) shows, precipitation projections for the same pair of 30-year periods as above are smaller than 10% for the whole year and the winter and spring seasons. During summer and autumn precipitation decrease of more than 10% is found for this simulation. Thus, the E1 scenario with WETTREG downscaling shows a comparable drying signal in summer, but a weaker moistening signal in winter compared to the time slice results using the SRES scenarios.

3.6 Avoidable climate change: comparing the E1-scenario with the A1B-scenario

Finally, we present ECHAM5C results for Hesse (downscaled using WETTREG) under the higher emission scenario SRES A1B for a 30-year period at the end of this century compared to the present-day reference period. The results are juxtaposed with the respective ECHAM5C/E1 downscaling results.
From the comparison of these signals with those presented in the previous two subsections we can assess the avoidable regional climate change in Hesse. As Fig. 8 shows, the most striking difference relates to the much larger warming signal in the A1B scenario, amounting to more than 3 °C relative to 1971–2000, while in the E1 scenario the warming in Hesse stays below 2 °C.
Ten simulations of WETTREG, forced by ECHAM5C A1B and ECHAM5C E1, are also used to analyze the number of heat days, shown in Fig. 9. A large increase can be found for the

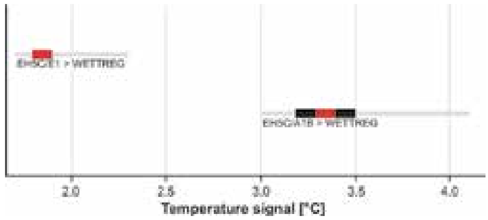


Fig. 8. Ensemble band diagram for the temperature signals (2071–2100 minus 1971–2000) derived from WETTREG regionalizations of the global model ECHAM5C results for scenarios SRES A1B (bottom) and E1 (top). Each band indicates the value range that occurs in the Hesse area. The grey part shows the entire range; the black bar displays the values between the 25 and the 75 percentile; the red bar indicates the median (the width of this bar is due to the fact that the computational accuracy of the signals is 0.1 °C).

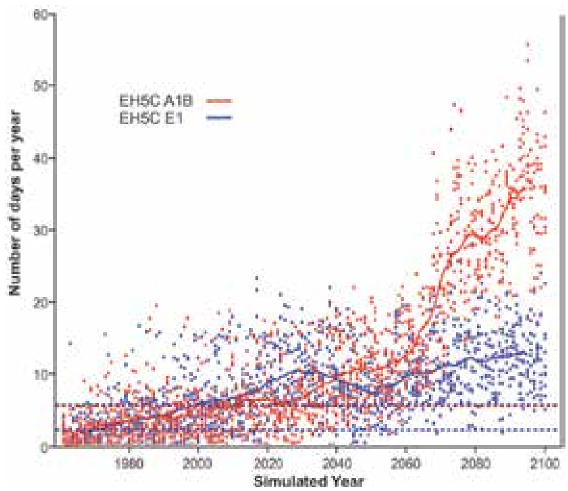


Fig. 9. Average number of heat days ($T_{max} \geq 30$ °C) per year from 1961–2100, determined from WETTREG regionalizations forced by ECHAM5C A1B, run 1 (red) and ECHAM5C E1, run 1 (blue). The dots show the results of the ten WETTREG runs; the continuous lines indicate the 11-year running mean and the stippled lines denote the range of heat days per year, determined for the regionalizations of the period 1971–2000.

A1B scenario: In the period 1971–2000 an average of 4 days per year is detected which rises to 30 days per year in the period 2071–2100. For the E1 scenario this increase is much smaller, reaching an average of about 12 days in the period 2071–2100. Moreover, Fig. 9 shows an increase in the variability of the individual WETTREG simulations towards the end of the 21st century for both scenarios.

Concerning precipitation change (Fig. 10) we find a similar shift in seasonal patterns in the results obtained using the two scenarios. While for winter the signals stay below 10%, the change in summer is around –10% for the E1 scenario and around –20% for the A1B scenario in Hesse at the end of the current century.

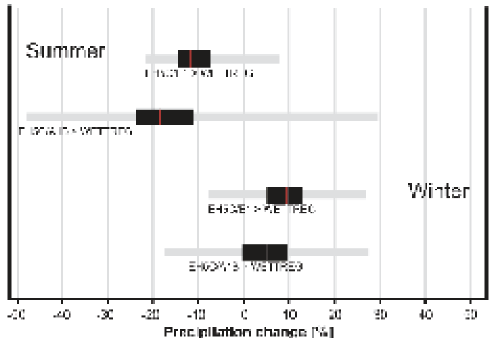


Fig. 10. As in Fig. 8 but for the precipitation change in summer (top two bands) and winter (bottom two bands). The computational accuracy of the values for precipitation change is 1%.

4. Summary and conclusions

In the analysis presented here, we assess the regional climate change that would occur under the global 2 °C target in the federal state Hesse in central Germany. In a first approach, we approximate the situation under the global 2 °C target from time slices (30-year periods) during simulations for higher emission scenarios (SRES A1B, A2 and B1), determining the time when the global 2 °C target is breached. From this analysis we also determine that a warming of about 0.5 °C has already occurred from the pre-industrial time until the end of the 20th century which means that a global increase of less than 1.5 °C over the 21st century would be necessary to keep the 2 °C target.

In the next step we analyze the local changes in Hesse for the respective 30-year periods, centred at the time determined in the previous step. While the global model (ECHAM5) shows a significantly higher warming in the 12 grid points representing Central Europe (2.3 to 2.9 °C) than the global mean (2 °C), this effect is less pronounced when considering results from dynamical (RCMs CCLM and REMO) and statistical (ESD WETTREG) downscaling for Hesse. Results show, that for the respective time frames, a mean annual warming between 1.3 and 2.0 °C (cf. Tab. 2) compared to the present-day climate reference period 1971–2000 occurs. When adding the already realized warming from the pre-industrial (1860–1889) time until 1971–2000 of 0.5 °C (cf. Tab. 1), we find a local warming of 1.8 to 2.5 °C in Hesse for a global mean warming of 2 °C with respect to the pre-industrial values.

The occurrence frequency of heat days in the simulations of present-day climate (4 heat days per year) would approximately triple even if climate change could be held to a level keeping the global 2 °C target. When considering precipitation changes we find a shift of rainfall from summer to winter, a tendency that is also found in several models for different emission scenarios for Central Europe (IPCC, 2007), in conjunction with slight reductions in atmospheric moisture and cloudiness and increasing sunshine duration during summer (signals uneven or not significant for winter).

Assessment from the first available global climate model simulations for a scenario that aims at keeping the global 2 °C target at the end of the 21st century gives similar results, even though for these simulations no high resolution dynamical downscaling results are available. The projected warming in the area of Hesse of 1.9 °C for the end of the 21st century in the E1 scenario relative to the present-day reference period 1971–2000 (downscaled using the ESD method WETTREG) is at the upper end of which was determined from the time slices analyzed previously (1.3–2.0 °C). As stated before, the value requires a +0.5 °C correction to compensate for warming that occurred since the pre-industrial time.

Precipitation projections for the E1 scenario at the end of the current century show non-significant changes of less than 10% for winter and spring and decreases of 10–15% for summer and autumn, thus smaller signals than those obtained from the time slices of the SRES scenarios presented before.

In the last Subsection (3.6) we compare end-of-the-century climate change for Hesse between the SRES scenario A1B (which approximately resembles or even slightly underestimates the current emission path, cf. Le Quéré et al., 2009) and the low-emission scenario E1 (Lowe et al., 2009).

The comparison of projected temperature increase over the area of Hesse for the analyzed GCM simulation shows a significant portion of avoided warming of more than 1 °C under the ambitious mitigation scenario E1 compared to the non-mitigation scenario A1B. Furthermore, the A1B scenario shows a large increase of heat days: On average there will be an increase in the number of heat days of about 25 heat days per year at the end of the current century relative to the present-day reference period (1971–2000). Even under the 2 °C target (scenario E1), an increase in heat days of 8 heat days per year must be expected. However, this means that two thirds of the increase simulated for the A1B scenario could be avoided when following the E1 scenario instead. This is of great concern, since heat days are typically causing heat stress with dangerous consequences: For example, in the year 2003 an excess of 16 heat days over the climatologically observed value of 6 heat days per year in the reference period led to a significant increase in mortality in Central Europe (Chase et al., 2006; De Bono et al., 2004). Additionally summer precipitation reduces under the A1B scenario by about 20% compared to a reduction of about 10% under the E1 scenario. The wintertime precipitation increase is below 10% in both scenarios.

While results between different GCMs vary (see, e.g., IPCC, 2007), they all show consistently a significant reduction of climate changes in the E1 scenario compared to the A1B scenario for the end of this century (Johns et al., 2011). It should be kept in mind, that under an emission scenario like A1B, significant further climate change beyond the year 2100 is to be expected (IPCC, 2007).

Thus, the resulting differences can be considered the avoidable climate change which would pertain to the implementation of necessary mitigation actions that lead onto a low-emission path like E1. The mitigation measures that are currently implemented, however, will lead to a much higher emission path (as in SRES A1B or higher). These avoidable changes can serve as a basis for calculating the gains from mitigation actions (in terms of avoided climate change impacts) compared to the costs of climate change impacts when no or little emission reduction is put into action.

While not for all regions of the world high resolution climate simulations are available, we show here that with some simple methods that are easy to apply and make use of data that are freely available, climate change assessments – on a continental scale – can be carried out. Further studies for a world that keeps the 2 °C target compared to the current emission path may complement and extend the studies and serve as information support for policy and economy. They are also a useful knowledge base for local stakeholders' decision making processes with respect to mitigating climate change versus adapting to the impacts of non-mitigated climate change.

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Intertemporal Evaluation Criteria for Climate Change Policy: Basic Ethical Issues

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1. Introduction

The results of cost benefit analysis crucially depend on the welfare criteria that are used to evaluate the streams of well-being over time generated by the investment projects under consideration. In economics and philosophy there is a long lasting and rather controversial debate as to which type of intertemporal social welfare function and, in particular, which social discount rate should be applied. This debate has been revitalized in the last few years because, especially since the release of the Stern Review in 2006, it has become clear which dramatic effect the choice of the social discount rate has on the design of climate policy. In this context it is important to decide how costs and benefits should be shared between generations and, in particular, to which extent the interests of future generations should be taken into account when projects with long-run consequences are carried out. From this perspective the choice of a specific intertemporal evaluation criterion becomes a matter of ethics, i.e. of justice between generations.

There exist two opposing "schools" in economics which have completely different positions concerning the importance of intergenerational ethics for intertemporal evaluation (see Aldy et al. (2010), p.912). On the one hand there is the positive ("descriptive") school for which ethical judgment is redundant since behavior of existing individuals and thus empirically observable market interest rates should be the benchmark for the determination of the social discount rate. On the other hand there is the normative ("prescriptive") school which has its roots in classical welfare economics and for which explicitly formulated normative criteria are of much importance. For this school an ethically oriented debate on the properties and implications of different intertemporal evaluation criteria and their normative foundations is essential (see Atkinson, A. (2011) for a general discussion on the relationship between ethics and welfare economics.). In the climate change literature arguments of both schools often are confounded which causes much misunderstanding and makes the debate on the appropriate method for intertemporal evaluation rather opaque (see e.g. Kaplow, L., Moyer, E. and D. A. Weisbach (2010) as some critical reflections on the debate).

In this paper we will adopt the perspective of the normative school (see also Roemer J. (2011), for an excellent defense of the ethical position). Our main objective then is to present the most important ethical issues that, particularly in the context of climate policy, are relevant for the choice of intertemporal welfare criteria. We will proceed as follows. In Section 2 we present various classes of intertemporal social welfare functions well-known from optimal growth theory (i.e. maximin, undiscounted utilitarianism, discounted utilitarianism and some recently developed hybrid criteria) and discuss which desirable and undesirable properties they have. In Section 3 we explore whether ethical criteria can also be employed to determine the parameter values (or at least to delimit their range) which, after the choice of some type of intertemporal social welfare function, are needed to specify the concrete criterion by which decisions on climate policy are made. In Section 4 we conclude and discuss some implications our general considerations may have for climate change policy.

2. Ethically relevant properties of different types of intertemporal social welfare functions

2.1 Preliminaries

In common with the literature we assume that c_t denotes well-being in period of time $t = 1, 2, \ldots$. Thus the vector of various determinants of well-being, i.e. material consumption, leisure, environmental quality etc, is mapped into the real-valued indicator c_t. The severe problems of measurement and aggregation of c_t are not treated in this paper[1]. Purely for terminological convenience, we identify the variable c_t with consumption in period t in all that follows. Time is discrete, with each period of time $t = 1, 2, \ldots$ representing just the lifespan of one single generation. So generations do not overlap, and for the sake of simplification, we suppose that population is constant over time thus neglecting the ethical aspects of population change[2]. If some technology and some initial resource endowment are given there is a class Γ of feasible consumption paths $(c_1, c_2, \ldots)$ of infinite length. These consumption paths are evaluated by an intertemporal social welfare function $W(.)$ which is weakly monotone in all variables and may assume values in the interval $[-\infty, +\infty]$. We now consider different types of those social welfare functions as suggested by the literature.

2.2 Maximin

Maximin as a criterion for intertemporal evaluation dates back to Rawls' "difference principle" (although Rawls, J. (1971) himself did neither accept the denomination "maximin" nor the application of this criterion in the intergenerational context). As an attempt to be "plus Rawlsien que le Rawls" - it was Solow, R. (1974) who applied this criterion to the Dasgupta-Heal-Solow growth model, in which the input of an exhaustible resource is continually substituted by reproducible man-made capital. Given an infinite number of generations the minimum level of consumption along a given consumption path may not exist, such that the maximin social welfare function must in this case be defined as

$$W(c_1, c_2, \ldots) = \inf_{t=1,2,\ldots} c_t \tag{1}$$

This social welfare function satisfies two commonly shared ethical objectives that play a major role in the intergenerational context.

(i) All generations have an equal weight in social evaluation. In particular future generations are not discriminated against simply because they have the bad luck to appear later on the time axis. This intergenerational neutrality also means that the value of the social welfare

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[1] d'Aspremont, C. and Gevers, L. (1977) offer a very comprehensive axiomatic approach towards different social welfare functions. Roemer, J. (1996) summarizes the extensive literature and contributions that deal with the measurability of well-being and its relevance for social welfare comparisons.

[2] We refer the reader who is interested in situations with a changing population to Blackorby, C. , Bossert, W. and Donaldson, D. (1995).

function (1) is not changed even if an infinite permutation of a given consumption path is made. For a long time (see already Sidgwick, H. (1874)), equal treatment of generations has been considered to be the basic requirement for intergenerational fairness. Maximin also respects some albeit rather weak version of the Pareto principle: If consumption does not decrease for any generation the new path obviously is not worse than the original one.
(ii) The maximin rule (1) implements specific non-decreasing and thus sustainable paths as optimal solutions: Assume that there exists a strictly positive consumption level $\bar{c}$ that, for the given technology and the given initial resource endowment, can be attained by any generation. Then it is clearly excluded by application of (1) that some later generation's consumption falls below $\bar{c}$ while some earlier generation enjoys a consumption level above $\bar{c}$. If such a constant consumption path $(\bar{c}, \bar{c}, \dots)$ is Pareto optimal it maximizes social welfare according to (1) among all feasible paths as in Solow, R. (1974) classical paper.
Even though the maximin rule shows these ethically appealing properties it also has some serious disadvantages, which limit its usefulness as a criterion for dealing with intertemporal resource allocation issues. This standard view may, however, be challenged if the economy's state of development is already very high and maximin does not apply to levels of material consumption but to basic and partly non-substitutable goods as staple food or health (see Roemer J. (2011)).
(i) Maximin does not respect more demanding versions of the Pareto criterion because it is insensitive to increases in consumption if the minimum/infimum of consumption does not change. In particular, the *strong* Pareto principle is violated, which means that any increase of consumption along a given path should lead to a strictly preferred new path. To give an example just consider the two consumption paths $\left(\frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots\right)$ and $\left(1, \frac{2}{3}, \frac{1}{2}, \dots\right)$. Both have the same infimum equal to zero but the second path has a higher level of consumption than the first one not only in one but even in each period of time. In the case of a finite number of generations strong Pareto can be obtained by adopting the leximin criterion, but with an infinite number of generations such an extension is neither straightforward nor does it allow a comparison of all paths (see e.g. Asheim, G. B. (1991)).
(ii) The maximin criterion excludes any investment of an earlier generation to increase well-being of future generations above the level enjoyed by itself - irrespective of the extent of that increase and the number of future generations which would benefit from this sacrifice. To give an example we start from the constant consumption path $(1, 1, 1, \dots)$ and assume that the economy is so productive that the path $(\frac{999}{1000}, 2, 2, \dots)$ is also technically feasible. I.e. if one single generation (the first one) makes a minor sacrifice of only $\frac{1}{1000}$ units of consumption each subsequent generation could double its level of well-being. Nevertheless, the maximin rule deems this path inferior to the original constant consumption path. Strict application of maximin thus condemns the economy to stagnation and precludes economic growth based on savings and investment. It was this reason why Rawls, J. (1971) did not recommend the difference principle for making choices in the intergenerational context.

2.3 Undiscounted utilitarianism

In his seminal paper on optimal growth theory Ramsey, F. (1928) used undiscounted utilitarianism to evaluate and compare feasible consumption paths. This approach shares some advantages and disadvantages with the maximin rule but has merits and shortcomings of its own. The standard version of an undiscounted utilitarian social welfare functions reads as

$$W(c_1, c_2, \dots) = \sum_{t=1}^{\infty} u(c_t) \tag{2}$$

where $u(c)$ - usually defined for all consumption levels $c > 0$ - is a strictly monotone increasing utility function through which the well-being of each generation is assessed before it enters social evaluation but which is not meant to be a felicity function in the sense of classical utilitarianism (see Kaplow, L. (2010) and Kaplow, L., Moyer, E. and D. A. Weisbach (2010) for this conceptual distinction). Often an isoelastic utility function given by $u(c) = \frac{c^{1-\eta}}{1-\eta}$ (or equivalently $u(c) = \frac{c^{1-\eta}-1}{1-\eta}$) is employed where the elasticity of marginal utility $\eta \geq 0$ (with $\eta \neq 1$) indicates the degree of inequality aversion in social evaluation. For $\eta = 1$ the utility function is defined as $\ln c$ (which is justified since $\lim_{\eta \to 1} = \frac{c^{1-\eta}-1}{1-\eta} = \ln c, \forall\, c > 0$). The main ethical advantages of undiscounted utilitarianism are as follows:

(i) In common with the maximin rule application of an undiscounted utilitarian social welfare function implies equal treatment of all generations and thus respects the fundamental postulate for intergenerational justice. Welfare is not changed when the consumption levels of a finite number of generations are permuted if, as assumed in (2), the utility function $u(c)$ is the same for all periods. Concerning distribution in the atemporal setting, i.e. within a society in a certain period of time, it is quite common in welfare economics to make judgments with unweighted sums of utility.

(ii) Undiscounted utilitarianism ensures sustainable development if the economy under consideration is productive in an intuitive sense: If some generation makes a consumption sacrifice to expand the economy's capital stock then it will be possible for some later generation to increase its consumption by more than this earlier sacrifice. Then it follows from a general argument (see Asheim, G. B., Buchholz, W. and Tungodden, B. (2001)) that a somewhere decreasing consumption path will never maximize a welfare function of type (2). So it is ensured that only non-decreasing paths are selected by applying an undiscounted utilitarian criterion. Along such paths no generation consumes more than it concedes to its successors, which gives sustainability.

(iii) If, as is usually assumed, the utility function $u(c)$ is concave, a rank-preserving Pigou-Dalton transfer from a rich generation with high consumption to a poorer generation increases aggregate welfare (2) (see in a general welfare theoretic framework Atkinson, A. (1970)). Thus undiscounted utilitarianism is also useful to take equality of the distribution of well-being among generations into account which, as an ethical objective, is conceptually different from the equal treatment of generations (see Asheim, G. B. (1991)). Employing utility functions $u(c)$ with more or less curvature, i.e. varying the parameter η in the case of an isoelastic utility function, makes it possible to capture different degrees of inequality aversion in social evaluation. Then the maximin criterion is the extreme case where inequality aversion η is infinite. Classical utilitarianism, where $u(c) = c$ and the pure consumption levels are summed up in (2), reflects the opposite extreme where inequality aversion is completely absent.

On the other hand undiscounted utilitarianism has some properties which are less desirable.

(i) For any utility function $u(c)$ the utility sum of many consumption paths will be plus or minus infinity. Simple comparisons of the scalars obtained by (2) will not provide a ranking of these paths. But one may readily refine the ranking somehow by using overtaking or catching up criteria. Thus, e.g., a consumption path $(c_1^a, c_2^a, \dots)$ is strictly preferred to a consumption path $(c_1^b, c_2^b, \dots)$ if there is a period $\tilde{T}$ such that for all $T > \tilde{T}$ the inequality

$$\sum_{t=1}^{T} u(c_t^a) > \sum_{t=1}^{T} u(c_t^b) \qquad (3)$$

holds (as a pioneering contribution on this overtaking criterion see v. Weizsäcker, C. C. (1965)). Weak preference is obtained if condition (3) is fulfilled with weak inequality $\geq$. For fundamental reasons, however, one cannot further extend the partial ordering given by (3) in a way that respects stronger versions of the Pareto principle and permits comparisons between any two consumption paths.

(ii) While in a productive economy maximin excessively favors the present, undiscounted utilitarianism may excessively favor the future, demanding very high savings from earlier generations. To illustrate this, we assume that, given a strictly increasing utility function and starting from a constant consumption path $(\bar{c}, \bar{c}, \dots)$, the consumption sacrifice s in the first generation allows all subsequent generations to increase their consumption by some amount $\epsilon > 0$. Then, as long as $u(\bar{c} - s) > -\infty$, the consumption path $(\bar{c} - s, \bar{c} + \epsilon, \bar{c} + \epsilon, \dots)$ will dominate $(\bar{c}, \bar{c}, \dots)$ irrespective of how small ϵ is. Under undiscounted utilitarianism the infinite number of future generations thus gains some dictatorial position towards any finite number of earlier generations. This well-known argument against undiscounted utilitarianism (see already Chakravarty, S. (1969) and Rawls, J. (1971) and more recently Arrow (1999) and Asheim, G. B. (2010)), however, needs some qualification as it does not hold for any path from which saving starts. Suppose for instance that the utility function is $u(c) = -c^{-1}$ and that the initial consumption path is $(1, 2, 4, 8, \dots)$ which then has aggregate welfare -2. Further assume that generation 1 saves $\frac{1}{4}$ which, for a certain technology, permits an increase of consumption of any subsequent generation by the uniform amount $\frac{1}{10}$. The new consumption stream $\left(\frac{3}{4}, 2 + \frac{1}{10}, 4 + \frac{1}{10}, 8 + \frac{1}{10}, \dots\right) = \left(\frac{3}{4}, \frac{21}{10}, \frac{41}{10}, \frac{81}{10}, \dots\right)$ is Pareto inferior to the consumption path $\left(\frac{3}{4}, \frac{21}{20} \cdot 2, \frac{21}{20} \cdot 4, \frac{21}{20} \cdot 8, \dots\right)$ whose welfare is $-\frac{4}{3} - \frac{20}{21} \cdot 1 = -\frac{48}{21} < -2$. So the new path is inferior to the original one, which means that the investment of generation 1 does not improve welfare even though all generations from generation 2 on benefit from an equal increase of consumption. If saving of generation 1 exceeded $\frac{1}{2}$ then any increase in future consumption along the given initial path would not be sufficient to restore welfare to its original level. Therefore, if we do not start from a constant, but from a strictly monotone increasing consumption path, undiscounted utilitarianism is able to prevent excessive saving and to restrict the rate of growth to an ethically acceptable degree (see Asheim, G. B. and Buchholz, W. (2003) for a further elaboration of this argument).

2.4 Discounted utilitarianism

Most frequently intertemporal evaluation is performed using discounted utilitarian social welfare functions which give utility of future generations less weight than utility of earlier ones. This type of social welfare functions is defined by

$$W(c_1, c_2, \dots) = \sum_{t=1}^{\infty} \delta_t u(c_t) \tag{4}$$

In (4) the function $u(c_t)$ again represents utility of consumption and $(\delta_t)_{t=1,2,\dots}$ is a non-increasing sequence of utility discount factors with $\sum_{t=1}^{\infty} \delta_t < \infty$. These utility discount factors indicate how much utility in period t counts in terms of period 1 such that naturally $\delta_1 = 1$. Traditionally, $(\delta_t)_{t=1,2,\dots}$ is assumed to fall geometrically, i.e. $\delta_t = \delta^{t-1}$ where $\delta = \frac{1}{1+\rho}$

and $\rho \geq 0$ is the constant discount or time preference rate[3]. If $\delta = 1$ all generations are treated equally, and undiscounted utilitarianism is obtained as a special case of (4).
Discounted utilitarianism has several desirable properties.
(i) For consumption paths that are strictly bounded away from zero and bounded above social welfare according to (4) is a well-defined scalar such that a complete ordering is obtained in an obvious way. Completeness is an attractive feature if one shares the view that a rational ethical observer should always be able to decide whether one of two arbitrarily given consumption paths is better than the other (or whether they are equivalent). But it may be questioned how important completeness really is, i.e. whether "incompleteness (is) such a defect of an ethical theory" (Roemer J. (2011), p. 370). So if the task is to choose a best element out of a class of technically feasible consumption paths one may be content with finding paths that dominate all other paths for a solely partial ordering, as e.g. the overtaking criterion considered above. Reducing demands on intertemporal evaluation criteria to a more modest level also reflects the view that it normally is quite unlikely that a single criterion integrates all properties that are normatively desirable. This problem is especially important in the case of infinitely many agents/generations. Since Diamond, P. (1965) thus impossibility results, which show the incompatibility of different plausible postulates, abound in the literature on intertemporal evaluation[4]. In particular, it has been shown that a social ordering which fulfils the equal treatment postulate and the strong Pareto principle cannot be represented by a cardinal social welfare function when there is an infinite number of generations (see Basu, K. and Mitra, T. (2003)). Nevertheless, having a numerical welfare measurement makes the determination of optimal consumption paths simpler and more transparent, which - from a purely technical viewpoint - is a non-negligible advantage of discounted utilitarianism. But it is questionable whether this argument can claim much ethical significance.
(ii) Applying a discounted utilitarian criterion is held to be an appropriate safeguard to avoid excessive savings and overburdening of earlier generations. This is particularly clear if, as in the example of the previous section, we start from a constant consumption path and any generation $t = 2, 3, \ldots$ has an equal increase in consumption ϵ when the first generation saves some amount s. Then given $\sum_{t=1}^{\infty} \delta_t < \infty$, the level of a welfare-improving investment in period 1 naturally is restricted by $\hat{s} = (\sum_{t=1}^{\infty} \delta_t)\,\epsilon$ which protects generation 1. But, as explained above, along non-constant consumption paths the same effect may also be brought about with undiscounted social welfare functions. Moreover, if the utility function and the time discount factors are fixed, discounted utilitarianism mitigates but not necessarily avoids excessive savings of the first generation. We will show this using a linear growth model where the capital stock k_{t+1} that generation t hands over to generation $t+1$ is given by $k_{t+1} = \alpha(k_t - c_t)$. Here, α is a productivity parameter which is assumed to be constant over time and which indicates the marginal rate of transformation between consumption in period t and period $t+1$. If k_1 is the initially given capital stock of generation 1 then all consumption paths $(c_1, c_2, \ldots)$ are technically feasible for which

$$\sum_{t=1}^{\infty} \frac{c_t}{\alpha^{t-1}} \leq k_1 \tag{5}$$

[3] We emphasize this point, because there is seemingly a remaining confusion of what is being discounted with the discount rate or the discount factor.

[4] One property of social orderings which the literature concentrates on but for which an ethical meaning is hard to detect is continuity w.r.t different topologies. See e.g. Svensson, L.-G. (1980), Asheim, G. B. and Buchholz, W. (2003) and Roemer J. (2011) for a discussion on this. Sakai, T. (2010) instead focuses on the compatibility between anonymity, strong Pareto and transitivity.

holds. Just as before we now start from the Pareto optimal constant consumption path $(\overline{c}, \overline{c}, \dots)$ (with $\overline{c} = \frac{\alpha-1}{\alpha}k_1$ for given k_1) and assume that generation 1 makes an additional saving of s units of consumption. Then it directly follows from (5) that this enables any subsequent generation to increase its consumption by $\epsilon = (\alpha - 1)s$ units. If we now consider the special case of an isoelastic utility function with $\eta = 1$, i.e. $u(c) = \ln c$, the sum of discounted utilities flowing from saving s is

$$\ln(\overline{c} - s) + \sum_{t=2}^{\infty} \delta^{t-1} \ln(\overline{c} + (\alpha - 1)s) = \ln(\overline{c} - s) + \frac{\delta}{1-\delta} \ln(\overline{c} + (\alpha - 1)s) \tag{6}$$

By an easy calculation it is shown that, assuming $\delta\alpha > 1$, the level of savings which maximizes (6) is

$$s^* = \frac{\delta\alpha - 1}{\alpha - 1}\overline{c} \tag{7}$$

Even for quite plausible values of δ and α, as e.g. $\delta = 0.9$ and $\alpha = 1.25$, (7) implies that generation 1 would be forced to sacrifice 45 % of its initial consumption to make future generations better off. If the productivity parameter α goes to infinity, the level of savings according to equation (7) converges to $\delta\overline{c}$, which for a small time discount rate ρ and a high α is close to k_1. This shows that time discounting with fixed parameters ρ or equivalently δ will not necessarily prevent overburdening of early generations independent of the underlying technology. Concerning their ability to deal with the danger of excessive saving, the difference between undiscounted and discounted utilitarianism thus turns out to be less fundamental than might appear at first sight.

The first order conditions along an optimal path in the linear growth model of the previous section are

$$u'(c_{t+1}) = \frac{1}{\delta\alpha}u'(c_t) \tag{8}$$

which for an isoelastic utility function means

$$c_{t+1} = (\delta\alpha)^{\frac{1}{\eta}} c_t. \tag{9}$$

It follows from (9) that the same optimal path is obtained for different combinations of δ and η. In particular, the optimal solution, which results for some originally given parameter values δ and η, can also be implemented without any pure time discount, i.e. $\delta = 1$, by choosing a different inequality aversion parameter $\tilde{\eta}$ given by

$$\tilde{\eta} = \frac{\eta \ln \alpha}{\ln \alpha + \ln \delta}. \tag{10}$$

This interchangeability of δ and α in addition confirms that the gap between undiscounted and discounted utilitarianism is less deep than usually suspected.

The ethically questionable properties of discounted utilitarianism which more or less mirror the advantages of undiscounted utilitarianism will now be discussed.

(i) Discounted utilitarian social welfare functions do not treat all generations equally as utility of later generations counts less than utility of earlier ones (which in the case of a finite number of agents would be a quite unusual assumption). Thus these criteria violate the basic postulate of intergenerational equity.

(ii) One cannot rule out the possibility that discounted utilitarianism leads to a non-sustainable development: Along consumption paths that maximize discounted

utilitarian welfare (4) consumption of later generations may be smaller than that of earlier ones and, moreover, consumption may go to zero in the long run (see Dasgupta, P. and Heal, G. (1979), p.299 for the Dasgupta-Heal-Solow model). This phenomenon in general occurs if productivity of capital is low as compared to the discount rate. So it immediately follows from (8) that in the linear growth model consumption along an optimal is falling and converges to 0 if $\delta\alpha < 1$. Declining consumption is inevitable for any constant discount factor $\delta < 1$ if, as in the Dasgupta-Heal-Solow model with an exhaustible resource, marginal productivity of man-made capital converges to zero while the strictly positive utility discount rate ρ is constant. Therefore, discounted utilitarianism not only is unfair towards later generations in the light of its normative *foundations* but also w.r.t. its possible *consequences* for the distribution of consumption across generations.
(iii) Discounted utilitarianism may violate the Pigou-Dalton transfer principle as the fundamental criterion for equality of distribution. This happens if the transfer goes from a rich early generation t_1 to a poor later generation t_2 whenever $\delta_{t_1} u'(c_{t_1}) > \delta_{t_2} u'(c_{t_2})$. This condition is fulfilled if $\frac{c_{t_2}}{c_{t_1}}$ is close to one but $\frac{\delta_{t_2}}{\delta_{t_1}}$ is rather small.

2.5 Hybrid criteria

In the recent literature on intertemporal evaluation a lot of suggestions for new criteria have been developed to overcome some of the deficiencies of the standard criteria. The conceptually simplest approach is to combine two criteria in order to preserve some of the merits of both. Modifying an approach of Chichilnisky, G. (1996), Alvarez-Cuadrado, F. and Long, N. V. (2009) have suggested some composition of discounted utilitarianism with the maximin rule such that

$$W(c_1, c_2, \dots) = (1 - \Theta) \sum_{t=1}^{\infty} \delta_t u(c_t) + \Theta \inf_{t=1,2,\dots} u(c_t) \tag{11}$$

emerges as a *mixed Bentham-Rawls welfare function*. Here, on the right-hand side of equation (11) the parameter Θ indicates the relative weight which maximin has in the aggregate criterion. A welfare function of this type makes it less likely than discounted utilitarianism alone that early generations enjoy a large increase in their well-being while the great many of future generations are driven into poverty. Thus a major possible shortcoming of discounted utilitarianism can be avoided and a more equitable balance of interest between the present and the future is achieved. But a sustainable development is not ensured in any case just if the parameter Θ is very small (see Alvarez-Cuadrado, F. and Long, N. V. (2009)), and the strong Pareto criterion is only fulfilled if the utility function $u(c)$ is bounded below. This, however, is not an innocuous assumption since in most empirical applications isoelastic utility functions $u(c)$ with inequality aversion $\eta \geq 1$ and thus $\lim_{c \to 0} u(c) = -\infty$ are used (see also the subsequent Section 3 for some justification of this). Moreover, if $\delta < 1$, the social welfare function does not imply equal treatment of all generations such that anonymity as the basic postulate of intergenerational equity is also violated with mixed Bentham-Rawls criteria.
In contrast Zuber, S. and G. Asheim (2010) have devised a criterion which combines anonymity with discounting. The idea underlying this approach is that discounting does not depend on the period of time in which some level of consumption accrues but on the rank which the consumption level of a generation has in the whole consumption path. A problem with this rank-discounted utilitarianism is that, given an infinite number of generations, a ranking of consumption levels does not exist for all consumption streams, e.g. for any strictly decreasing path, such that additional constructions are required to extend and complete the social ordering and to get strong Pareto. Nevertheless, rank-discounted utilitarianism

gives later generations more protection against rapacity of the earlier ones than the mixed Bentham-Rawls welfare functions which, from the perspective of sustainability, constitutes an important advantage. With the Asheim-Zuber criterion discounting serves as an "added expression of aversion to inequality" (Asheim, G. B. (2011), p. 8). But some further discussion seems to be required to justify rank-discounted utilitarianism in this respect as preferable to undiscounted utilitarianism.

Llavador, H., Silvestre, J. and J. Roemer (2008) reject the utilitarian framework completely and suggest a criterion in which an exogenously given constant growth rate g of well-being is the objective that optimal paths have to fulfill. Proceeding in this unconventional way outside traditional welfare economics the maximin rule (where $g = 0$) is generalized to a sustainable growth criterion which allows for economic progress and which thus cures the major defect of pure maximin. The question, however, is through which normative concepts the choice of some growth target g may be motivated. Moreover, in some technological environments as the Dasgupta-Heal-Solow model, consumption growth with any constant positive rate is not possible which somewhat reduces the applicability of the Llavador-Silvestre-Roemer criterion.

2.6 Some preliminary assessment

All intertemporal social welfare functions that we have discussed have their pros and cons. Since maximin - with its exclusion of investment and economic progress - mostly deserves primarily attention for fixing basic ideas the real choice is between undiscounted and discounted utilitarianism. Which of these criteria is to be preferred thus is the major field of controversy in the scientific debate. Until now we have only compared these two types of evaluation criteria at an abstract level without saying anything about the parameter values that are needed to specify them. In particular, appropriate levels of the degree of inequality aversion η incorporated in the isoelastic utility function $u(c)$ and the discount rate ρ need to be chosen in order to make the criteria operational.

In simulation studies on climate change policy (as e.g. the DICE-model applied by Nordhaus, W. and J. Boyer (2000) to assess the economic impacts of climate change) η and δ are, in the tradition of the descriptive school, usually determined by calibrating numerical growth models such that the Ramsey equation $r = \eta g + \delta$ (see e.g. Dasgupta, P. and Heal, G. (1979) or Stern, N. (2007)) is fulfilled given the empirically observed consumption growth rate g and the real interest rate r. Proceeding this way (Nordhaus, W. (2007), p. 692) finds "the ethical reasoning on discount rates (...) largely irrelevant for the actual investments and negotiations about climate change". But from the viewpoint of the prescriptive school adopted here the parameter choice should also be made on the basis of normative principles. What at least is required "is adjusting certain parameters so as to reach a conclusion more in line with our intuitive judgements" (Rawls, J. (1971), p. 298). The possibility of determining these parameters by ethical reflections may also have some repercussions for the acceptability of the criteria as such. These additional, and, in contrast to the topics up to now in this paper, less familiar ethical issues will now be dealt with.

3. Choice of parameters from a normative perspective

The degree of inequality aversion of the utility function plays a central role for the specification of undiscounted, discounted and the hybrid criteria discussed above. The pattern of the time discount rate is only important for discounted utilitarianism and the hybrid versions. In the case of the mixed Bentham-Rawls criteria the weighing factor for the maximin part would have to be determined in addition.

3.1 Inequality aversion

The Stern Review (see Stern, N. (2007)), in contrast to much previous work on climate change, explicitly addressed the ethical dimension of intergenerational evaluation and in principle adopted the equal treatment postulate for generations. Therefore, in Stern's approach the elasticity of marginal utility η automatically became the main tool for bringing about an ethically acceptable balance of interest between different generations. But, somewhat surprisingly, the highly crucial choice of η was not discussed explicitly from the ethical viewpoint. In this context the Review's reflections remained rather brief, and no convincing normative justification for specifically choosing $\eta = 1$ as inequality aversion index for the main part of the empirical study was given. At the central place of the Report (see Stern, N. (2007), p. 184) there is only a short remark that employing $\eta = 1$ is "in line with recent empirical estimates". Reference is made to two empirical papers by Stern, N. (1977) and Pearce, D. and D. Ulph (1995), but it is not explained in detail why such empirical estimates might at all be of much value for making ethical decisions. Ethically relevant arguments on the choice of η, in principle, might be found in three different ways.

(i) Adopting an ethical perspective does not exclude that the ethical values of existing people become the yardstick of evaluation. Then the debate is not about what seems to be just in the eyes of an impartial and detached ethical observer but which altruistic attitudes are prevalent in a society. This approach, which is in fact applied by Stern, N. (2007), combines prescriptive and descriptive elements. The observed data do not come from the market-place but from political decisions where ethical motivations on distributional issues manifest. Although many political decisions (e.g. on pension reform and the size of the government deficit) clearly affect distribution between generations, it is very difficult if not impossible to find out the level of the inequality aversion η underlying just these decisions. Therefore, results from empirical studies on quite different topics in public policy as e.g. tax policy are transferred to the field of intergenerational distribution. The various studies on inequality aversion as expressed by income tax progressivity in a society suggest different values for η which sometimes lie in the interval between 1 and 2 (see Evans, D. (2005)) but are lower than 1 in other studies (see Atkinson, A. and Brandolini, A. (2010)). These data certainly give some hint at existing normative beliefs on inequality. But individual attitudes towards income distribution within a society and in a certain period of time are multi-dimensional and also include aspects of effort and merit which are absent in the intergenerational context (where instead motivations as responsibility and stewardship play an important role). So it may be doubted whether estimates for η that are obtained from income tax studies can easily be applied to intergenerational evaluation and climate policy.

(ii)The ethical acceptability of different values of η can also be assessed by "thought experiments" through which their implications in specific theoretical models are assessed and, in the end, some "reflective equilibrium" (see at a general level Rawls, J. (1971) and with specific application to intergenerational equity Asheim, G. B. (2010)) on distributional norms might be achieved. In this vein Stern himself has conducted hypothetical "leaky bucket" experiments focusing on the tolerable losses when income transfers from a rich to a poor individual are made (see also Dietz, S. and Stern, N. (2008), p. 106). So e.g. if the giver were five times as rich than the receiver this accepted loss would be 96 % for $\eta = 2$. But note that for $\eta = 1$ this loss also amounts to heavy 80 % so that from this perspective Stern's preference for $\eta = 1$ is not really substantiated.

In his critique of the Stern Report Dasgupta, P. (2008) has instead examined which consequences the choice of $\eta = 1$ has for the rate of optimal growth in a linear Ramsey growth model where productivity of investment leads to an "incubation bucket" in the sense of Schelling, T. C. (1995). Under otherwise plausible assumptions (but without exogenous technical progress) Dasgupta showed that $\eta = 1$ implies an extremely high savings rate amounting to almost 100 % such that early generations would suffer extremely and a fair intergenerational balance would not be come about. In this way the traditional oversaving argument that usually is applied to disprove undiscounted utilitarianism is brought into play again, now to make judgments about sensible values of η. Then higher levels of η (e.g. $\eta = 2$ as proposed by Dasgupta, P. (2008) and other authors like Weitzman, M. (2007)) seem to be appropriate, which entail more equal optimal consumption paths and protect earlier generations from overburdening through excessive saving.

(iii) It is also possible to start from some explicitly formulated postulates (or "axioms") which a social welfare function should fulfill. Such a property is "circumstance solidarity" (Fleurbaey, M. (2008)) which in the context of growth theory means that no generation should lose when the technological conditions improve, i.e. in the linear growth model when productivity α increases. In order to satisfy this condition all values $\eta < 1$ have to be excluded since with such a low inequality aversion the early generations would get lower consumption in the optimal solution when the α grows (see Buchholz, W. and Schumacher, J. (2010)). Therefore $\eta = 1$ turns out to be the minimum degree of inequality aversion which is acceptable if circumstance solidarity is adopted as a normative postulate. In the framework of such an axiomatic approach one can consider other ethical postulates, such as e.g. non-envy criteria which are also familiar in ethical social choice theory. With this approach $\eta = 1$ results when non-envy refers to *absolute* consumption levels of different generations. Alternatively, $\eta = 2$ would be obtained if the non-envy comparison referred to *relative* consumption levels (for details see again Buchholz, W. and Schumacher, J. (2010)).

Different values of η reflect value judgments on fair distributions, either at the level of voters or at the level of an ethical observer. These value judgments unavoidably have a subjective element such that it cannot be expected from the very beginning that a unique and uncontroversial estimate for η is obtained. In spite of this general caveat, the thought experiments desbribed above support the view that low degrees of inequality aversion with values $\eta < 1$ do not conform to ethical intuition. Recent empirical studies on revealed ethical preferences in tax policy give some support for this lower bound as most of them suggest values for η lying somewhere between 1 and 2. Therefore, we can conclude that, from the perspective of both theoretical as empirical ethics, Stern, N. (2007) works with an extremely low degree of inequality aversion which gives the future (too) much weight.

Concerning an upper bound for η, things are less clear. No one in the debate around the Stern Review seems to advocate a value of η being much higher than 3. But, as with the "trio of twos" from Weitzman, M. (2007), specific proposals for appropriate values of η mostly follow from pure guesswork. Additional research therefore is required to find more precise foundations for ethically motivated choices of the parameter η.

3.2 Pure time preference

Determination of pure utility time discount factors $(\delta_t)_{t=1,2,...}$ is even more problematic than of inequality aversion η. There are three approaches which - similar as in the case of η - either refer to stated preferences of individuals or to normative ideas of an ethical observer.

(i) Aggregating opinions of more than 2000 economists Weitzman, M. (2001) obtained discount rates not being constant but falling to zero over time. Specifically, he got a discount rate of 4 % for the next 5 years as the "immediate future", then 3 % for the subsequent years until year 25 from now, 2 % between year 26 and 75, 1 % between year 76 and 300 and, finally thereafter for the "far-distant future", the discount rate 0. But since Weitzman's study had the character of a black box and the motives of the respondents have not been explored systematically, it does not become transparent what the elicited discount

rates really express. In particular, it is left open whether the answers reflect pure time preference as such or whether they are confounded by other aspects as inequality aversion or predictions of future growth rates. The difficulties to isolate pure time preference as a separate behavioral motive are well-known from the empirical literature on discounting in every-day individual choices. Trying to control for these additional factors normally leads to discount rates that are substantially lower than those originally inferred (see Frederick, S., Loewenstein, G. and O'Donoghue, T. (2002)).
Another difficulty with Weitzman's approach concerns his specific method to aggregate the elicited time discount rates. To illustrate this problem we consider a simple example, in which there are two respondents a and b. Agent a has the constant time preference rate $\rho^a = 0$ such that for that agent's time discount factors $\delta_t^a = 1$ holds for all periods $t = 1, 2, \ldots$. Agent b instead has the time preference rate $\rho^b = 1$ which implies $\delta_t^b = \left(\frac{1}{2}\right)^{t-1}$ in period t. Taking the average of these both discount factors gives

$$\delta_t^m = \frac{1}{2} \cdot 1 + \frac{1}{2} \cdot \left(\frac{1}{2}\right)^{t-1} \tag{12}$$

as discount factor for period $t = 1, 2, \ldots$. Clearly, $\lim_{t\to\infty} \delta_t^m = 1$ which implies that the discount *rates* ρ_t^m obtained from this averaging procedure converge to zero in the long run. A similar result holds when there are not different opinions on time preference but when discount rates are uncertain (Weitzman, M. (1998)). Our small theoretical exercise shows that Weitzman's main result, i.e. that costs and benefits accruing in the far-distant future should be discounted at a very low and even at the lowest possible rate, does not so much rest upon the collected opinions on appropriate discount rates. Rather it is a direct consequence of his aggregation method which is not at all naturally given. So, alternatively, one could simply average the different stated discount rates, which based on Weitzman's data would give a constant discount rate of about 4 % or consider - as suggested by Gollier, C. (2004) - the average of *future* instead of present values. This would change the outcome totally since then the far-distant future would have to be discounted not at the lowest but at the *highest* possible rate. In any case it is required that the ideas, and possibly their normative content, lying behind the different aggregation methods are explained and motivated carefully (see Buchholz, W. and Schumacher, J. (2008) for some comparison of Weitzman's and Gollier's aggregation methods and Gollier, C. (2010) for an attempt to reconcile both approaches). Otherwise, the aggregation procedure appears to be arbitrary and its results thus only are of limited value.
(ii) Assume that (as in the classical approach by Harsanyi, J. (1955)) there is an ethical observer behind a veil of ignorance who applies expected utility theory to compare different distributions across generations. If in this situation the "states of the world" will not occur with the same probability she will take these differences into account - even if, in principle, she is impartial and does not favor any generation. Thus it may be ethically well acceptable to give later generations some lower weight in social evaluation since there is some risk that mankind (e.g. by an asteroid or by a devastating epidemic disease) is extinct. Later generations then would not exist and thus were not able to enjoy the fruits of savings today. If this risk of extinction from one period to the next is constant over time and equal to π the discount factor in period t is the survival probability $\delta_t = (1 - \pi)^{t-1}$. Estimation of π obviously is very speculative and a matter of subjective belief. In particular, Stern, N. (2007) has assumed a probability of 10 % that civilization may be extinct within one century which leads to the annual utility discount rate $\rho = 0.1\%$ being used in the Stern Review. From a different ethical

perspective one could, however, raise some doubts whether it is justified at all to make such a bet on the existence of future generations.
(iii) If we return to the linear growth model described above it becomes clear that non-decreasing and thus sustainable consumption paths emerge as optimal solutions if $\delta\alpha > 1$, i.e. $\delta > \frac{1}{\alpha}$ or $\rho < \alpha - 1$, which means that the time discount rate is lower than the economy's productivity. Growth of consumption along an optimal path is reduced if ρ is increased. If $\delta = \frac{1}{\alpha}$ or $\rho = \alpha - 1$ a constant consumption path is obtained. Playing around with ρ in this way means that the time discount rate which is considered to be appropriate depends on the underlying technology and thus becomes endogenous. As in Llavador, H., Silvestre, J. and J. Roemer (2008) the ethical objective then is some desirable speed of growth which is also in line with Rawls, J. (1971) "just savings principle" and his justification of pure time discount. A problem with this approach, however, is that the familiar idea that time discount rates are part of fixed social preferences being independent of the technological conditions has to be abandoned completely. But by adjusting the time discounting to the productivity of capital at least gives some upper bound for the admissible discount rate if a non-sustainable development is to be ensured.

4. Conclusion

If the choice of a specific intertemporal evaluation criterion is seen to be an ethical one, which is the viewpoint taken in this article, an uncontroversial solution clearly does not exist. Following M. Weber's famous "Wertfreiheitspostulat" it can never be decided on an objective scientific base what should be considered as an equitable distribution between agents in general and among generations as an important special case. Nevertheless, our considerations allow some tentative conclusions on the adequacy of intertemporal evaluation criteria in climate change policy.
(i) Rejection of the undiscounted in favor of discounted utilitarianism, as often suggested in the literature, seems neither necessary nor desirable. In the first place, undiscounted utilitarianism implies equal treatment of all generations and ensures sustainability. These are real virtues of an evaluative criterion. In the second place, it does not completely rule out making choices among increasing consumption paths - in particular, the introduction of pure time discount is not really required to avoid the excessive saving problem that is typically attributed to undiscounted utilitarianism and, indeed, often seen as its major shortcoming. Moreover, endorsement of undiscounted utilitarianism at a basic level need not preclude the application of a - possibly very small - pure time discount rate in order to account for the uncertainty of costs and benefits falling on future generations. Irrespective of the level of the time discount rate such a kind of "discounted utilitarianism light" gives numerical representability of the underlying social ordering which, from a practical perspective, faciliates application of the evaluation criterion to cost-benefit analysis and, from a theoretical perspective, ensures completeness of the social ordering and fulfillment of the strong Pareto principle. Seen from such a pragmatic viewpoint the extensive discussion on impossibility results in the case of infinitely many generations becomes a little redundant and some doubts may arise to which degree the recently developed more complicated hybrid criteria represent an improvement. So, partly for the same and partly for additional reasons as put forward by Stern, N. (2007) himself, we are essentially backing Stern's basic preference for undiscounted utilitarianism which gives the ethical dimension of the problem due respect and seems to represent a substantial shift of paradigm in the literature on intertemporal evaluation.

(ii) Concerning the parameters that specify the social welfare function we consequently accept Stern's choice of a very low pure time discount rate ρ but reject his choice of the inequality aversion parameter η as too low. Various thought experiments conducted in growth theoretic models as well as empirical observations of actual political decisions on redistribution suggest values of η that are higher than 1 and mostly lie closer to 2 than to 1. By now, unfortunately, no clear-cut normative criteria seem to be available which might help to determine more precise values for η. Thus there is much room left for the choice of η. This suggests that in specific applications sensitivity tests with different values of η are advisable. Employing some higher level of η gives less weight to the future. In the context of climate policy this means that the abatement of greenhouse gas emissions could happen more slowly than demanded by Stern, N. (2007). Applying Stern's approach but working with higher and more plausible values of η, would help to approach the different positions and thus take much edge off the heated controversy on the Stern Review and its urgent call for strong and immediate action in climate change policy.

Even though he uses the descriptive approach on discounting, Nordhaus, W. (2007) makes essentially the same point when he conducts a further run of his DICE integrated assessment model with the same near zero pure time discount rate ρ as in the Stern Report but a much higher elasticity of marginal utility $\eta = 3$. With these parameter values Nordhaus obtains quite similar results as in his original calculations which had been based on $\rho = 1.5\%$ and $\eta = 2$. In both simulations the "price of carbon" which equilibrates the marginal cost of environmental damages with the marginal abatement costs would lie between 200 and 300 $ per ton of carbon by the end of this century. This price would be much lower than with Stern's original parameter choice where the price of carbon would rise steeply to almost 1000 $ which makes the climate change problem appear much more dramatic. In his postscript to the Stern Review, Stern, N. (2008) himself presents related results concerning the interchangeability between η and ρ showing, e.g., that increase of η from 1 to 1.25 may have a similar effect on the monetary costs of climate change as an increase of the pure time discount rate ρ from 0.1 % to 0.5 %.

These simulation studies on the costs and benefits of climate change policy thus confirm a basic and empirically quite relevant message of this paper: The question whether to use undiscounted or discounted utilitarianism is to some degree futile concerning practical policy implications. What in the end matters much more is the selection of specific parameter values. However, it is hard to provide some well-founded normative justification for the precise values chosen.

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21

Carbon Bio-Economics and Forests: Getting the BESF Out of Climate Policy

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1. Introduction

One of the most remarkable debates in the ongoing climate policy refers to carbon removal through biological terrestrial sinks. Since nearly 40 per cent of the planet's surface is covered with forests or forested areas (Ciesla, 1997), forestland stands out as one of the major terrestrial carbon sinks.

Nonetheless, ever since energy-efficiency-CDM (Clean Development Mechanism) was established by Article 12 of the Kyoto Protocol, in 1997, during the COP-3 (3rd Conference of the Parties signing the United Nations Framework Convention on Climate Change – UNFCCC), in Kyoto, Japan, forest-rich countries have complained that energy projects either saving or removing carbon emissions from fossil fuels would largely favour industrialised nations. Only at the COP-5, in 1999, in Bonn, Germany, Latin American, Asian and African countries made their point of including, in the Kyoto Protocol, the so-called "forestry-CDM", for reforestation and afforestation projects. Such an amendment was though very cautiously endorsed by countries like Germany and the United Kingdom (Moura-Costa & Aukland, 2001). Due to geo-political imbalances caused by differences in fossil-fuel prices across a few industrialised nations, they have strongly campaigned for reducing emissions at *source* – like in energy-efficiency-CDM projects – against mitigating them by *sinks* – like through avoiding deforestation (Fearnside, 2001).

Later on, forestry-CDM was blamed for favouring only planted (unnatural) forests and disregarding any effort towards conservation of natural woodlands. Therefore, at the COP-13, in 2007, in Bali, Indonesia, forest-rich countries demanded that the protection of natural forests, by avoiding deforestation, had also to be rewarded. Thenceforth, at the following COP's (COP-14, in 2008, in Poland; COP-15, in 2009, in Denmark; and COP-16, in 2010, in Mexico), forest-rich countries had been arguing that avoiding deforestation was the cheapest and fastest way of curbing carbon emissions and combating climate change. On top of this argument, labelled REDD (Reduced Emissions from Deforestation and forest Degradation), a REDD+ one was added, at COP-15, to include, in the protection strategy (ecosystem conservation and damage prevention), the enhancement of forest stocks.

Although, unlike CDM, the REDD mechanism is still under construction, the current state of affairs concerning the role played by forests in the climate policy comes down to the clash between forest plantations (forestry-CDM) and natural forests (REDD and REDD+). First and foremost, vegetation sinks, such as forests, are often claimed to "buy time" or play a "bridging role" until cleaner technologies become available to greatly curb future anthropogenic CO_2 emissions (Kirschbaum, 2003). However, changes in spatial relations (*where-flexibility*), like those splitting forestland into natural and unnatural forests, imply changes in temporal relations (*when-flexibility*) as well (Martínez-Alier, 2002). Insofar as the time and growth speed of the economic output demands additional producing territories, the bio-geochemical time underlying environmental processes is increasingly overlooked. The greater the lag between the economy's faster and nature's slower production times, the larger the ecological imbalances (credit or debt) accruing over time.

The model (BESF – Bio-Economic model for carbon Sequestration by Forests) presented here not only can address the trade-off between forestry-CDM and REDD, but can also be applied to countries or regions with different endowments of forestland – both unnatural (**u**) and natural forests (**v**). It thus highlights the link between the spatial distribution (λ) of instant emissions across sinks (exports Z) and the demand for emissions over time (imports *M*) caused by economic growth (*k*).

As far as emissions given off by economic activities must be removed, it is demonstrated how the geographical distribution of ecological sinks (forestland) – *where-flexibility* – can influence the rhythm of economic growth over time – *when-flexibility* (Giacomelli Sobrinho, 2009). The usual *when-where-flexibility* argument relies on spatially uneven endowments of removing sinks both to lower the monetary costs of carbon removal or mitigation and to slow down mitigation investments. However it can be shown that, by and large, the more uneven the distribution of carbon sinks (the greater λ) is in the present, the longer it takes for the ecological-economic system to lessen the increasing biophysical cost of mitigation over time, as recorded by the mean long-run growth of the biophysical overshoot rate (Eq. (17)).

In this regard, the main objective of the model is to ground economic growth (emission source), translated by an emission supply (removal demand) function ($\hat{h}_t$), on its ecological limits, expressed by an emission demand (removal supply) function ($\hat{G}(X_t)$) sustained by forestland (forest sinks). Whereas $\hat{h}_t$ is fuelled by the economic growth rate (*k*), $\hat{G}(X_t)$ ultimately depends on the availability of forestland, split into natural and unnatural (plantations) forests. Therefore *k* and λ are supposed to be linked by an underlying ecological variable, guiding changes in both emission supply (ln *k*) and demand (ln λ). This invisible variable (ε), labelled the *bio-economic exchange rate*, works as a *shadow price*, which is found through dynamic optimisation methods (Fig. 1).

Because both *k* and λ are functions of ε, they can come together like in Fig. 2. That picture translates, at the macroscopic level, the effects of changes in $\hat{h}_t$ and $\hat{G}(X_t)$ triggered at the microscopic level. If an upper boundary (K_h) to the emissions arising from human economy could be signalled to their micro-economic sources ($\hat{h}_t$), biomass (forest) sinks would have to supply corresponding removing stocks ($\hat{G}(X_t)$) to counterbalance emission outflows. Macro-economically, whenever this ecological balance holds for any change in emissions, then $\varepsilon = 1$; whenever it does not, then $0 < \varepsilon < 1$ (ecological credit) or $\varepsilon > 1$ (ecological debt). However, a point such as **P**, in Fig. 2, does not necessarily mean that $\varepsilon = 1$.

Long-run macro-bio-economic equilibrium might as well occur either with ecological credit or debt. In the former case, the ecological buffer to economic growth is greater than in the latter. Although this might sound environmentally friendly, ecological credit means exporting the ecological burden (bio-capacity overshoot) to elsewhere, whereas ecological debt implies carrying the ecological burden within an economy's boundaries over time (imports of bio-capacity).

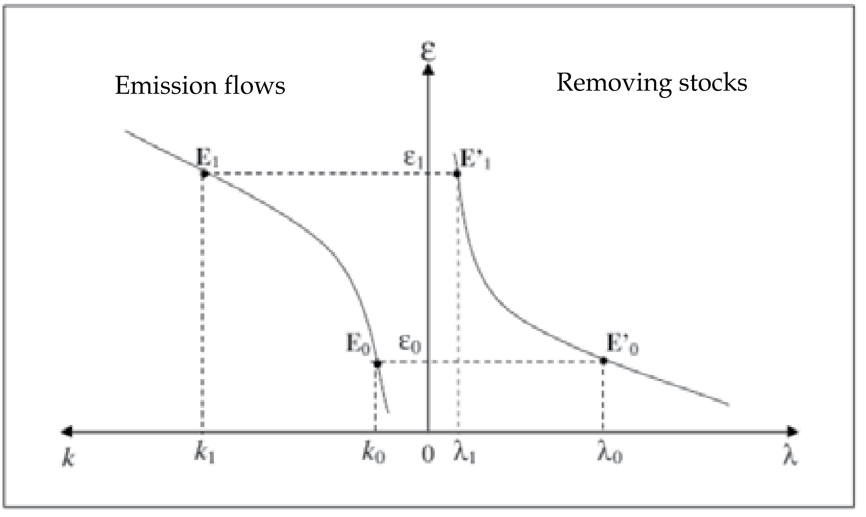


Fig. 1. Adjustment of *k* and λ by the bio-economic exchange rate (ε)

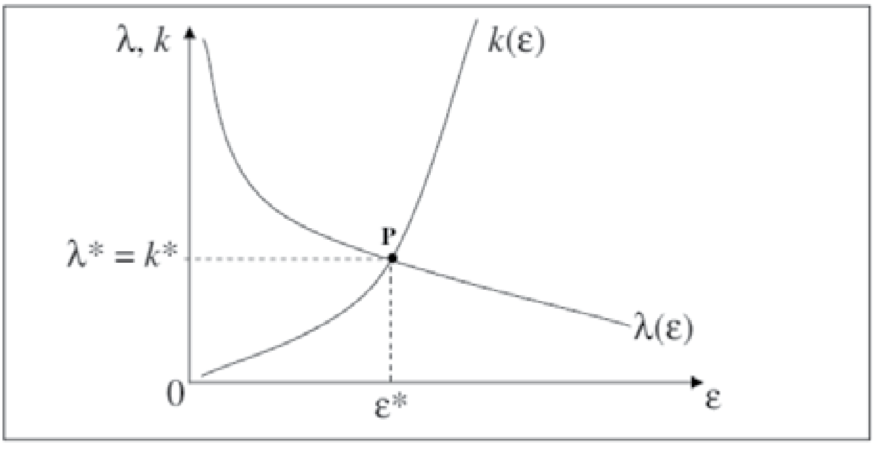


Fig. 2. Long-run macro-bio-economic equilibrium

Last but not least, none of the ecological imbalances are properly caught by monetary measures. Mainly because money takes on the function of value reserve, it allows not only for carrying wealth over time, but also for splitting up buying and selling, thereby setting its holder free to decide *when* to use the purchasing power of money. Moreover, money is the only commodity that is (not) demanded when its price – i.e., its purchasing power – goes up (down). However, the more (less) it is demanded, the less (more) it is spent. As fewer (more) goods and services are consumed, the lower (higher) their prices turn out to be; then again, the purchasing power (price) of money increases (decreases), thereby reinforcing (discouraging) the demand for it. In other words, the utility (use value) of money only depends on its own *exchange value* (Carvalho et al., 2007). As Soddy (1934, p. 24) defines it: "Money now is the *nothing* you get for *something* before you can get *anything*".

Such a unique feature makes money and monetary prices unreliable guides for the biophysical reality and its ecological commodities (natural resources and environmental services). Therefore, mindful of these shortcomings, the BESF model does not make use of any monetary measure. Yet, the only methodological purpose in that is to point out how the economic analysis can fully give up money values and still get a reliable picture of real life problems.

2. Methodology

2.1 Theoretical background

Bio-economic models, such as forestry and fishery, are concerned with the age and size (Clark, 2010) of their biomass stocks (trees and fish). Whereas age mostly matters to biologically biased forestry models, size prevails in economically driven fishery ones. Whereas forestry models enhance the maximum sustainable yield (MSY) provided by even-aged stocks to be harvested at the end of every rotation period, fishery models highlight the maximum economic yield (MEY) (rent) to be earned under regulated competition and even before the MSY can take place. Because fishermen would like to maximize the difference between economic revenue and cost, they cannot wait until that biological maximum happens. Therefore fishery models follow most population studies, which, by making use of autonomous differential equations, leave aside time and take, instead, the size of stocks into closer account. After all, the growth of a biological population, like fisheries, depends rather on its initial stock than on the instant of time in which it began to be studied (Simon & Blume, 2004).

Anyway, despite the emphasis being placed either on the age or size of biomass stocks, both forestry and fishery models are evenly source-biased and output-driven. Both of them care about natural stocks (trees and fish) provided by natural sources (forests and oceans). None of them is concerned with the *environmental service* (input) or waste-sinking capacity provided by the natural pool in which the resource stock grows. It has been learned, though, that any sustainable and successful achievement in environmental planning is only supposed to come out if the management of both sources (environmental management) and sinks (environmental policy) take place altogether.

Whereas, in forestry and fishery models, the stock harvested ($\hat{h}_t$) becomes the source of economic gains (revenue), in the BESF model, it means the *environmental cost* of storing into forest biomass the emissions from the atmospheric pool given off by the production of the economic output. Thus, in the latter model, the biomass stock is an *input* rendering an environmental service (emission removal), instead of an *output* yielding biological (MSY) and economic (MEY) gains. However, as fruitfully demonstrated by input-output methods, the output is ultimately limited by the provisioning of minimum needed inputs. Therefore, whenever the supply of inputs is overlooked, caring about the output has usually proven frustrating in the long run.

Because in the BESF model the optimal stock stands for the environmental cost of removing emissions, it is supposed to be smaller than in standard bio-economic models, in which resource stocks are used as sources of revenue. Therefore MEY, in the former case, is expected to be slightly smaller than in the latter. Notwithstanding, MEY is still the greatest possible, given now the constraint of supplying ecological services (emission removal) with the least possible use of natural resource stocks (forest biomass). This constraint is needed because the availability of forest biomass is limited by the supply of forestland.

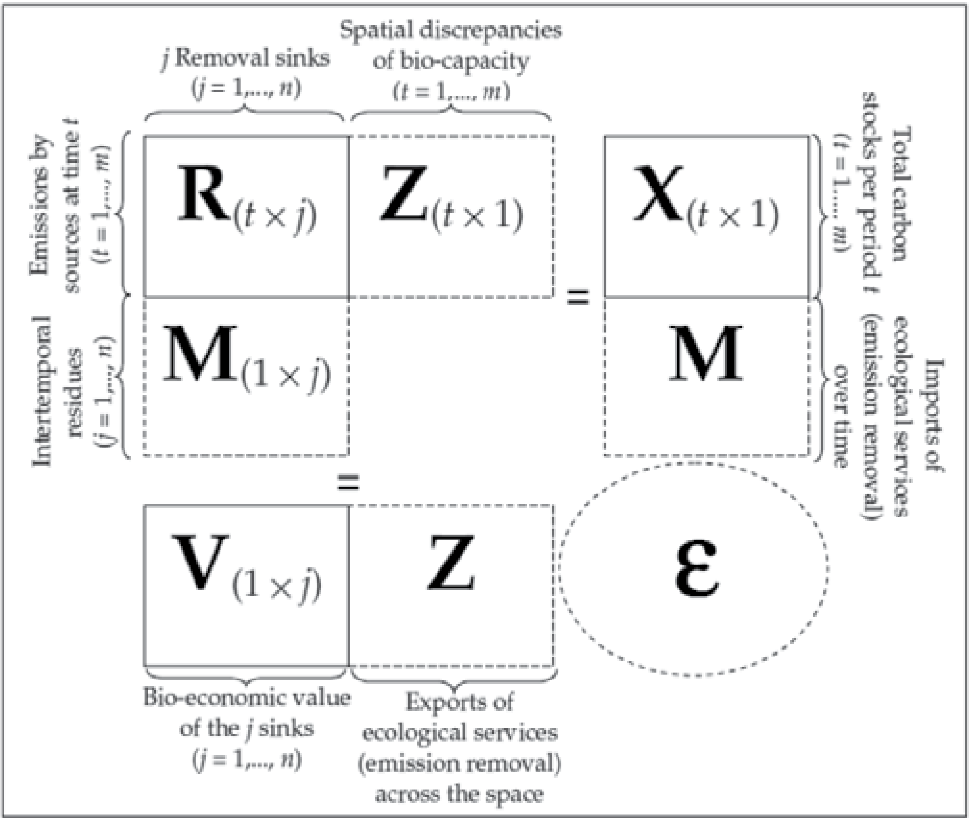
On the other hand, the availability of forest biomass depends, at the micro-level, on the demand for removing forest stocks ($\hat{h}_t$), which, by its turn, is, at the macro-level, set by the rate (k) of carbon emissions from economic growth. Thus, in this low carbon economy, the removal push comes, primarily and exogenously, from the *macro-economic* level.
Next, as long as emissions from economic growth have to be removed by forests, a *micro-economic* demand for forest stocks comes out. Then, to meet this demand, removing forest stocks have to be supplied ($\hat{G}(X_t)$), provided the supply of emissions (demand for removal) from economic growth would meet an upper boundary (K_h) somewhere. Such an upper boundary depends ultimately on λ – a variable indicating the current distribution of forestland as between natural and unnatural forests.

2.2 Assumptions

The model BESF departs from a geometric framework (Fig. 3), algebraically described (Table 2) by an emission-removal matrix (Klaassen & Amann, 1992) containing biophysical (PIOT – Physical Input-Output Table) instead of monetary (MIOT – Monetary Input-Output Table) figures (Hubacek & Giljum, 2003). Fig. 3 reminds an architectonic array in which the stability of the blocks building the horizontal upper beam relies on the weight that the blocks piling upon the column can support. The "height" of the building block **M** grows with time (t = 1,…, m) and sets the vertical weight to be borne; the "length" of the upper beam extends with the number of j (j = 1,…, n) sinks providing increasingly higher biomass stocks and depends on the "width" of **Z**. The balance between each other is regulated by a spherical ε (the bio-economic exchange rate). If **M** is too "high", it causes ε to flatten (i.e., its value is positively high) and the upper beam to bend downwards. Conversely, if **Z** is too "wide", it squeezes ε (i.e., its value is positively low), thereby lifting the rightmost end of the upper beam and increasing the pressure upon its supporting column.
When the supporting column is subject to any additional pressure, it means that the amount of emission removal transferred to other sinks (**Z**) must be reduced. This turns the width of **Z** smaller and blows ε out back, thereby causing its value to rise (depreciate). Conversely, the "height" of the supporting column owes to the transfer of emission removals over time (**M**). The larger these transfers, the lower the biophysical value (**V**) of the j removing sinks, which will increasingly become saturated. Then, when **M** is too high, it must be reduced, by pumping ε up again and making its value drop (appreciate). Just like in standard international trade models, excess imports (**M**) make the exchange rate (ε) go up (depreciate); excess exports (**Z**) make it go down (appreciate).

From	To	
	Human	Non-human
Human	(2) economy – economy standard economics **economic commodities**	(1) economy – ecology waste sinks **ecological commodities (environmental services)**
Non-human	(3) ecology – economy energy and material sources **ecological commodities (natural resources)**	(4) ecology – ecology standard ecology **ecological commodities**

Table 1. Augmented input-output model. Source: Adapted from Daly (1968, p. 401)



(*) Dotted shapes stand for underlying distributional variables not only recording emission-removal surpluses within the source-sink system, but also guiding its structural balance.

Fig. 3. Geometric framework of the BESF model*

The mechanics of such a structure (Fig. 3) falls back on a few underlying assumptions:

a. The emission-removal matrix (Table 2) includes forestland only, represented by silvicultural plantations, unnatural forests or lower biomass stock forests (**u**) and natural or higher biomass stock forests (**v**). To each forest sort a production bio-technology or bio-technological strategy is assigned: forestry-CDM (mitigation) to **u** and REDD (conservation or prevention) to **v**;
b. The emission-removal matrix (Table 2) is a PIOT (Physical Input-Output Table) rather than a MIOT (Monetary Input-Output Table) array (Hubacek & Giljum, 2003). When the economy-environment relationship is to be assessed, the physical measurement of material flows (input-output) is more useful than the monetary one (Dietzenbacher, 2005). After all, monetary prices hardly bear, if any, correlation with either energy or mass content (input) of the output produced (Ayres, 2004);
c. The link between the economic activity and land-use greatly draws on the assumptions underlying the *ecological footprint* method (Wackernagel & Rees, 1996). Whenever the avoidance, storage or removal of carbon emissions from economic growth is assigned to forest sinks, then some land appropriation is needed to supply forest carbon stocks. In these circumstances, economic growth can be translated into availability of forestland;

d. The framework depicted by Fig. 3 and Table 2 points to cell (1) in Daly's (1968) augmented input-output model (Table 1). Any cell like (1), (3) and (4) in Table 1 holds the "biophysical foundations of economics" (Daly, 1968, p. 401). By following Soddy (1934), whatever bigger world including both economic (cell 2) and ecological commodities (cells 1, 3 and 4), it could not rely on an invention like money which concerns not what is given up for it, but merely what is received in exchange for it. In this regard, the only "price" in the BESF model, which is represented by ε – the bio-economic exchange rate (Førsund & Nævdal, 1998) –, is dimensionless, although it can, through k and λ, be respectively translated into either percentage economic growth rates or carbon-equivalent tonnes and hectares of land;
e. Both **u** and **v** forests are taken as *sinks* (Fearnside, 2001).

2.3 Variables and equations

Algebraically, Fig. 3 is described by Table 2 and Eqs. (1) through (15), in Table 3.

t periods (emission sources)	j removal sinks* ($\mathbf{u} < \mathbf{v}$)		X	Z	λ
	u	**v**			
1	x_{11}	x_{12}	X_1	Z_1	λ_1
⋮	⋮	⋮	⋮	⋮	⋮
m	x_{m1}	x_{m2}	X_m	Z_m	λ_m
V	V_1	V_2	$V = X$	Z	λ
M	M_1	M_2	M	ε	
k	k_1	k_2	k		

(*) j = **u** = the smallest biomass stock sink; j = **v** = the largest biomass stock sink. However large j may be, sinks must always be displayed on an increasing biomass stock order.

Table 2. Emission-removal algebraic matrix

Variable	Description	Equation	
u	Vector of the smallest biomass stock sink	$\mathbf{u} = (x_{11}, \ldots, x_{m1}) = (u_1, \ldots, u_m)$	(1)
v	Vector of the largest biomass stock sink	$\mathbf{v} = (x_{12}, \ldots, x_{m2}) = (v_1, \ldots, v_m)$	(2)
x_{tj}	Emissions by sources at time t to be stored at (removed by) sink j	–	
X_t	Total removing stock at time t	$X_t = \sum_{j=1}^{n} x_{tj}$	(3)
X	Total removing stock through time	$X = \sum_{t=1}^{m} X_t$	(4)
Z_t	Exports of removing capacity at time t by the largest biomass stock sink (**v**)	$Z_t = x_{t2} - x_{t1}$	(5)

Z	Total exports over time	$Z = \sum_{t=1}^{m} Z_t = \Delta V = V_2 - V_1$	(6)
λ_t	Bio-diversity ratio of the largest (**v**) to the smallest (**u**) biomass stock sink	$\lambda_t = \frac{\mathbf{v}}{\mathbf{u}} = \frac{v_t}{u_t}$	(7)
λ	Source-sink system's bio-diversity ratio	$\lambda - 1 = \frac{Z}{V_1}$	(8)a
		$\ln \lambda = \frac{Z}{V_j}$	(8)b
V_j	Bio-economic value of sink *j* given by its supply, in the long-run, of biomass stocks for emission removal	$V_j = \sum_{t=1}^{m} x_{tj}$	(9)
V	Total spatial bio-economic value	$V = \sum_{j=1}^{n} V_j$	(10)
M_j	Imports (indebtedness) of removing stock needs (environmental services) caused by overshooting economic growth rates over time at sink *j*	$M_j = x_{mj} - x_{1j}$	(11)
M	Total spatial imports (across all sinks *j*)	$M = \sum_{j=1}^{n} M_j = \Delta X = X_m - X_1$	(12)
k_j	Economic growth rate at sink *j*	$k_j = \frac{x_{mj}}{x_{1j}}$	(13)
k	Source-sink system's economic growth rate	$k - 1 = \frac{M}{X_1}$	(14)a
		$\ln k = \frac{M}{X_t}$	(14)b
k	Source-sink system's economic growth rate	$k = \frac{X_t}{X_{t-1}}$	(14)c
ε	Bio-economic exchange rate	$\varepsilon = \frac{M}{Z} = \frac{\ln k}{\ln \lambda} \times \frac{X_t}{V_j}$	(15)
ψ_t	†Biophysical overshoot rate at time *t*	$\psi_t = \frac{k_t}{k^*}$	(16)
ψ	Long-run overshoot rate	$\psi = \sqrt[m]{\prod_{t=1}^{m} \psi_t}$	(17)

(†) k^* = optimal value for k.

Table 3. Variables and equations of the BESF model

Eq. (15) demands an important remark. Although $0 < \lambda_t < 1$ (Eq. (7)) and $0 < k_j < 1$ (Eq. (13)), thereby rendering $Z_t < 0$ (Eq. (5)) and $M_j < 0$ (Eq. (11)), there must always be $\varepsilon > 0$. Whereas for continuous calculations (Eqs. (8)*b* and (14)*b*), $Z < 0$ and $M < 0$ whenever $0 < \lambda < 1$ and $0 < k < 1$, for discrete figures (Eqs. (5), (6), (11) and (12)), the calculations must always turn both $\Delta V > 0$ (Eq. (6)) and $\Delta X > 0$ (Eq. (12)). The reason why it has to be so is that the bio-economic exchange rate (ε) does *not* seek to rule the *direction*, either across the space (Z) or over time (M), of the emission removal transfers. Rather, it cares about the *amounts* transferred across the space and over time.

Furthermore, when $0 < \lambda_t < 1$, it can be inferred, from Eq. (7), that $\mathbf{u} > \mathbf{v}$. Although this is an acceptable assumption when international removal trade is at sight, it cannot hold any longer when deforestation (i.e., falling $\mathbf{v}$) is strictly forbidden. In this case, the only allowed range for λ-values might at best be $\lambda \geq 1$, with any fall in λ thereby implying enhancement of forest stocks through greater use of forestry-CDM techniques, such as Sustainable Forest Management (SFM).

Because λ is primarily modified by the economic growth rate, k is the variable triggering ecological overshoot. Although k and λ are exogenously set at the macro-economic level, both of them can be optimised to check how much their observed values have been close to or far from the optimal (*) ones. When it comes to k, that distance is meant to be the overshoot rate at each period (Eq. (16)). The geometric mean of all k-distances gives the long-run overshoot rate (Eq. (17)).

Of course, for any given k_t in Eq. (16), ψ_t becomes smaller as k^* grows. Paradoxically, this sounds as if economic growth could be the solution for ecological overshoot. Yet, in an emission removing economy, larger values for k mean that more forestland is needed to store increasing amounts of emissions from economic growth. Thus, the cost of maintaining a high k would be an abrupt fall of λ.

A falling λ means either shrinking natural forests ($\mathbf{v}$) by increasing deforestation or causing unnatural forests ($\mathbf{u}$) to rise by enhancing their stocks through forestry-CDM techniques, such as Sustainable Forest Management (SFM). When it comes to international trade of removing stocks, a rising $\mathbf{u}$ means exporting deforestation, by causing $\mathbf{v}$ to fall, in exchange for imports of environmental services, such as emission removal. Should that be likely, the long-run overshoot rate (ψ) would go down too, along with λ.

Whereas a falling $\lambda \rightarrow 0$ implies higher *where-flexibility* in favour of unnatural forests ($\mathbf{u} > \mathbf{v}$), a *natural where-flexibility* ($\mathbf{u} < \mathbf{v}$) occurs with a growing $\lambda \rightarrow +\infty$. Whereas the latter case implies higher overshoot rates, the former yields *lower* ones. This is so because, when the picture changes from $\mathbf{u} < \mathbf{v}$ to $\mathbf{u} > \mathbf{v}$, exports $Z = \mathbf{v} - \mathbf{u}$ become highly negative, whereas imports M become lowly negative. Since Z indicates how much of the removing capacity depends on somewhere else's forests, $Z < 0$ means that the provision of removing capacity has greatly been switched over to the sink (economy) with the smallest biomass stock ($\mathbf{u}$). Over time, a shift like this implies reducing the transfers into the future of non-removed emissions – which is meant by a low $M < 0$. Hence, by making reduce both imports (M) – over time – and exports (Z) – across the space – of bio-capacity, this scenario can be paralleled with increasing autarky in trade, when hardly does any commerce take place.

2.4 Parameter

Table 2 and Eqs. (1) through (15) concern changes in removing stocks across the space and over time. However, they fail to set an upper boundary both to emissions and to the supply of removing stocks. After all, ε is essentially affected by the ratio energy (k) to land (λ), which points out, in each period, how much emissions from economic growth can be sustained by every hectare of ecologically productive land (Wackernagel & Rees, 1996). Hence, there ought actually to be an upper boundary that balances the effect of two opposite forces. On one hand, the push for economic growth (measured by k) raises the demand for removing stocks; on the other hand, the supply of these stocks is constrained by biophysical limits given by existing forests (λ).

Unless the macro-level signs emitted by k and λ can be caught at the micro-level of economic activities, removing stock changes, recorded by Table 2, will meet no boundary at all. This bridge is, of course, supposed to, first and foremost, lie on k, for, by modifying λ, it is the variable triggering ecological overshoot. Even so, what still remains is how to rationally set that non-existing upper boundary.

Like in standard bio-economic (forestry and fishery) models, it is assumed that (removing) stocks grow by following a logistic pattern. Accordingly, they are supposed to reach an upper level beyond which stock losses outstrip stock growth. As the BESF model is rather concerned with emission flows than with output stocks, it claims for an upper limit (K_h) to the growth of emissions ($\hat{h}_t$) rather than to that of stocks ($\hat{G}(X_t)$). However, by all means, there is a removing stock level (X_T) associated with those maximum emissions (K_h) at some terminal time T.

Rationally, K_h can be found when two ideal equilibrium conditions are achieved at the same time T:

a. *Maximum economic efficiency* ($k_j = k$): whenever the rates of economic growth or return across the sinks even off, either *conservation* (investment on natural forest sinks) or *mitigation* (investment on unnatural forest sinks) can be indifferently traded off for one another (Common, 1996);
b. *Perfect ecological efficiency* (ε = 1): when every waste generated (emitted) is removed, any allocation and redistributive move across the sinks turns out to be over (Ayres, 1999, 2004).

Theoretically, these conditions stand for both the economic and ecological sustainability of the source-sink system. The terminal stock level (X_T), though, represents the time interval required to get k stable ($k_j = k$) and ε = 1. Therefore it means the "bio-economic cost" of achieving a stable state of sustainability. Such a cost is called the "bio-economic carrying capacity". It thus rather translates a loss to be incurred than a target to be complied with (Giacomelli Sobrinho & Schneider, 2008).

Mathematically, both conditions can be found by vector algebra (Eqs. (18) and (19)). The data used in the calculations (Table 4) were collected from FAO (2011) and are related to biomass forest stocks in Austria (AUT) and Brazil (BRA).

$$\begin{bmatrix} 1 & \bar{k}^{-1} \\ \bar{k} & 1 \end{bmatrix} \begin{bmatrix} 377 \\ -64927 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} 1 & \bar{k}^{-1} \\ \bar{k} & 1 \end{bmatrix} \begin{bmatrix} 377 \\ \bar{v}_{2010-T} \end{bmatrix} = \begin{bmatrix} 65304 \\ \bar{X}_{2010-T} \end{bmatrix} \tag{19}$$

with the bar over the letter standing for mean values.

Mean values from available time series can be worked out to feed in Eqs. (18) and (19). Arguably, mean values can cover a wider range of the relevant time horizon than instantaneous values could. From solving Eq. (18), it is found that $\bar{k}$ = 172.22. By substituting this into Eq. (19), it comes out that $\bar{v}_{2010-T}$ = 11194310.34 and $\bar{X}_{2010-T}$ = 11259237.28. When $\bar{X}_{2010-T}$ is used to obtain $\hat{h}_t$ (Eq. (23)),the corresponding value of $\hat{h}_t$ is then called K_h.

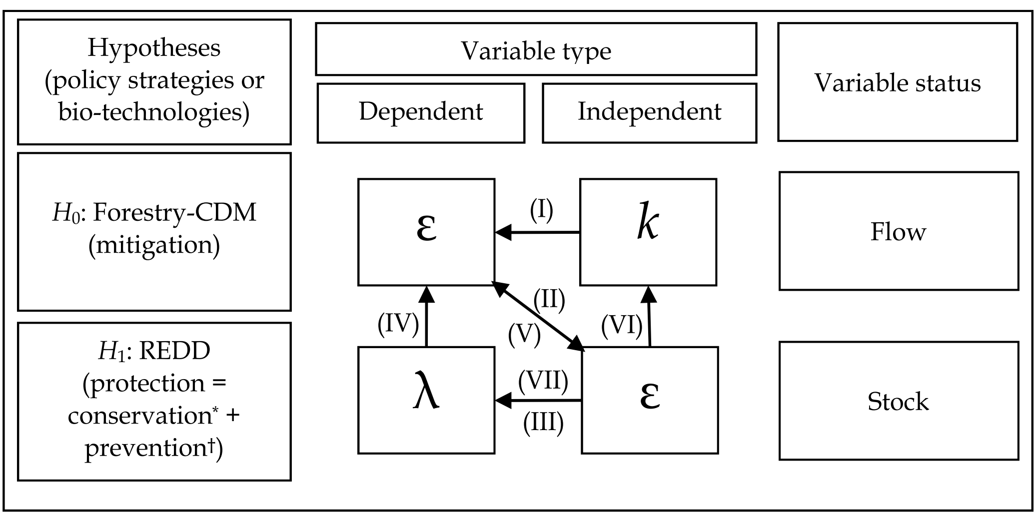
Time *t* (in years)	Forest stocks* *j* (in ktC)		X	Z	λ	λ_t/λ_{t-1}
	u (AUT)	**v** (BRA)				
1990	339	68119	68458	67780	200.94	–
2000	375	65304	65679	64929	174.14	0.8666
2005	399	63679	64078	63280	159.60	0.9165
2010	393	62607	63000	62214	159.31	0.9982
Mean	**377**	**64927**	**65304**		**173.50**	**0.9255†**

Source: FAO (2011, pp. 123 and 126)
(*) Here, vectors **u** and **v** do not necessarily stand, respectively, for *unnatural* and *natural* forests. (†) Geometric mean.

Table 4. Biomass stocks in Austria's and Brazil's forests

2.5 Functions and hypotheses

Structurally, the model BESF takes into account the interplay of macro and micro-economic tiers. Changes in *k* and λ taking place at the *macro-bio-economic* level affect, correspondingly, the *micro-bio-economic* demand ($\hat{h}_t$) and supply ($\hat{G}(X_t)$) of emission removal. Whereas *micro-bio-economics* pinpoints removing stock levels yielding MSY (biological equilibrium), MEY (restricted access equilibrium, RA), economic rent dissipation (open access equilibrium, OA) and the steady-state (SS) equilibrium ($\hat{G}(X_t) = 0$), *macro-bio-economics* shows how the rate of economic growth (*k*) affects forestland use (λ) and overuse (ψ_t), as recorded by ε (Fig. 2 and



(*) Enhancement of stocks or stock maintenance approach (REDD+). (†) Avoided deforestation (REDD). (‡) Arrows indicate the direction of the causation flows; roman numerals describe the circuit of causation. It is worth noticing that, at the two last steps (VI and VII) of this circuit, both k and λ are turned into dependent variables, yet, for drawing reasons only, k still appears to be an independent one.

Fig. 4. Causation flows‡ between the macro-bio-economic variables of the BESF model

Fig. 4). In other words, whereas, through the parameter K_h, *micro-bio-economics* sets limits to the *supply* of emission removal, thereby ultimately determining λ at the macro-level, *macro-bio-economics*, by the interplay of k and λ, informs to the micro-level activities the changes in demand for removal the economy is allowed to grasp.

2.5.1 Micro-bio-economic removal demand or emission supply function ($\hat{h}_t$)

The estimation of the removal demand function draws on the *Permanent Income Hypothesis* (PIH), put forward by the American economist Milton Friedman, in the late 1950's. His basic intuition was that "individuals would wish to smooth consumption and not let it fluctuate with short-run fluctuations in income" (Meghir, 2004, p. F293). In an emission-saving (low carbon) economy, consumption can be replaced by emissions released, whereas income arises from emission savings or removals.

Actually, the PIH divided both consumption and income into a permanent and a transitory component. The permanent income is thought of as the mean income regarded as permanent by consumers, which in turn depends on their horizon and foresightedness. On the other hand, "the transitory component consists of unforeseen additions or subtractions to income, which are supposed to cancel out[1] over the period considered and to be uncorrelated with the permanent income" (Houthakker, 1958, p. 397). Shortly, the PIH claims that consumption is planned over a fairly long period, on the basis of expected income (removal) during that period ($E(X_t)$) and that consumption plans (demand for emission removal, h_t) are not supposed to change because income (removing stocks, X_t) in a particular year falls short of or exceeds expectations ($E(X_t)$) (Houthakker, 1958). Thus, the *observed* demand for emission removal ("measured consumption") is given by:

$$h_t = X_t - E(X_t), \quad \text{for } X_t > E(X_t) \tag{20)a}$$

$$h_t = E(X_t) - X_t, \quad \text{for } X_t < E(X_t) \tag{20)b}$$

where $E(X_t)$ is some function of X over time t (X_p). $E(X_t)$ can be obtained from Table 8 as follows:

a. By regression of X_t over time, it is found out there to be a *cubic* relationship guiding (permanent) removal consumption over time (X_p):

$$X_{p(t)} = 0.001859t^3 - 0.141161t^2 + 5.113131t \tag{21}$$

t-stat.	6.286	-7.282	16.856
sig. t	0.0000	0.0000	0.0000

b. By regression of X_p (Eq. (21)) on observed X_t, then Eq. (22) comes out:

$$E(X_t) = 0.993992X_t \tag{22}$$

t-stat.	88.184
sig. t	0.0000

[1] This rule, however, does not apply to Eqs. (20)*a* and (20)*b*, which must always render positive outcomes. The reason is that these equations account for the biophysical rather than the monetary worth of consumption. According to the First Law of Thermodynamics (*material and energy balance*), in the biophysical world, nothing can be ruled out at all. As Soddy (1934, p. 96) adds on, "so long as physical tokens exist it is not possible to make them less than zero. But by book-keeping this obvious limitation can be got round, and in figures it is just as easy to count in negative numbers as in positive (...)".

Eq. (22) holds mean values for Eq. (21). In this case, as $E(X_t) < X_t$, then Eq. (20)*a* applies (see footnote 1). The results are displayed in Table 8. Now, by running the regression of the h_t values given by Eq. (20)*a* on the observed X_t, the demand function for emission removal ($\hat{h}_t$) can be finally estimated:

$$\hat{h}_t = 0.00601205X_t \tag{23}$$

t-stat. 85216.783
sig. t 0.0000

2.5.2 Micro-bio-economic removal supply or emission demand function ($\hat{G}(X_t)$)

By substituting $\bar{X}_{2010-T}$ = 11259237.28, found through Eqs. (18) and (19), in Eq. (23), the parameter K_h = 67690.53 arises. This is the *upper boundary* needed to establish, on the supply side, a logistic pattern of growth for the emission removing stocks, thereby indicating that, on the demand side, an upper level of emissions is supposed to be met somewhere, at a certain point in time.

K_h is next used in a conditioned optimisation programme (Eqs. (24) through (26)) to find $g(v(X_t))$ – the *logistic growth rate for emission removing stocks* (Eqs. (25)*a* and (25)*b*):

Objetive-function:

$$MIN \sum_t S_t = \left[g\big(v(X_t)\big) - \hat{h}_t\right] \tag{24}$$

Constraints:

I.

$$\hat{h}_t = 0.00601205X_t \tag{23}$$

II. (Boyce & DiPrima, 2006, p. 45)

$$g\big(v(X_t)\big) = \frac{K_h\hat{h}_1}{\hat{h}_1 + \left[\big(K_h - \hat{h}_1\big)e^{-b_1X_t}\right]} \tag{25a}$$

$$g\big(v(X_t)\big) = \frac{67690.53 \times 0.127}{0.127 + [(67690.53 - 0.127)e^{-0.01738464X_t}]}$$

$$g\big(v(X_t)\big) = \frac{8596.70}{0.127 + 67690.40e^{-0.01738464X_t}} \tag{25b}$$

III.

$$g\big(v(X_t)\big) \geq \hat{h}_t \ , \tag{26}$$

where S_t = instantaneous surplus arising from the gap between removal growth rates ($g(v(X_t))$) and removal consumption rates ($\hat{h}_t$). In Eq. (25)*b*, $\hat{h}_1$ = 0.127 is taken out of Table 8, when t = 1 (1960), whereas that of b_1, another parameter of the logistic function (Eq. (25)*a*), is provided by the optimisation programme above, run in version 22.8 of GAMS (General Algebraic Modelling System). At last, the condition laid down by Eq. (26) ensures that emission removal rates will never be smaller than the emission removal demanded. The optimal values for $g(v(X_t))$ are also displayed in Table 8.

Next, by knowing the optimal $g(v(X_t))$ at each period, it is then possible figure out how much removal should be periodically supplied ($G(X_t)$). Yet, that amount is formerly up to the relationship between future ($\hat{F}(X_t)$) and currently observed (X_t) needs of emission removing stocks (Eq. (27)).

$$G(X_t) = \hat{F}(X_t) - X_t \tag{27}$$

Variable $\hat{F}(X_t)$, by its turn, results from an emission *outflow-inflow* ratio (Eq. (29)), in which the *outflow* component (Eq. (28)) is also supposed to follow a logistic growth pattern. It is worth noticing that the *hat notation* for variable $\hat{F}(X_t)$ does not mean it is an estimate in the statistical sense, but rather that $\hat{F}(X_t)$ is inferred from an *optimal* and *non-observable* logistic rate of growth for emission removing stocks.

a. Emission *outflow* (rate of demand for removing stocks):

$$\frac{d\hat{h}_t}{dX_t} = \hat{h}_t\left(K_h - \hat{h}_t\right) \tag{28}$$

b. Emission *inflow* (rate of supply of removing stocks):

$$g\left(v(X_t)\right) = \frac{K_h \hat{h}_1}{\hat{h}_1 + \left[\left(K_h - \hat{h}_1\right)e^{-b_1 X_t}\right]} \tag{25)a$$

$$\hat{F}(X_t) = \frac{d\hat{h}_t/dX_t}{g\left(v(X_t)\right)} = \frac{\hat{h}_t\left(K_h - \hat{h}_t\right)}{g\left(v(X_t)\right)} \tag{29}$$

By feeding in Eq. (27) the values provided by Eq. (29) and the observed X_t, displayed in Table 8, it is possible to arrive at the amount of $G(X)$ per period. By carrying out the regression of these so calculated values on the observed X_t ones, from Table 8, the supply function of emission removal can then be estimated (Eq. (30)).

$$\hat{G}(X_t) = -0.008164X_t^2 + 1.087793X_t + 30.775753 \tag{30}$$

t-stat.	-29.275	27.579	24.765
sig. t	0.0000	0.0000	0.0000

2.5.3 Macro-bio-economic removal supply or emission demand function ($\hat{\lambda}(\hat{\varepsilon})$)

The estimation of macro-bio-economic functions requires knowing the behaviour of ε for every given (observed) k and λ. As shown by Fig. 3, ε is an underlying variable, the role of which resembles very much that of a *shadow price*, informing, along an optimal path, the marginal bio-economic value of the asset (forestland) at time t (Clark, 2010).

Although ε is not an observable variable, it can, through Table 2 and Eqs. (1) through (15), be inferred from *observed* k and λ. This amounts to say that ε is a function of both k (Method I) and λ (Method II) – or, in symbols, $\hat{\varepsilon}(k)$ and $\hat{\varepsilon}(\lambda)$. Yet, these estimates are just intermediate steps to obtain their inverse functions, namely, $\hat{k}(\hat{\varepsilon})$ and $\hat{\lambda}(\hat{\varepsilon})$. The latter are those that actually account, respectively, for macro-bio-economic demand (supply) and supply (demand) of removal (emissions). As they are *long-run* (mean) functions, they carry no time (t) index.

To get $\hat{\varepsilon}(\lambda)$, it is first needed to hold fixed *observed* $k = \bar{k} = 1.03742$ (Table 8) and, by recalling Eq. (14)c, apply it evenly to every period, starting at $t = 1$. In this way, new values of X_t (X'_t) will be arrived at. The rationale behind this trick is to check, for every single period, the impact of λ itself onto ε, thereby tearing the effect of λ apart from that of k.

Although λ values cannot be obtained from economic data, they can be retrieved from forestry data, such as those displayed in Table 4. Yet, even so, data for λ are available for only four periods, thereby rendering unlikely to know the evolution of λ over time. Therefore, to ground the calculations on, at least, a slice of reality, the geometric mean of the changes in λ throughout 1990-2010 (in the last line and column of Table 4) is also supposed to hold all over the 1960-2007 period, for which economic data are available. As the latter is made up of $t = 48$ time periods, the (geometric) mean growth of λ (g_λ) throughout is given by:

$$g_\lambda = \sqrt[48]{0.9255} = 0.9984 \quad (31)$$

By taking the natural logarithm of the outcome of Eq. (31) and multiplying the result by 100, it is found the rate of (de-)growth of λ from 1960 through 2007 (Eq. (32)).

$$\ln g_\lambda = \ln 0.9984 = -0.00161242$$

$$g_\lambda\% = \ln g_\lambda \times 100 = -0.161242\% \quad (32)$$

By observing the evolution of λ, in Table 4, it can be seen that this variable has been falling over time. Hence, should the starting point for λ be its least value, during the 2005-2010 period (Table 4), its earlier values ought to be found by increasingly raising $\lambda_{2005\text{-}2010}$ = 159.31 by $g_\lambda\%$ = 0.161242%, so as to get $\lambda_{1960} > \lambda_{2007}$.
Now, by consecutively taking the values of X'_t, yielded from holding $k = \bar{k}$ = 1.03742, and using, accordingly, the corresponding λ_t's found by making them change by $g_\lambda\%$ = -0.161242% (Eq. (32)), from t = 1 (1960) through t = 48 (2007), ε can then be calculated for every year. At last, λ and ε must be ordered pairwise, according to increasing λ figures.
For scaling reasons, ln λ is taken instead of λ itself. Logarithms scale down larger values of λ as compared with those too much smaller of k (Table 8). The resulting estimations for both $\hat{\varepsilon}(\lambda)$ (Method II) and $\hat{\lambda}(\hat{\varepsilon})$ are, respectively, given by Eqs. (33) and (34). Eq. (34) is, of course, the *macro-bio-economic removal supply* or *emission demand* function.

$$\hat{\varepsilon}(\ln\lambda) = 0.020497 - 0.000234\ln\lambda \quad (33)$$

t-stat.	10181.248	-594.029
sig. t	0.0000	0.0000

$$\ln\hat{\lambda}(\hat{\varepsilon}) = 87.546334 - 4271.091093\hat{\varepsilon} \quad (34)$$

t-stat.	–	–
sig. t	–	–

2.5.4 Macro-bio-economic removal demand or emission supply function ($\hat{\boldsymbol{k}}(\hat{\boldsymbol{\varepsilon}})$)

Removal demand-side estimations, namely, $\hat{\varepsilon}(k)$ and $\hat{k}(\varepsilon)$, must follow through the same rationale guiding the former removal supply-side estimations. This time, though, it is needed to hold fixed *observed* $\lambda = \bar{\lambda}$ = 173.50 (Table 4). Next, every observed k_t, in Table 8, is, consecutively pairwise (i.e., k_t and k_{t+1}; k_{t+1} and k_{t+2}; ...; k_{t+m-1} and k_{t+m}), placed into Table 2. Whenever $X_m < X_1$ or, more generally, $X_t < X_{t-1}$, thus rendering $M < 0$ (Eq. (12)), two single tricks can allow, as required, for $M > 0$. As long as $\mathbf{v} > \mathbf{u}$ and $|M_\mathbf{v}| > |M_\mathbf{u}|$, M becomes positive by applying: *a*) $M = -\sum_{j=\mathbf{u}}^{\mathbf{v}} M_j$, if $M_\mathbf{v} < 0$; and *b*) $M = \sum_{j=\mathbf{u}}^{\mathbf{v}} M_j$, if $M_\mathbf{v} > 0$, but $M_\mathbf{u} < 0$.
At last, while keeping $\lambda = \bar{\lambda}$ = 173.50 throughout, Eqs. (1) through (15) are used to reckon the impact of the various observed k on the value of ε. Again, as in removal supply-side estimations, k and ε must be ordered pairwise, according to increasing k figures.
The resulting estimations for both $\hat{\varepsilon}(k)$ (Method I) and $\hat{k}(\hat{\varepsilon})$ are, respectively, given by Eqs. (35) and (36). Eq. (36) is, of course, the *macro-bio-economic removal demand* or *emission supply* function. For both solution and domain reasons, ln k is taken instead of k itself. The removal market solution requires that removal supply (Eq. (34)) equals removal demand (Eq. (36)). Therefore it is handier to the solution, if both functions can match their scales.

$$\hat{\varepsilon}(\ln k) = 3.106921(\ln k)^2 + 0.088291 \ln k + 0.010558 \quad (35)$$

t-stat.	8.930	2.678	10.456
sig. t	0.0000	0.0104	0.0000

$$\ln \hat{k}(\hat{\varepsilon}) = -45.321413\hat{\varepsilon}^2 + 5.626990\hat{\varepsilon} + 0.059203 \quad (36)$$

t-stat.	-5.484	9.378	-7.284
sig. t	0.0000	0.0104	0.0000

3. Equilibrium and scenario analysis

In this section, the *removal bio-economics* described so far is applied to Austrian (AUT) and Brazilian (BRA) economies, for a 48-year-long time period, spanning from 1960 through 2007 (Table 8). The analysis is split into *removal micro-bio-economics* and *removal macro-bio-economics*.

3.1 Micro-bio-economic analysis

By following suit equilibrium analysis in standard fisheries, five equilibrium points are spotted: *a*) *BESF* equilibrium; *b*) *restricted access* (RA) or *maximum economic yield* (MEY) equilibrium; *c*) *maximum sustainable yield* (MSY) *d*) *open access* (OA) equilibrium; and *e*)

Equilibrium	Equilibrium conditions	Optimal† stock (X_t^*) (ktC)‡	Emission savings ($\hat{G}(X_t^*)$) Eq. (30) (MtC)‡	Emission consumption ($\hat{h}_t^*$) Eq. (23) × 10² (tens of tC)‡	Rate of return†† $\frac{d\hat{G}(X_t)}{dX_t}$	Rate of depletion§ $\frac{d\hat{h}_t}{dX_t}$	Economic yield or rent‡ $Y_t = \hat{G}(X_t^*) - \hat{h}_t^*$
BESF/ MEY′	$\frac{d\hat{G}(X_t)}{dX_t} = \frac{d\hat{h}_t}{dX_t}$ $0 < X_{BESF} < X_{MSY}$	29.80083293	55.94252661	17.91626076	**0.601205000**	**0.601205**	**38.0262658498285**
RA/ MEY″	$\frac{d\hat{G}(X_t)}{dX_t} = \frac{d\hat{h}_t}{dX_t}$ $0 < X_{RA} < X_{OA}$	29.80083303	55.94252667	17.91626082	**0.601204998**	**0.601205**	**38.0262658498290**
MSY	$\frac{d\hat{G}(X_t)}{dX_t} = 0$	66.62	**67.01**	40.05	0.000000	0.601205	26.96
OA	$\hat{G}(X_t) = \hat{h}_t$	98.05	58.95	58.95	-0.513147	0.601205	**0.00**
SS	$\hat{G}(X_t) = 0$	157.22	**0.00**	94.52	-1.479293	0.601205	-94.52

(†) Provided by GAMS 22.8. (‡) For scaling reasons, carbon units diverge. Actually, the barter ratio of $\hat{G}(X_t)$ to $\hat{h}_t$ is 1 MtC per 10 tC (Table 8). Of course, carbon rent (economic yield) can surely be calculated, but its values will not correspond to those displayed in the last column of Table 5. Even though, scale discrepancies themselves do not rule out the rationale underlying the calculations of the economic yield or rent. However, when carbon units are matched up, rent values will not exactly look like those figures appearing in the last column of Table 5. (††) "... a private profit-maximising steady-state equilibrium ... will be one in which the resource stock is maintained at a level where the rate of growth ($d\hat{G}(X_t)/dX_t$) equals the market rate of return on investment (...)" (Perman et al., 1996, p. 179). (§) Before calculating this derivative, Eq. (23) must be multiplied by 10^2, because the barter ratio of $\hat{G}(X_t)$ to $\hat{h}_t$ is 1 MtC per 10 tC or 10^6 tC ÷ 10 tC = $10^2 \times 10^3$ tC ÷ 1 tC = 10^2 ktC per tC. So, multiplying 1 tC by 10^2 gives the *unit* barter ratio of $\hat{G}(X_t)$ to $\hat{h}_t$, namely, 10^2 ktC : 1 × 10^2 tC = 1 ktC : 1 tC.

Table 5. Results from micro-bio-economic equilibrium analysis

steady-state (SS) equilibrium. The results are displayed in Table 5 and shown by Fig. 5. Although Y_{BESF} (MEY') is slightly smaller than Y_{RA} (MEY''), the rate of return at BESF equals the rate of depletion, whereas at RA the rate of return is slightly smaller than the rate of depletion (Table 5). As explained earlier, this was expected, because BESF is input-driven (emission saver), whereas RA is mostly concerned with the economic output arising from the consumption of emissions to be later stored in biomass stocks (emission removal).

By comparing X_t^*, in Table 5, with the observed X_t, in Table 8, it is possible to approximately know *when* each micro-bio-economic equilibrium happens. Both X_{BESF} and X_{RA} took place somewhere in-between 1967 and 1968; X_{MSY}, between 1985 and 1986; X_{OA}, between 1995 and 1996, thus, one decade after X_{MSY}; X_{SS} seems to be still to come.

The major warning coming out of this micro-bio-economic equilibrium analysis is that, given the observed growth of emissions (X_t in Table 8) in their economies, Austria and Brazil's forests have already left behind their potential to generate MEY (1967-1968). Likewise, the point of biological equilibrium (MSY) was also surpassed around 1985-1986. Thenceforth, it took only one decade longer (1995-1996) to reach the removing stock level (X_{OA}) at which emission savings just even off emission needs. Such a stock level is thought of dangerously driving to that of removal overshoot (X_{SS}), beyond which emission consumption becomes increasingly larger than emission savings. In the sink-based (environmental service) approach, X_{SS} can be compared with exhaustion or extinction, in the source-based (natural resource output) one. At present, Austrian and Brazilian economies are already in the neighbourhood of that overshoot point.

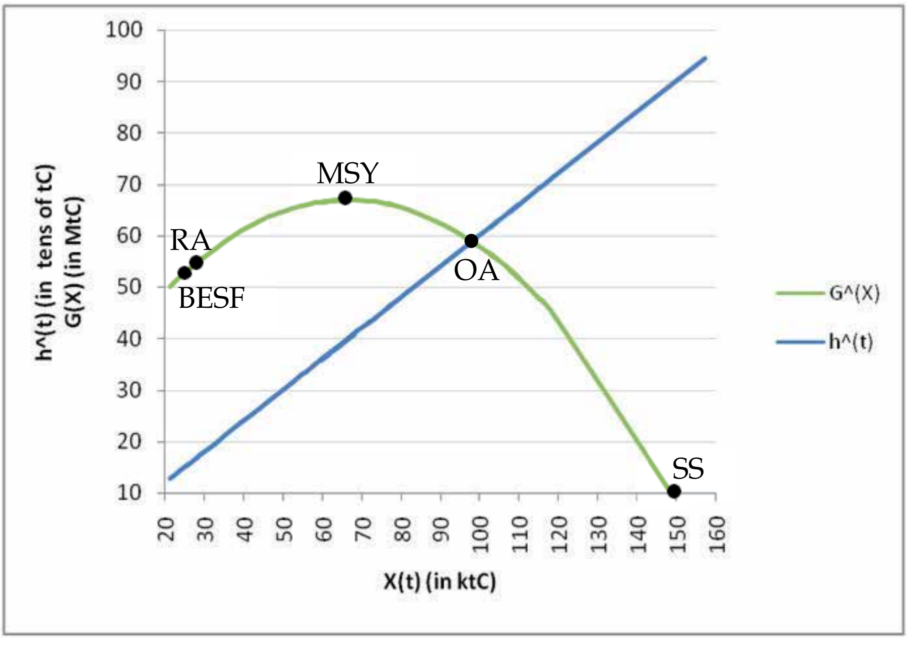


Fig. 5. Micro-bio-economic equilibrium points for Austria and Brazil's economies (1960-2007)

3.2 Macro-bio-economic analysis

In this section, five scenarios are tried out to make it clear how ε responds to the long-run overshoot rate ψ (Fig. 7). The scenarios range from an extreme situation in which λ is minimum (Scenario 3, in Table 6) – therefore deforestation in sink **v** is maximum (Eq. (7)) – to the opposite setting in which $\lambda \rightarrow +\infty$ (Scenario 4, in Table 6) – and thus, by Eq. (7), conservation (REDD) in sink **v** is maximum. Sink **v** (Brazil's forests) commands conservation not only because it shelters the largest biomass stocks, but also because, by definition (Eq. (7)), λ is the variable guiding the exports Z (Eqs. (5) and (6)) of emission removing services across sinks and, thereupon, the *supply* of emission removing stocks (Eq. (34)).

Scenarios*	Constraints†	Objective-function (*W* or *W'*)‡
1. BEE (Bio-Econ. Equil.)	$\ln\hat{\lambda} \geq \ln\hat{k}$	MIN *W*
2.a. Max. REDD *a*	$\ln\hat{\lambda} \geq \ln\hat{k}$; $0 < \hat{\varepsilon} < +\infty$	MAX *W*
2.b. Max. REDD *b*	$\ln\hat{\lambda} \geq \ln\hat{k}$; $0 < \hat{\varepsilon} < \hat{\varepsilon}_{\mathrm{BEE}}$	MAX *W*
3. Full CDM	$\ln\hat{\lambda} \leq \ln\hat{k}$; $\hat{\lambda} \rightarrow 0$	MAX *W'* or MIN *W'*
4. Full REDD	$\ln\hat{\lambda} \geq \ln\hat{k}$; $\hat{\lambda} \rightarrow +\infty$	MAX *W* or MIN *W*
5. CDM = REDD	$\ln\hat{\lambda} \leq \ln\hat{k}$; $\ln\hat{\lambda} = 0$; $\hat{\lambda} = 1$	MAX *W'* or MIN *W'*

(*) Forestry-CDM is assigned to vector **u**; REDD, to vector **v**. By Eq. (7), λ rules both.
(†) Where $\ln\hat{\lambda}$ is given by Eq. (34) and $\ln\hat{k}$, by Eq. (36).
(‡) $W = \ln\hat{\lambda} - \ln\hat{k}$ and $W' = \ln\hat{k} - \ln\hat{\lambda}$

Table 6. Scenario analysis

Sce-nario	$\ln\hat{\lambda}^*$	$\ln\hat{\lambda}^*$ † ($\times 10^{-2}$)	$\ln\hat{k}^*$	$\hat{k}^*$ (%)	$\hat{\varepsilon}^*$ ($\times 10^{-2}$)	Long-run overshoot rate ψ	$\ln\psi$	ψ (%)
3	-23.026	-0.2303	0.05609	5.609	2.59	0.980834	-0.01935	-1.935
5	0.000	0.0000	0.03709	3.709	2.05	0.999650	-0.00035	-0.035
1	0.037	0.0004	0.03706	3.706	2.05	0.999682	-0.00032	-0.032
–	2.000	0.0200	0.03532	3.532	2.03	1.001425	0.00142	0.142
–	3.000	0.0300	0.03442	3.442	1.98	1.002322	0.00232	0.232
–	5.000	0.0500	0.03262	3.262	1.93	1.004132	0.00412	0.412
2a	16.667	0.1667	0.02169	2.169	1.66	1.015161	0.01505	1.505
2b	18.656	0.1866	0.01976	1.976	1.61	1.017122	0.01698	1.698
4	23.016	0.2302	0.01546	1.546	1.51	1.021504	0.02128	2.128

(†) Once $\ln\hat{\lambda}^*$ (Eq. (34)) is much larger than $\ln\hat{k}^*$ (Eq. (36)), the former must be scaled down, by multiplying it by 10^{-2}, so that both function values can be plotted together. (‡) Results provided by GAMS 22.8.

Table 7. Optimal‡ (*) results from scenario analysis

After running the scenarios from Table 6, the outcomes displayed in Table 7 are achieved. The results from Table 7 are plotted in both Fig. 6 and Fig. 7. The curves in Fig. 6 show the optimal long-run path for economic growth rates ($\hat{k}^*$) as well as for forest and climate policy (forestry-CDM and REDD, driven by $\hat{\lambda}^*$). Whereas the removal supply function ($\ln\hat{\lambda}^*$) is highly sensitive (steeper) to changes in the bio-economic exchange rate ($\hat{\varepsilon}^*$), the removal demand function ($\ln \hat{k}^*$) is just slightly modified (smoother) by changes in $\hat{\varepsilon}^*$. This means that economic growth rates are not supposed to considerably change in response to any movement in the bio-economic exchange rate.

As the movements of the bio-economic exchange rate ($\hat{\varepsilon}^*$) are found to offset changes in the long-run overshoot rate (ψ) (Fig. 7), it can be stated that economic growth is rather insensitive (inelastic) to ecological overshoot – large shifts in overshoot rates can only make the economic growth rate slightly change, or, conversely, small changes in the economic growth rate cause large changes in the long-run overshoot rate. On the other hand, just small changes in $\hat{\varepsilon}^*$ are suffice to bring about large changes in $\hat{\lambda}^*$ – thus rendering the bio-diversity ratio quite sensitive (elastic) to ecological overshoot. In a nutshell, this means that the longer it takes to control long-run economic growth rates in order to make long-run

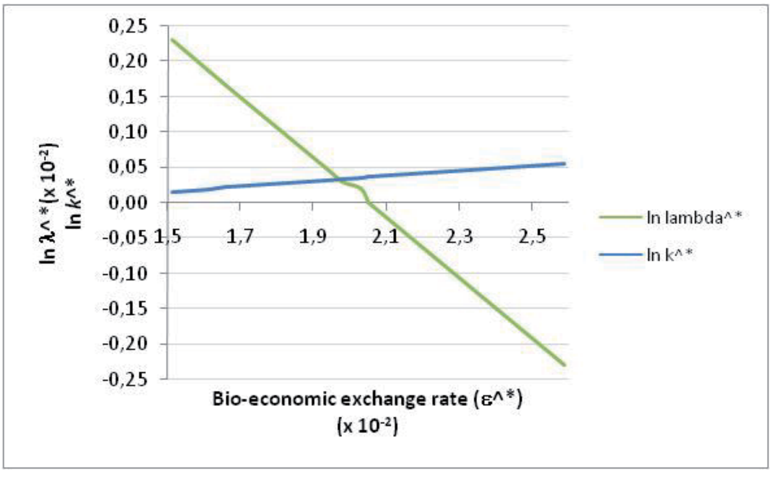


Fig. 6. Bio-economic market for long-run emission removal in Austria and Brazil (1960-2007)

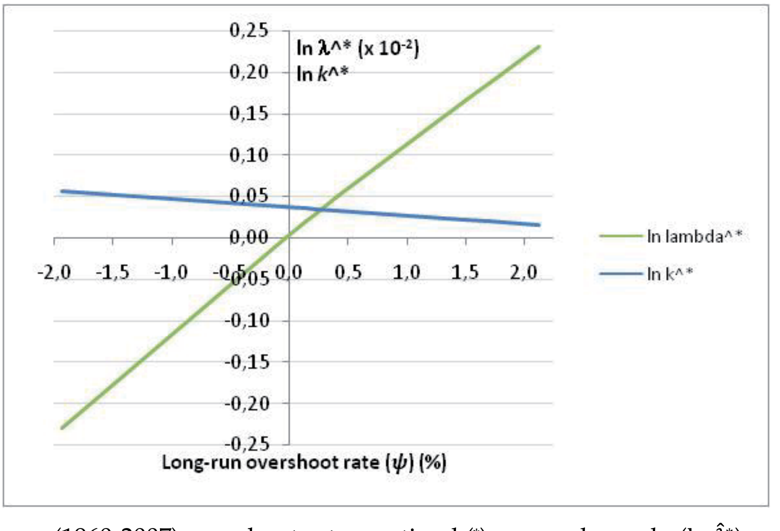


Fig. 7. Long-run (1960-2007) overshoot rates, optimal (*) removal supply ($\ln \hat{\lambda}^*$) and demand ($\ln \hat{k}^*$) for Austria and Brazil's economies

Time periods	Years	Obs. emis-sions[†] (ktC)	Obs. econ. growth	Estimated emissions over time (ktC)	Expected removal consump-tion (ktC)	Obs. removal consump-tion (ktC)	Estimated removal consumption (tens of tC)	Optimal[‡] logistic rate (tens of tC)	Optimal[‡] emission removal (in MtC)	Estimated emission removal (in MtC)
t		X_t	$k=X_t/X_{t-1}$	Eq. (21)	Eq. (22)	Eq. (20)*a*	Eq. (23) x 10^2	Eq. (25)*b*	Eq. (27)	Eq. (30)
1	1960	21.16	–	4.97	21.04	0.127	12.72	18.40	46.84	50.14
2	1961	22.07	1.04293	9.68	21.94	0.133	13.27	18.70	48.08	50.81
3	1962	23.85	1.08061	14.12	23.71	0.143	14.34	19.20	50.38	52.08
4	1963	25.21	1.05718	18.31	25.06	0.151	15.16	19.70	52.00	53.01
5	1964	26.05	1.03314	22.27	25.89	0.157	15.66	20.00	52.96	53.57
6	1965	25.75	0.98858	26.00	25.60	0.155	15.48	19.90	52.62	53.37
7	1966	28.20	1.09491	29.51	28.03	0.169	16.95	20.80	55.22	54.96
8	1967	28.90	1.02507	32.82	28.73	0.174	17.38	21.00	55.91	55.40
9	1968	32.61	1.12822	35.94	32.41	0.196	19.60	22.40	59.14	57.57
10	1969	35.12	1.07712	38.87	34.91	0.211	21.12	23.40	60.98	58.91
11	1970	39.33	1.11972	41.64	39.09	0.236	23.64	25.20	63.46	60.93
12	1971	42.14	1.07156	44.24	41.89	0.253	25.34	26.50	64.75	62.12
13	1972	46.43	1.10184	46.70	46.16	0.279	27.92	28.50	66.22	63.68
14	1973	52.44	1.12941	49.02	52.13	0.315	31.53	31.60	67.36	65.37
15	1974	54.70	1.04308	51.21	54.37	0.329	32.89	32.90	67.56	65.85
16	1975	55.96	1.02305	53.29	55.63	0.336	33.65	33.60	67.61	66.08
17	1976	58.15	1.03898	55.26	57.80	0.349	34.96	34.90	67.63	66.42
18	1977	59.67	1.02627	57.14	59.31	0.359	35.88	35.90	67.59	66.62
19	1978	63.82	1.06948	58.94	63.44	0.383	38.37	38.60	67.25	66.95
20	1979	68.04	1.06616	60.67	67.63	0.409	40.91	41.50	66.62	66.99
21	1980	65.18	0.95790	62.34	64.79	0.392	39.18	39.50	67.08	66.99
22	1981	62.06	0.95213	63.96	61.68	0.373	37.31	37.40	67.43	66.84
23	1982	61.54	0.99170	65.54	61.17	0.370	37.00	37.10	67.47	66.80
24	1983	59.52	0.96713	67.10	59.16	0.358	35.78	35.80	67.59	66.60
25	1984	60.81	1.02169	68.64	60.45	0.365	36.56	36.60	67.53	66.74

Table 8. Carbon emissions and estimation of the BESF micro-bio-economic functions, for Austria and Brazil together (1960-2007)

Time periods	Years	Obs. emis-sions (ktC)[†]	Obs. econ. growth	Estimated emissions over time (ktC)	Expected removal consump-tion (ktC)	Obs. removal consump-tion (ktC)	Estimated removal consumption (tens of tC)	Optimal[‡] logistic rate (tens of tC)	Optimal[‡] emission removal (in MtC)	Estimated emission removal (in MtC)
t		X_t	$k=X_t/X_{t-1}$	Eq. (21)	Eq. (22)	Eq. (20)a	Eq. (23) x 10^2	Eq. (25)b	Eq. (27)	Eq. (30)
26	1985	64.24	1.05638	70.18	63.85	0.386	38.62	38.80	67.20	66.96
27	1986	68.87	1.07211	71.73	68.46	0.414	41.41	42.10	66.47	66.97
28	1987	72.22	1.04866	73.30	71.79	0.434	43.42	44.60	65.75	66.75
29	1988	71.52	0.99031	74.89	71.09	0.430	43.00	44.10	65.92	66.81
30	1989	73.00	1.02070	76.53	72.56	0.439	43.89	45.20	65.57	66.68
31	1990	73.47	1.00636	78.22	73.03	0.441	44.17	45.60	65.45	66.63
32	1991	77.65	1.05697	79.97	77.19	0.467	46.68	49.00	64.32	66.02
33	1992	76.57	0.98604	81.80	76.11	0.460	46.03	48.10	64.63	66.20
34	1993	78.67	1.02743	83.71	78.20	0.473	47.30	49.90	64.02	65.83
35	1994	81.61	1.03734	85.72	81.12	0.490	49.06	52.50	63.10	65.18
36	1995	91.53	1.12159	87.84	90.98	0.550	55.03	62.40	59.55	61.95
37	1996	98.64	1.07765	90.08	98.04	0.593	59.30	70.60	56.70	58.64
38	1997	104.15	1.05588	92.45	103.52	0.626	62.61	77.70	54.39	55.51
39	1998	102.63	0.98540	94.95	102.01	0.617	61.70	75.70	55.03	56.43
40	1999	104.49	1.01819	97.62	103.87	0.628	62.82	78.20	54.24	55.30
41	2000	106.69	1.02102	100.44	106.05	0.641	64.14	81.30	53.30	53.90
42	2001	109.86	1.02967	103.44	109.20	0.660	66.05	85.90	51.94	51.75
43	2002	108.99	0.99212	106.63	108.34	0.655	65.53	84.60	52.31	52.35
44	2003	107.52	0.98649	110.01	106.87	0.646	64.64	82.40	52.95	53.36
45	2004	111.80	1.03982	113.60	111.13	0.672	67.21	88.80	51.10	50.35
46	2005	115.09	1.02942	117.41	114.40	0.691	69.19	94.00	49.67	47.83
47	2006	115.52	1.00377	121.45	114.83	0.694	69.45	94.70	49.49	47.49
48	2007	118.99	1.03001	125.74	118.27	0.715	71.54	100.60	47.98	44.62
Mean			**1.03742**							

Source: World Bank (2011). Notes: (†) Original data in tCO2 converted in tC after division by 3.67. (‡) GAMS 22.8.

Table 8. Carbon emissions and estimation of the BESF micro-bio-economic functions, for Austria and Brazil together (1960-2007)

overshoot rates fall, the larger the need of forestland will be to remove that additional emission burden over time. In other words, the increase of the long-run overshoot rate is rather powered by the need to increase $\hat{\lambda}^*$ than by the growth of $\hat{k}^*$ itself.

At last, from Table 7 and Fig. 7, a paradoxical proposition appears to arise. How come that the higher the economic growth rate ($\hat{k}^*$), the lower the long-run overshoot rate (ψ) turns out to be? This ironically suggests that economic growth is the solution for ecological overshoot – as most standard economic theories claim. What is meant here, though, is that, if $\hat{k}^*$ should be kept high in the long run, then $\hat{\lambda}^*$, described by a steeply down-sloped curve, would have to abruptly drop. Nevertheless, the only possible way for $\hat{\lambda}^*$ to fall that low would be when the long-run overshoot rate already were considerably negative.

4. Conclusion

Due to a remarkable *where-flexibility* (high λ_t in Table 4) between Austria and Brazil, their removal economies can fall back on a large ecological credit ($0 < \hat{\varepsilon} < 1$, as in Table 7 and Fig. 6) in the long run. By Eq. (15), this means high exports (Z) of removal services by the largest stock sink (**v** = Brazil) and low transfers of emission removal over time (*M*). Throughout the years (1960-2007), however, the maintenance of this ecological credit has cost these economies lower optimal rates of economic growth. As a result, Table 7 shows that, along the optimal path, increasing conservation (REDD) would only make things worse (scenarios 2 and 4), by exchanging smaller economic growth rates for higher long-run overshoot rates and thus causing the bio-economic exchange rate to drop (appreciate) even further.

Actually, in Austria-Brazil case, REDD alone would deepen *where-flexibility*, thereby raising the costs of removal over time, in terms of supply of forestland and removing forest stocks. Therefore, to deliver higher economic growth rates and lower long-run overshoot rates, the large ecological credit must be reduced, by raising the bio-economic exchange rate through increasing forestry-CDM. Although this conclusion might sound somewhat common place, it holds a quite interesting policy proposition, namely, that greater environmental equity in the provision of ecosystem services (lower λ and *Z*) might favour, instead of discouraging, economic growth.

First and foremost, this proposition means that the economy does get along with the environment, especially when ecological credit, arising from higher λ and *Z* (greater *where-flexibility*), prevails. Of course, whenever a forest-rich economy joins a forest-poorer one, the removal trade between them can not only bring forth ecological credit for both, but also let them enjoy higher economic growth rates. That is what is meant by biophysical foundations of economic growth. However, unlike widespread arguments towards cost-effectiveness in climate policy, the BESF model seems to point out that lesser, rather than greater, *where-flexibility* gears up investments on natural assets (sinks) providing environmental services. Otherwise, the quest for ecological credit to increase *where-flexibility* might end up deepening ecological overshoot, even though favouring economic growth. Therefore, a further step towards policy analysis would be to estimate the overshoot rate function, as close as that of Fig. 7.

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22

Forecasting the Future of Renewables

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1. Introduction

The global electric power consumption has increased for decades and the growth seems to continue in the foreseen future. At the same time the known conventional fossil energy resources will be decreasing and, evidently, we will be short of them. On top of that we are facing serious problems of climate change due to CO_2 emission. These kind of giant problems ahead of us have finally raised a genuine interest on the utilization of alternative energy sources. First we will face the shortage of oil and gas, which can be substituted for some time with energy sources like coal and beat, if environment and climatic issues are ignored. However, climatic change is a major driver in energy sector at the moment, and only renewable energy sources provide a sustainable outlook.

Renewable energy sources cover only a fraction of the present energy consumption, because most of them are not competitive on the market. Only hydropower is clearly competitive. In special cases also other renewable energy sources can be competitive, for example, biomass as a source of combined heat and power. Major technology development is still needed for most of the renewable energy sources to achieve market penetration. Both on public finance and private business decision point of view it is essential to know, when these evolving electric power production technologies are competitive on the market and what is their foreseen market volume, i.e., electric energy production potential. Market penetration depends on the development of the evolving energy production technology in question and on the forthcoming cost of electric energy production using conventional primary energy sources.

To forecast the market diffusion of new evolving electric energy production technologies, the dependence of the market diffusion on technology and energy market variables need to be analysed. Market diffusion can be analysed with various qualitative or quantitative methods, which all involve a considerable amount of uncertainty. If a reasonable amount of historical data of the evolution of the technology is available, quantitative methods can be applied to forecast the market penetration. Due to numerous uncertainties related to the input parameters it has turned out that a simple and straightforward method is usually as good as a more sophisticated method. At the end on long term market mechanics will rule out the development and the analyses can be based on the production cost of electrical energy. Production cost depends basically on environmental variables, such as the availability of the energy source used, and on variables related to the production technology in question, like the investment cost.

Production costs of electrical energy for most renewable energy sources are mainly due to investment costs and to some extend on production and maintenance costs, but the energy source is free of costs. In these cases production costs can be estimated based on technology learning, i.e., concepts like learning factor and progress ratio. In addition to investment, production and maintenance costs power production costs for conventional non-renewable energy sources are based on fuel prices. Conventional technologies are already quite mature with slow learning rate. Therefore, changes in power production costs are mainly due to changes in fuel prices.

In this chapter it will be demonstrated how technology development and market penetration of evolving energy production technologies can be forecasted by quantitative methods. In particular, we look on electric power production, because its role in the energy sector increases both absolutely and relatively. We have analyzed the relevant variables for power production costs, their dependencies on each other and their future development on long term. These issues have been combined with feasible technology evolution and market diffusion models (Armstrong, 2001; Junginger, 2005; Martino, 1993; Meredith & Mantel, 1995; Rogers, 2003). We will show that a plausible model can be developed to forecast, when an evolving new power production technology becomes competitive on the market. We also analyse the market penetration of photovoltaic power production with this model. This simple model can be applied quite easily also to other evolving power production technologies to obtain useful forecasts.

2. Production cost of electrical energy

World net electricity generation has globally increased until 2010 with an average annual rate of 3.0 % outpacing the growth of total energy consumption by 1.3 %. World net electricity generation will increase by an average of 2.3 % per year until 2035 according to the IEO2010 Reference Case continuing to outpace the growth in total energy usage throughout the projection period. This will end up to an increase by 87 % to 35 000 TWh until 2035. High fossil fuel prices recorded between 2003 and 2008, combined with concerns about the environmental consequences of greenhouse gas emissions, have renewed interest in the development of alternative energy sources with respect to fossil fuels—specifically, nuclear power and renewable energy sources. In the IEO2010 Reference Case, long-term prospects continue to improve for generation from both nuclear and renewable energy sources. Coal is foreseen to cover most of the growth of electricity generation with 7000 TWh and renewable energy sources are the second sources covering 4500 TWh of the growth. Renewable energy sources have the largest growth rate in electricity generation in the IEO2010 Reference Case with an average annual growth of 3.0 %. This will end up to an increase by almost 130 % until 2035. Accordingly, the renewable share of world electricity generation would grow from 18 % in 2007 to 23 % in 2035. Majority of this growth will be due to the increase in wind and solar power production. (EIA, 2010b)

The era of change from the utilisation of fossil energy to renewable energy seems to be inevitable when we run out of fossil fuel resources. The transition will be ruled out by “market forces” on demand and supply basis. It is quite realistic to anticipate that the prices of conventional energy resources will increase while their stock decreases. This means that alternative energy production technologies will become more competitive. At the same time the cost of new evolving energy technologies can be estimated to decrease following typical technology development trends. In the following basic outlines are given how to forecast this technology transition. First the basic outlines to evaluate production costs of electricity generation from conventional energy sources are presented and then for evolving electricity production technologies from renewable energy sources.

2.1 Conventional power production technologies

Oil, natural gas, coal and beat covered 81.2 % of the global primary energy consumption in 2008 and 87.0 % of the total primary energy usage was covered by non-renewable fuels. 5.5 % of the total electrical energy was produced by oil, 21.3 % by natural gas, 40.0 % by coal and beat and 13.5% by nuclear energy. Hydropower covered 15.9 % leaving only a share of 2.8 % for other renewable energy sources. (IEA, 2010a) The average global growth rate of electric power usage has been estimated to be larger than the growth rate of total energy usage in the future and new renewable energy sources will have the highest relative growth. However, the biggest total grow in power production will be in the use of coal. (EIA, 2010b)

Conventional power production technologies have been utilized for several decades and they are quite mature. The main technologies have also very high volumes in power production, which means that their relative capacity does not increase rabidly. Therefore, the technological development can be expected to be quite modest in the future and no major changes in investment, production and maintenance costs are expected. For simplicity, these variables can be supposed to stay constant as a function of time for conventional power production technologies.

Production cost of electrical energy C with conventional technologies can be calculate by

$$C = \frac{aC_I + C_P}{t_c} + \frac{C_F}{\eta}, \tag{1}$$

where a is the annuity factor of the investment, C_I the investment cost, t_c the annual capacity factor, C_P the annual production and maintenance cost, C_F the fuel price and η the energy efficiency of the power station. Emission cost of CO_2 could be included in the fuel price, but has not been included in this analysis, because emission cost is more a political than a technological parameter.

Globally the main energy sources in power production are coal, natural gas, hydropower, nuclear energy and oil. Hydropower and nuclear power are the low cost basic sources of electrical energy. In most parts of the world the marginal price of electrical energy follows the cost of natural gas or coal thermal electric power production, and changes in the production costs are primarily due to changes in fuel prices. Oil has a quite global price and, therefore, it would be an ideal reference price for analysing global energy cost issues. However, oil is not a basic source of electrical energy in all parts of the world due to its limited resources and high price. Therefore, it is not suitable for defining global marginal price of electrical energy.

Natural gas has quite global price, which follows the oil price closely. Coal price is more local, but it also follows the oil price to some extent. As an example of this, the oil, natural gas and coal prices in the European Union are presented in Figure 1 from 1985 to 2005. Market prices of natural gas and coal follow the oil price closely having correlation coefficients of 0.88 and 0.76, respectively. Furthermore, there seems to be a direct pricing mechanism between oil and gas, because the gas price and the oil price shifted one year ahead have a correlation of 0.94. Due to these strong correlations oil, natural gas and coal prices can be expected to have roughly the same increase rate in the future.

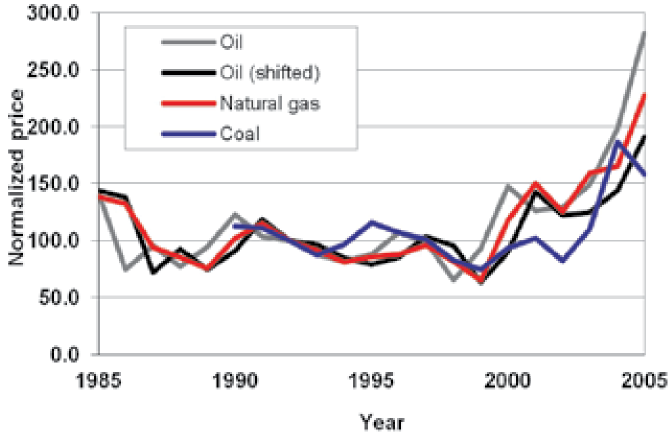

Fig. 1. Oil, natural gas and coal prices in EU in the period from 1985 to 2005 normalized to 100 in 1992. The black line is the oil price of the previous year. (British Petroleum, 2006; Valkealahti & Nevaranta, 2007)

Coal has the largest resources of conventional energy in the world and its resources are distributed quite evenly around the world. It also has the lowest market price. For example, in 2008 in electric power sector the price of natural gas was over 4 times higher than the price of coal in term of energy content and oil was over 7 times more expensive (EIA, 2010a). Therefore, it is plausible to assume that in most parts of the world the marginal price of electrical energy is determined by the coal price. This situation can be anticipated to stay also in the future, because the fossil fuel prices are strongly connected to each other and no major relative changes are expected. For these reasons, coal thermal electric power production has been selected to be the reference fossil source of electrical energy in analysing market diffusion of evolving power production technologies based on renewable energy sources.

All variable values used in this work correspond to the state of the art modern technology. For all variables we have defined a reference value, which is in many cases a mean value of a representative sample of technologies or a value from a most probable scenario given for the future. In 2008 the average investment costs of modern thermal coal power stations around the world have been analysed to be close to 1400 €/kW (IEA, 2010b). Based on Valkealahti and Nevaranta (Valkealahti & Nevaranta, 2007) investment costs for about 80 % of the coal power stations can be estimated to be between 1250 and 1550 €/kW. These values have been used as the minimum and maximum values to describe the variation of the investment costs in the analyses later on (Table 1).

Annual production and maintenance costs for coal thermal electric power production are typically around 4 % of the investment costs (IEA, 2010b). Annual production time of a thermal power plant varies considerably depending on a large number of variables. Typically electric loads in the network have seasonal and also shorter term variations causing breaks in production, regular maintenance is needed etc. If a power plant would operate the whole year with nominal power without breaks, the capacity factor t_c would reach its maximum value of 8760 hours. However, a typical utilization rate of a thermal power plant corresponds to a capacity factor of the order of 6000 hours. A maximum capacity factor of 8000 hours is achievable with normal service breaks. In areas with high seasonal variations effective time for annual power production can be around 4000 hours, which can be used as a practical lower limit. Economic lifetime of a coal thermal electric power plant is typically around 30 years and efficiency of a modern power plant is around 40 %. The annuity factor has been calculated with a fixed annual interest of 5 %. These values have been used in this analysis as reference values and they are presented also in Table 1. Also the minimum and maximum limits for the technology related parameters have been introduced to study the sensitivity of technology diffusion on different parameters. Only annual interest rate has been fixed, because it is not directly related to technology development. (IEA, 2005; IEA, 10b)

Variable	Minimum	Reference	Maximum
Investment cost (€/kW)	1250	1400	1550
Annual production and maintenance cost (€/kW)	50	60	70
Economic lifetime (y)	25	30	35
Capacity factor (h)	4000	6000	8000
Efficiency	0.35	0.40	0.45
Interest rate (%)		5	
Coal price (€/MWh)		8	
Annual coal cost growth rate by IEA (%)	-0.8	1.9	3.3
Annual coal cost growth rate by EPIA (%)	0.4	2.0	3.6

Table 1. Input variables to calculate production costs of coal thermal electrical energy. The reference values are considered to be the most probable values. Also estimated 10 % and 90 % uncertainty ranges are given. (IEA, 2005; IEA, 10b; EPIA, 2010)

The known fossil energy resources of coal, oil, natural gas and U^{235} have been estimated to last about 220, 40, 60 and 70 years, respectively, with the present consumption and roughly the same amount of resources are estimated to be found more (British Petroleum, 2006; British Petroleum, 2004; EIA, 2002). Based on this information it has been estimated that somewhere between 2020 and 2050, the primary energy consumption of non-renewable energy sources will start to decrease. This transition will be preceded by a considerable increase of primary energy prices. Therefore, the long term primary energy price development of fossil fuels has to be taken into account in technology diffusion analyzes.

Coal prices have typically changed marginally mostly due to the large resources compared to other fossil fuels and to the current usage of coal. During the last decade coal price has increased considerably following the rapid growth of oil price, but during the last years it has returned close to the long term price level. To have a realistic starting point for analysing the future coal thermal electric power production costs, an average of the last 10 year has been used as a current coal price. By this way the most dramatic effects of short term price fluctuations were reduced.

In Table 1 there has been presented also scenarios for the future coal price by International Energy Agency and European Photovoltaic Industry Association until 2035 and 2030, respectively (IEA, 2010a; EPIA, 2010). Both scenarios actually predict fluctuating growth rates for the projection period from which we have calculated average growth rates to be used in our analysis. In both scenarios low and high coal costs estimates are given in addition to the most probable reference estimates for price development. The reference cost growth rates in the two scenarios are almost the same and also the high cost growth rates are close to each. Only the low cost estimates differ considerably from each other, IEA providing even a negative annual growth rate estimate of -0.8 %. This does not seem to be feasible and, therefore, the coal cost growth rates predicted by EPIA have been used as our reference in the analysis.

2.2 Evolving renewable power production technologies

The cost of electrical energy produced by evolving renewable power production technologies can be calculated with equation (1) basically in the same way as for conventional technologies. The main difference is that the investment, production and maintenance costs of evolving technologies are still decreasing strongly due to technical, manufacturing, process etc. development. This kind of technology cost development can be described by a learning curve (Junginger, 2005), where a variable, like the investment cost C_I, is a function of the cumulative manufacturing volume q of the technology

$$C_I(t) = C_I(t_0)\left[\frac{q(t)}{q(t_0)}\right]^{-b}, \tag{2}$$

where t is the time of interest, t_0 the reference point of time and b the learning factor. Learning factor b is typically defined by the relative price change called progress ratio PR, when cumulative production has doubled

$$PR = 2^{-b}. \tag{3}$$

Technology development is commonly known to follow learning curves, where product cost or some other market related quantity decreases exponentially as a function of cumulative production. Also the development of solar photovoltaic electricity generation technology, which we use as an example of evolving renewable electric power production technologies to demonstrate the method of forecasting market penetration of new evolving renewable electric energy production technologies, follows the exponential learning curve development. Several studies have been done on the development of solar photovoltaic power technology providing progress rations for investment costs in the range from 0.75 to 0.82. For example, a progress ratio 0.75 has been obtained for the period from 1976 to 2002 (Poponi, 2003) and 0.77 for the period from 1981 to 2000 (Parente et al., 2002). A resent analysis for the period from 1980 until 2015 provides a progress ratio 0.80 (Beneking, 2007). Progress ratio tends to increase with increasing cumulative production volume meaning that the learning rate $LR = 1 - PR$ decreases. Simple explanation for this is that it is easier to improve a new technology than a mature technology. This seems to be the case also with solar photovoltaic technology to some extent.

We have used the progress ratio 0.80 for solar photovoltaic power technology in the analysis corresponding to a 20 % decrease of the investment cost, when the cumulative manufacturing volume doubles. This is in line with historic development and resent estimates (Beneking, 2007). Investment cost is a major cost factor in generating electricity with solar photovoltaic power plants. Energy source for solar photovoltaic power is totally free, it is free of annual production costs and also maintenance costs are minimal. Therefore, solar photovoltaic electricity costs are predominantly based on the investment cost C_I and its future development can be estimated by using equations (2) and (3). In practice, electricity production cost by solar photovoltaic depends also on the capacity factor in addition to the investment cost. Capacity factor is a local quantity depending on the latitude, climatic conditions etc. For example, Central and North Europe have roughly the same capacity factors, but in South Europe, like in Spain, the capacity factor is much larger. In realistic areas on the Earth for solar photovoltaic electricity generation costs are between 220 and 440 €/MWh (EREC, 2008) due to different capacity factors. We have used these productions costs as low and high estimates for current costs and the median value of 330 €/MWh as the most probable value at our reference point of time (Table 2). Other cost variables for solar photovoltaic power production are considered to be time independent.

To be able to calculate the future investment or production cost of an evolving electricity generation technology based on technology learning rate we need to know the development of the manufacturing volume. International Energy Agency (IEA) and European Renewable Energy Council (EREC) have both estimated the future increase of installed capacity for different power production technologies, which use renewable energy resources (IEA, 2004; EREC, 2003). Most resent estimates for the cumulative growth of installed production capacity of solar photovoltaic power have been done by European Photovoltaic Industry Association (EPIA), EREC and IEA (EPIA, 2008; EREC, 2008; IEA, 2010). All these estimates have decreasing trends for the cumulative capacity growth rate starting from the current level of about 33 % per year decreasing down to around 5 % after 2040 as shown in Figure 2. Almost identical cumulative capacity, investment cost and production cost estimates for solar photovoltaic electricity generation were achieved by using these growth rate estimates, because they differ so little from each other. Therefore, we have used the estimated growth rate by EREC in our detailed analysis later on, which extends to 2050.

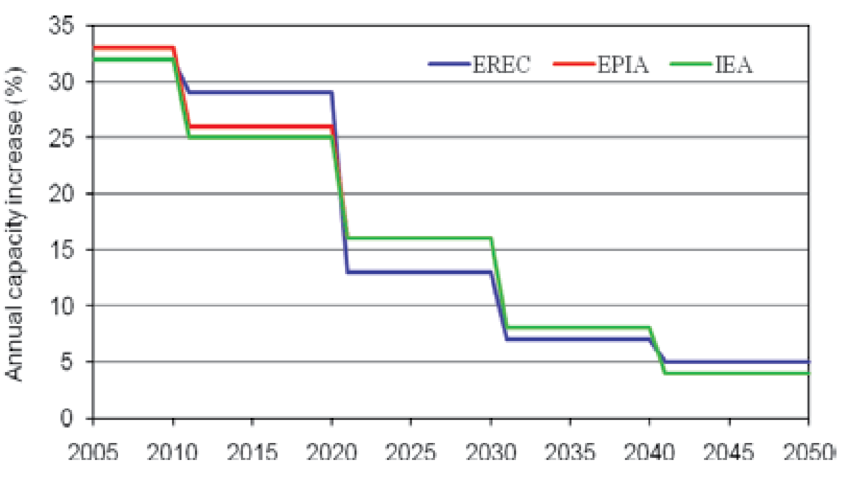

Fig. 2. Annual increase of the cumulative installed production capacity of solar photovoltaic electricity generation estimated by EPIA, EREC and IEA for the period from 2005 to 2050. The estimate by EPIA extends only to 2030. (EPIA, 2008; EREC, 2008; IEA, 2010)

To introduce range of variation for the estimated annual increase of the cumulative installed production capacity, it has been multiplied by a capacity growth factor (Table 2). A growth factor of 1.0 gives the original EREC estimate and factors 0.50 and 1.50 give low and high extremes for the growth. By this way it was possible to analyse the sensitivity of our forecasting model and the technology development on uncertainties in input variables. The same was done also with progress ration by introducing low and high limits of 0.75 and 0.85, respectively.

Variable	Minimum	Reference	Maximum
Electricity production cost (€/kWh)	220	330	440
Capacity growth factor	0.5	1.0	1.5
Progress ratio	0.75	0.80	0.85

Table 2. Input variables to calculate production cost for solar photovoltaic electrical energy. The reference values are considered to be the most probable values. Also estimated 10 % and 90 % uncertainty ranges are given. (EREC, 2008; Poponi, 2003; Parente et al., 2002; Beneking, 2007)

3. Market penetration of solar photovoltaic electricity generation

Market penetration of solar photovoltaic electricity generation has been analysed with respect to thermal coal based power generation to demonstrate how diffusion of evolving renewable electricity generation technologies and their market penetration can be plausibly estimate by using a simple and straightforward method. Development and market penetration of evolving renewable power production technologies involve so many uncertainties and variables that it is, in practice, waste of time for doing very sophisticated analyses. It is actually more fruitful to figure out causes and effects of the most important factors for the development by a simple method.

There are several rational ways to define market penetration and none of those is the best without objection. Our choice for the reference is the production cost of coal thermal power, which in most parts of the world defines the marginal cost of electrical energy production. Coal is the cheapest source of fossil energy due to its largest recourses. Also coal price can be expected to incline least of all the fossil energy sources. Furthermore, solar photovoltaic electricity is available only when Sun is shining. For economical reasons it should be produced and used always when the energy source is available. Therefore, it can be considered as a basic source of energy in the same way as coal thermal electricity.

For each input variable of solar photovoltaic or coal thermal electricity generation a medium or most probable value has been used as a reference. These reference values have been used to calculate the reference forecast of market penetration, i.e., the point of time when solar photovoltaic achieves grid parity with coal thermal electricity generation. In Figure 3 the reference forecasts for the costs of solar photovoltaic and coal thermal electricity have been presented for the period from 2010 to 2050. The point of grid parity in the reference case takes place in 2036 and has been marked by “Ref” in Figure 3.

In addition to the reference values feasible minimum and maximum values have been introduced for each variable to be able to evaluate the sensitivity of the market penetration on different factors. When statistical data on a certain variable was available 10 % and 90 % uncertainty values have been used as minimum and maximum values. For many variables value range or extreme forecasts from reliable reference sources have been used as minimum and maximum values. Sensitivity of the market penetration on different input variables has been tested by changing the value of one variable at a time while other variables have their reference values.

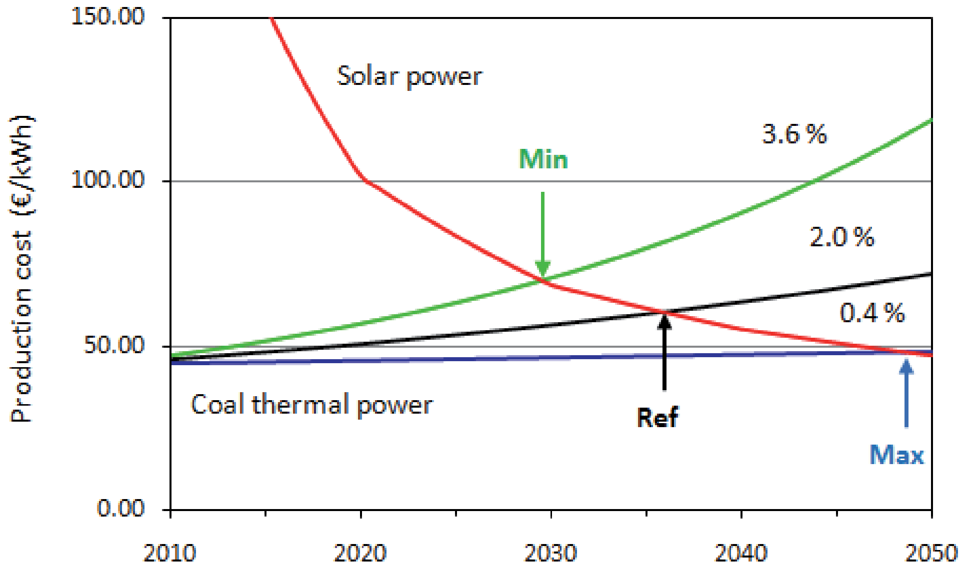

Fig. 3. Estimated electrical energy production costs for the period from 2010 to 2050 by solar photovoltaic and coal thermal power stations. Electricity production costs using coal are shown with estimated minimum, reference and maximum annual coal price growth rates of 0.4, 2.0 and 3.6 %, respectively. (EPIA, 2010)

One of the main uncertainties to forecast market penetration of solar photovoltaic technology is related to the uncertainty of the forthcoming cost of coal. To foresee the price of coal in the future is very difficult. Therefore, the use of a conservative forecast is justified, like the one provided by Europian Photovoltaic Industry Association with an annual coal price growth rate of 2.0 % as a reference scenario and 0.4 and 3.6 % as low and high growth rate scenarios, respective (EPIA, 2010). Calculated electricity generation costs with growth rates of 0.4 and 3.6 % are shown in Figure 3. Grid parities are achieved in 2048 and 2030, accordingly. Market penetration of solar photovoltaic takes place only 6 year earlier, if the coal price growth rate increases from 2.0 to 3.6 %, but will be delayed by 12 years, if the growth rate is decreased to 0.4 %. This demonstrates that coal price, and more commonly fossil fuel prices, has a major effect on the market penetration of solar photovoltaic technology.

Capacity factor of coal thermal electricity generation has also a major effect on solar photovoltaic electricity market penetration. The coal thermal electricity generation costs until 2050 for capacity factors 4000, 6000 and 8000 hours are shown in Figure 4. The cost curve shifts to higher costs with decreasing capacity factor as expected. With the capacity factor of 4000 h the grid parity will be achieved already in 2030, but with a capacity factor of 8000 h only in 2039. This demonstrates that market penetration of solar PV is strongly a local issue. If coal thermal power is used to generate electricity for basic loads with a capacity factor of 8000 h, market penetration will take place 9 years later than in the case of seasonal usage of coal thermal power with a capacity factor of 4000 h.

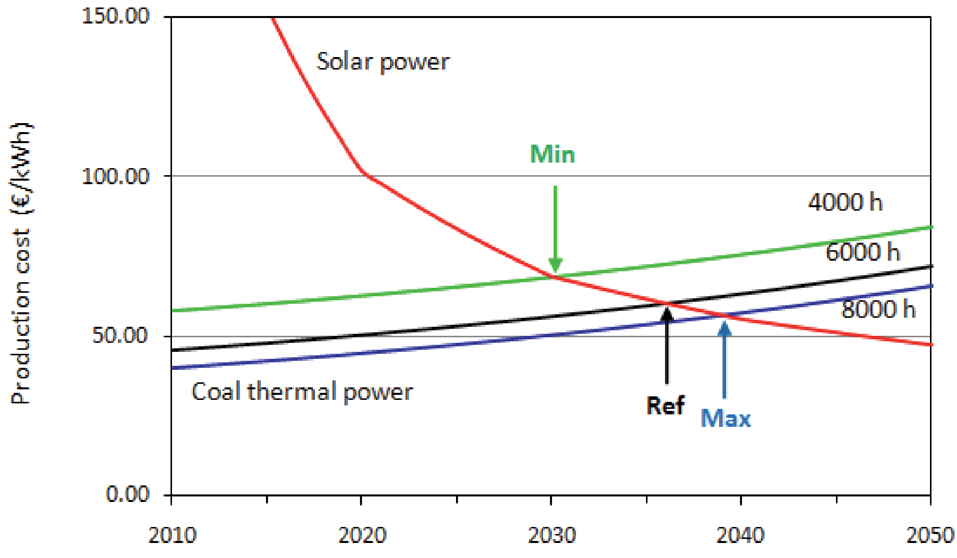

Fig. 4. Estimated electrical energy production costs for the period from 2010 to 2050 by solar photovoltaic and coal thermal power stations. Electricity production costs using coal are shown with estimated minimum, reference and maximum annual coal thermal power capacity factors of 4000, 6000 and 8000 hours, respectively.

As already discussed in section 2.2, solar photovoltaic power production costs are between 220 and 440 €/MWh in realistic areas on the Earth for photovoltaic power production (EREC, 2008). Electricity production costs by solar photovoltaic power plants for the period from 2010 to 2050 are shown for current production costs of 220, 330 and 440 €/MWh in Figure 5. Solar photovoltaic electricity cost curve shifts upwards with increasing initial production cost so that the grid parity moves from 2026 for the lowest cost of 220 €/MWh up to 2045 for the highest cost of 440 €/MWh. Solar photovoltaic electricity production costs have been reported to be 440 €/MWh in Berlin, 390 €/MWh in Paris, 330 €/MWh in Washington, 300 €/MWh in Hong Kong, 280 €/MWh in Sydney and Madrid, 250 €/MWh in Bangkok and 220 €/MWh in Los Angeles and Dubai in 2007 (EPIA, 2008). This means that in places like Los Angeles and Dubai solar photovoltaic technology would penetrate fully to the market already in 2026, but in Central and North Europe the market penetration would take place only in 2045.

The uncertainties on market penetration of solar photovoltaic electricity due to uncertainties in input variables of the model have been presented in Figure 6. The reference market penetration in the year 2036 has been calculated using the reference values of variables for solar photovoltaic power and coal thermal power (Tables 1 and 2). Minimum and maximum variable values have been used to evaluate the sensitivity of the market penetration on the uncertainty of each input variable. Minimum and maximum market penetration times have been calculated by changing the value of one input variable at a time while the other input variables have their reference values.

The biggest uncertainty seems to come from the production capacity growth (capacity growth factor) of solar PV power. If the cumulative solar photovoltaic electricity production capacity growth rate is only half from the forecasted growth rate (Figure 2), the market

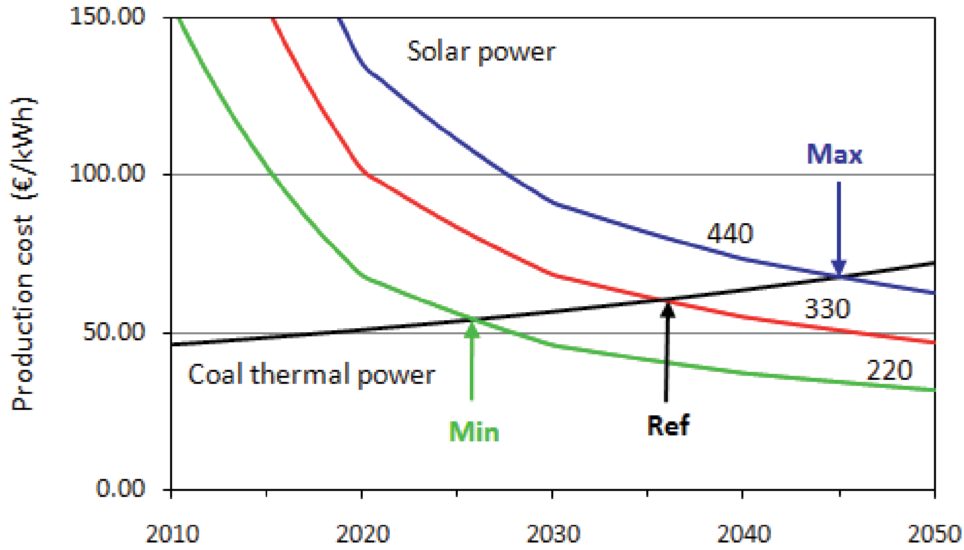

Fig. 5. Estimated electrical energy production costs for the period from 2010 to 2050 by solar photovoltaic and coal thermal power stations. Electricity production costs by solar photovoltaic are shown with estimated current minimum, reference and maximum production costs of 220, 330 and 440 €/MWh, respectively. (EREC, 2008)

penetration will be out of the scope of the study (later than in 2060). On the other hand, if there would be a 50 % increase in the growth rate, the market penetration would take place already in 2023. This shown clearly that technological development depends strongly on the manufacturing volume, when learning rate is high. Electricity production capacity by solar photovoltaic power has been growing during the last decade with the growth rates presented in Figure 2 and there are no reasons to anticipate that the growth rate would be lower than the forecasted ones (EPIA, 2008; EREC, 2008; IEA, 2010). The growth rate forecasts can be actually considered to be slightly pessimistic and even somewhat higher growth rates can be expected. The strong dependence between technology development and production volume of evolving renewable electricity production technologies with high learning rates is also a clear signal for political decision makers. Market penetration of evolving renewable electricity production technologies can be can facilitates by supporting the market growth.

Uncertainties due to other solar photovoltaic electricity generation related variables are also considerable. The second largest uncertainty is related to the learning rate causing a market penetration range from 2026 to 2055. It is not plausible to anticipate that learning rate would increase meaning that the historical long term progress ratio trend would decrease, for example from 0.80 to 0.75. Progress ratio of a technology does not usually decrease but increases as a function of time, because technology becomes gradually more mature. On the other hand, technological development has turned out to follow learning rates quite consistently. The used reference progress ration of 0.80 for solar photovoltaic was a slightly conservative choice from the set of published progress ratios and, therefore, there are no reasons to anticipate a larger ratio for the near future. Perhaps the main message in here is that one should select the progress ratio carefully to get plausible results.

The third input parameter related to the development of solar photovoltaic was production cost of electricity. On the contrary to earlier variables, the wide range in production costs

actually exists on the market and does not originate from uncertainties of predictions. Phenomena related to this variable have been already discussed in connection of Figure 5.
It is not a surprise that uncertainty or range of variation of most variables affecting the coal thermal electricity generation have minimal effects on market penetration of solar photovoltaic electricity. Plausible changes in investment costs or production and maintenance costs can change the time of market penetration only by a year or two (Figure 6). Also the power plant efficiency can change the time of market penetration by five years in maximum. A more important input variable on forecasting point of view is the capacity factor of coal thermal electricity generation introducing a range of 9 years for market penetration. Future development of the coal prize has the biggest effect and uncertainty of 18 years to the forecasted market penetration. The effects and phenomena related to these input variables have been already discussed in more detail in connection of Figures 3 and 4.

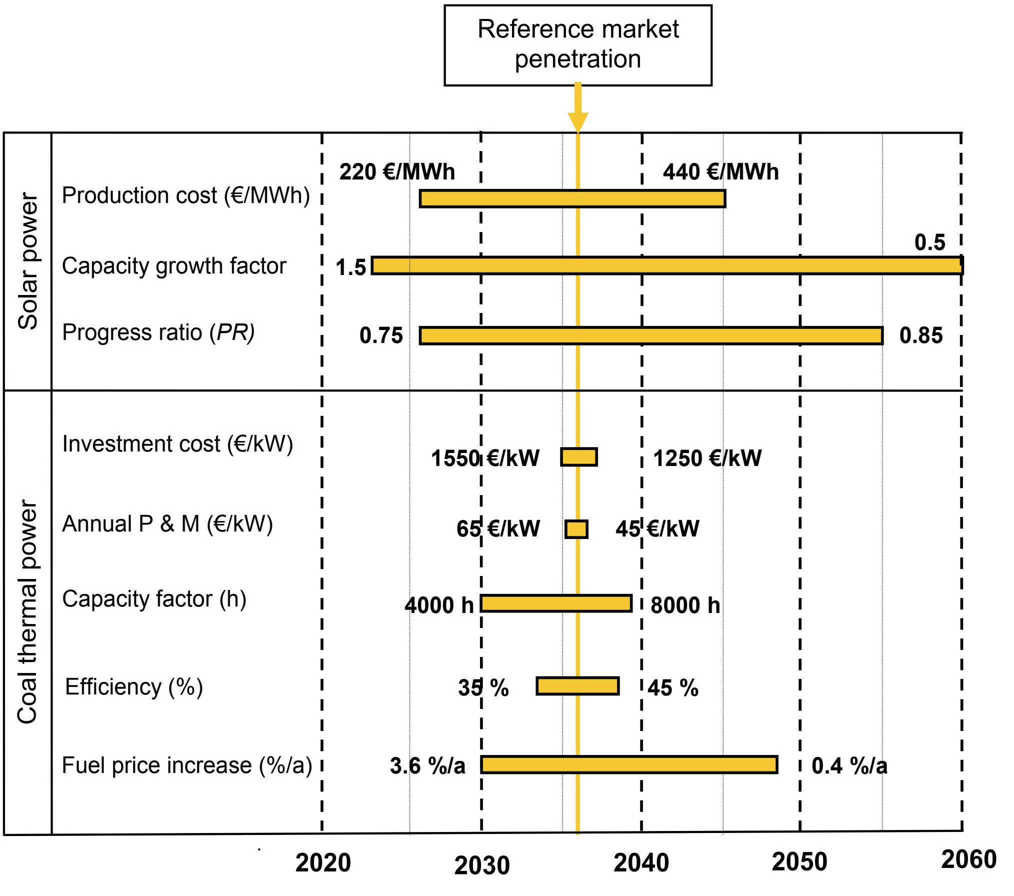

Fig. 6. Time when electrical energy produced by solar photovoltaic power plant has the same production cost than by thermal coal power stations. The reference market penetration time is shown by a solid line. The bars show the uncertainty of the market penetration with respect to the range of variation of each variable (maximum and minimum values in Table 1) when other variables have their reference values.

There are also other ways to evaluate the sensitivity of market penetration on uncertainties and range of variation of input variables than to compare their effects one by one to the reference case. For example their combined effect could provide interesting information. However, the uncertainties due combined effect of several variables can be deduced quite reliably from the effects of single variables. Furthermore, the combined effects of several variables are not usually much bigger than the largest effects due to single variables, because the variable with the largest effect dominates the combined effect. To demonstrate this, the market penetration of solar photovoltaic electricity generation was calculated using the minimum and maximum input variable values of coal thermal electricity generation, which led to an earlier market penetration than in the reference case. The outcome was that market penetration would take place in 2025, just five years earlier than in the case of having only the capacity factor changed to its minimum value of 4000 h. One must also point out that it is highly unlikely that all variables would have the extreme values at the same time.

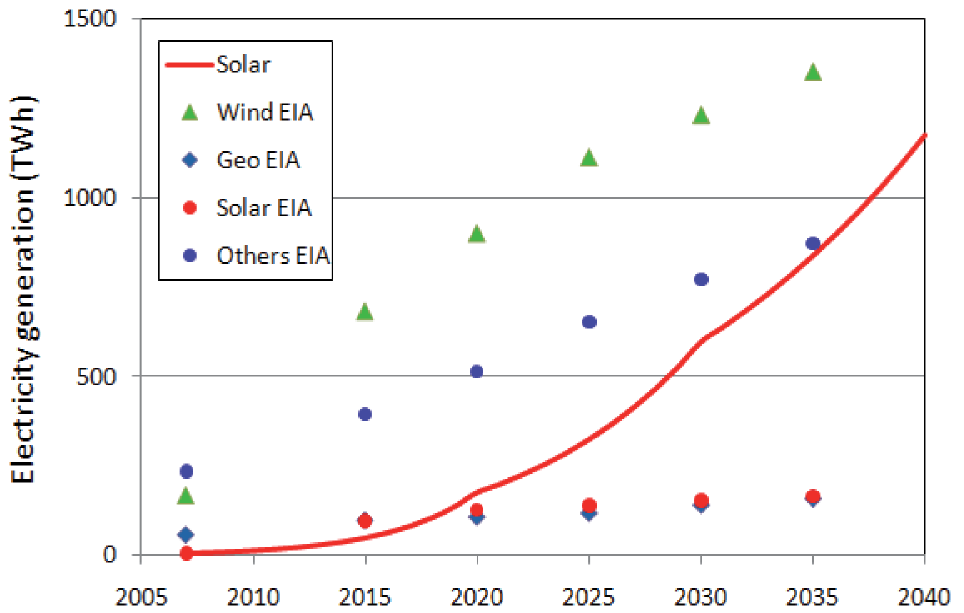

Fig. 7. Annual electricity generation with evolving renewable power production technologies for the period from 2007 to 2035 according to the IEO2010 Reference Case (EIA, 2010b). Values for 2007 are realised historical generation volumes. Others include biomass, waste, tidal, wave and ocean energy. The solid line corresponds to the estimated cumulative solar photovoltaic electricity production according to EREC (Figure 2) using the EIA solar generation in 2007 as a reference value.

Cumulative electricity generation estimates according to the IEO2010 Reference Case (EIA, 2010b) for evolving renewable energy sources for the period from 2005 to 2040 are shown in Figure 7. Also the cumulative solar photovoltaic electricity production corresponding to the estimated capacity growth rate by EREC (Figure 2) is provided using the EIA solar electricity generation in 2007 (EIA, 2010b) as a reference value. The overall renewable energy production growth forecasted by EIA seems to be in balance except for solar power, which is in contradiction with other estimates (Figure 2). There are no reasons to believe that solar photovoltaic as a source of electrical energy would stay constant for decades, while it has had the highest capacity growth rate of all forms of producing electrical energy for years. On the other hand the solid line for solar photovoltaic electricity production is consistent with existing information. Around 2020 it will be the second largest renewable source of electrical energy after wind power when hydropower is excluded. Production capacity of wind power will grow fastest during the next few decades, but somewhere around 2050 solar photovoltaic will outpace it being then the largest source of renewable energy in producing electric power.

4. Conclusion

The aim of this study was to demonstrate how the market diffusion of new evolving electrical energy production technologies can be forecasted. The dependence of the market diffusion on technology and energy market variables has been analysed. A simple forecasting method has been presented together with uncertainty analyses on the studied variables. The results confirm that it is possible to quantitatively forecast the market penetration of evolving energy technologies. These kinds of analyses can support decision making both on National level and in companies developing energy technology.

The market penetration of solar photovoltaic electricity generation has been studied in detail, because it will be in a major role in generating electrical energy on long term in the future. Coal thermal electricity generation was used as a reference technology for market penetration. The analyses showed that in the reference case solar photovoltaic electricity generation should be competitive without subventions somewhere around 2036. In areas with favourable solar radiation conditions, such as in Los Angeles and Dubai, solar photovoltaic power will achieve grip parity with thermal coal power already in 2026. In less favourable areas, like in Central and North Europe, grid parity will be achieved just around 2045. Also periodicity of the electricity demand affects the market penetration of photovoltaic electricity. If the capacity factor of coal thermal electricity production is only 4000 h instead of 6000 h used as a reference value, market penetration will happen in 2030 5 years earlier than in the reference case. If the capacity factor is 8000 h, market penetration will be delayed until 2039. As a summary, the market penetration is strongly a local matter.

Market penetration of solar photovoltaic electricity depends also on the forthcoming production capacity growth and the learning rate of the technology. If the learning rate of the solar photovoltaic technology would improve by 5 % from the current trend so that the progress ration would decrease from 0.80 to 0.75, market penetration would happen 10 years earlier that in the reference case. However, this kind on increased technology learning does not usually take place. The annual increase of the solar photovoltaic electricity production capacity is huge, around 33 %/a. In principle, the growth rate could still increase by half leading to a market penetration already in 2023. Market penetration depends also on the development in other areas of energy technology. One important parameter turned out to be the coal price. If, for example, the high coal price scenario by EPIA (EPIA, 2010) comes true, market penetration of solar photovoltaic will take place 6 years earlier than in the reference case. As a summary there are many technology related uncertainties having major effects to the market penetration of solar photovoltaic electricity generation.

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23

Hitting the Headlines and Falling Down Again: Newspaper Coverage of Climate Change in Finland

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1. Introduction

Many of the current environmental problems are cross-national. Perhaps the best example is anthropogenic climate change that is altering climatic conditions and ecosystem services and thus affecting economic, political and social structures of human communities throughout the world (Intergovernmental Panel on Climate Change [IPCC], 2008; Millennium Ecosystem Assessment [MEA], 2005).

The transnational character of many environmental problems is further emphasised by their connections with various other globalization processes. These include, e.g. global trade with long production and consumption chains and the creation of global product brands, advertising, and marketing (Lebel & Lorek, 2008). Global consolidation of media ownership, development of new information and communication technologies detached from place, and the increasing use of English are key trends of the globalization of the media (Hopper, 2007).

Climate change has been recognised as a key concern by an overwhelming majority of scientists (Oreskes, 2004) and by a growing amount of policy-makers, businessmen and citizens. However, the public and policy concern over climate change is unevenly distributed between and within countries. One explanation for the country-by-country differences is the variation of quantity and quality of mass media coverage. Media visibility and the framings can vary considerably. This was shown by the media treatment of the international climate negotiations of the United Nations Framework Convention on Climate Change (UNFCCC) in Bali 2008 (Eide et al., 2009) or Copenhagen 2009 (Painter, 2010) that varied across countries despite the commonly shared objects of news reporting. The high visibility of climate sceptics or climate contrarians in the US mainstream media compared to European countries such as Finland is another example (Boykoff & Boykoff, 2007; Uusi-Rauva & Tienari, 2010).

National level media institutions combine international influences with local practices determined by social, political, economic and ecological contexts (Olausson, 2009; Adelekan, 2009). For example, the comparison between the commercially oriented US media system and public service oriented system, such as in Finland, shows that public service television devotes more attention to public affairs and international news, and fosters greater knowledge in these areas (Curran et al., 2009).

Different languages are one factor creating local level variation and diversity to the social construction of global environmental issues. Most of the studies of the climate change media coverage – and environmental coverage more generally – focus on the English language material, especially to the US news coverage (Boyce & Lewis, 2009; Boykoff, 2009). Analyses of climate coverage in vernacular languages other than English are relatively scarce. Furthermore, many of these analyses are published in "grey literature" written in national languages and therefore their availability to international audience is limited (Lyytimäki & Palosaari, 2004; Lyytimäki & Tapio, 2009).

More cross-national analyses of climate change media coverage has been called for in order to discover similarities and dissimilarities in the information and interpretations that people in various countries receive (Dirikx & Gelders, 2009). The aim of this paper is to generate one missing piece to this puzzle by outlining the development of long-term media coverage of climate change in Finland and by identifying critical discourse moments related to the Finnish climate debate.

Here critical discourse moments are understood as key turning points of the quantity or qualities of the media coverage (Gamson, 1992; Carvalho & Burgess, 2005). First, the early development of the Finnish climate debate is reviewed in order to give background and to contextualise the Finnish case. Second, climate coverage is reviewed trough a content analysis of the leading national level newspaper from the period of 1990–2010. The analysis is partly based on material collected for previous studies (Lyytimäki & Tapio, 2009; Lyytimäki, 2011).

Finnish is spoken as a first language by five million people, almost all of them in Finland. Because of the small population, the direct impacts of activities in Finland to the global environmental problems such as the climate change are relatively limited. However, Finland serves as a potentially interesting case since the per capita environmental impacts of the Finns are considerable (Seppälä et al., 2009). On the other hand, Finland is considered as one of the forerunners of environmental protection and sustainability issues (Udo & Jansson, 2009). The Finnish case may provide relevant insights on the local level debate over global environmental problems such as the climate change, but caution is needed when comparisons are made with other countries.

2. Research material

This paper is based on a literature review synthesizing earlier studies on the climate debate in Finland – most of them published in Finnish – and a content analysis of newspaper coverage. The literature review included both international and national literature. In addition, the archives of selected Finnish university departments were screened since many of the earlier studies of the topic were conducted as master's thesis or doctoral dissertations. A bibliography of environmental communication research served as an additional source (Lyytimäki & Palosaari, 2004).

The media content analysis is based on data from the broadsheet Helsingin Sanomat (HS). HS is the leading national-level newspaper in Finland and it has a major influence on public and policy agenda (Suhonen, 1994; Herkman, 2010). It can be characterised as a "prestige" newspaper. Despite the growing use and influence of electronic media, newspapers remain an important source of environmental information in Finland (Ekholm et al., 2007; Kiljunen, 2010). The circulation of HS has slightly declined during the recent years but it still stands at about 400 000 copies daily and about one million readers, i.e. almost a fifth of the entire population (Finnish Audit Bureau of Circulations [FABC], 2010). Furthermore, the internet site of the newspaper is one of the most popular in Finland.

The data on news coverage were collected from the online database of HS (http://www.hs.fi/arkisto). This electronic archive contains material published by the newspaper from 1990 onwards. It includes the titles and texts of the printed material, including news articles as well as Letters to the Editor, columns and commentaries. Information on pictures, picture captions, graphics and other visual illustrations, cartoons and advertisements is not included. The weekly supplement (NYT-liite) concentrating mainly on TV-programs and entertainment and the supplementary monthly magazine (Kuukausiliite) are also excluded.

After testing different keywords (see Lyytimäki & Tapio, 2009), the search string “climate change” (ilmastonmuutos) was used. In Finnish, the search term “global warming” is not suitable, since there is no corresponding and widely used direct translation for it. The accuracy of search results was checked. Only few references unrelated to climate issues were found, but the amount of duplicates typically resulting from the inclusion of different editions of the newspaper was substantial. The highest yearly percentage of duplicates was 33% from year 1990. During the 2000s the yearly share of duplicates was 5% or less.

3. Early climate debate in Finland

It took a relatively long time before the warming of the global climate due to anthropogenic climate change became a widely acknowledged environmental problem in Finland. The potential of carbon dioxide, released to the atmosphere from human activities, to increase the global temperature was first mentioned on the pages of HS in the 1950s (Karppinen, 1993). For example, in 1958, one news story published by the HS focused on the potential effects of nuclear weapon testing to weather. The article concluded that such effects do not exist but mentioned that the strengthening of the greenhouse effect is likely to increase the global temperature by 1 °C (Lähteenmäki, 2006).

With the exception of occasional news items mentioning the subject, the climate change remained almost absent from public debate until the 1970s (Rinne, 2003). Both in Finland and internationally, most experts and the general public found it difficult to believe that human activities could alter the climate of the planet as a whole (Weart, 2008). Warming of the climate was especially difficult to perceive as a threat in a Northern country characterised by long and cold winters, with spring and autumn frosts threatening the harvests. The individual speculations about the issue typically welcomed the potential warming as a positive development. Already in the 18th century the educated Finnish clergy had speculated that agricultural practices modifying the Earth – and thus fulfilling the God’s will – could improve the harsh weather conditions (Niemelä, 2008).

Finland was predominantly an agricultural country until 1950s. A majority of Finns had first-hand experiences of the deleterious impacts of unfavourable weather to food production and livelihoods. Finnish industrialisation progressed rapidly during 1950s and 1960s, causing an increase of greenhouse gas emissions. The carbon dioxide emissions from the use of fossil fuels increased from about five million tonnes in late 1930s to about 50 million tonnes in late 1960s (Kunnas, 2009).

As the economic prosperity increased, the social structures of the Finnish society and lifestyles of the people faced dramatic changes. For example, from mid-1960s onwards package tour flights directed typically to the Canary Islands and Southern Europe become increasingly available for Finns. Related to this, sun-bathing on warm beaches became a common theme of newspaper travel advertisements (Juutilainen, 2001). Thus, warm climate was increasingly connected with positive connotations such as leisure time and high social status.

During the 1970s, global warming was a non-problem also because the weather statistics did not indicate a warming of climate but rather a continuation of a relatively cool period following the warm period of the 1930s (Jylhä et al., 2004). Instead, the fears related to the cooling of the climate were emphasised (Weart, 2008; Lyytimäki, 2009). On the one hand, these fears were connected to the speculations suggesting the possibility of a new Ice Age looming somewhere in the distant future. On the other hand, they were related to the risk of "nuclear winter" resulting from large scale use of nuclear weapons in the context of the Cold War. In the early 1980s, additional interest towards global cooling was raised by scientific findings suggesting that global cooling which resulted from the global dust cloud caused by an asteroid collision to Earth was partially responsible for the great mass extinction 65 million years ago (Alvarez et al., 1980). However, instead of climate debate, this finding was primarily linked to the debate on current loss of biodiversity caused by human activities.

During the late 1980s the number of news items dealing with global warming and other issues related to climate and air protection increased in the Finnish press (Heiskala, 1993; Suhonen, 1994). In the mid-1980s, environmental coverage in foreign news pages of HS increased as the number of news items quadrupled from about 50 to about 200 news items annually. This was partially explained by the coverage given to the Chernobyl nuclear accident (1986). Other international key topics of the 1980s and 1990s included the greenhouse effect, destruction of rainforests, stratospheric ozone depletion, and the environmental problems of the Eastern Europe that were caused primarily by heavy industry and energy production. Related to this, the debate over acidifying precipitation, or "acid rain", and the Central European "forest deaths" highlighted the cross-border characteristics of air pollution (Väliverronen, 1996).

In the late 1980s, consensus over the climate change was largely missing. In order to answer the need for a science-based synthesis, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. Since the first reports published in 1990, the IPCC has been a key source of climate information. The year 1988 has been identified as a turning point of the global debate on climate change also because of the hot and dry summer in the USA (Ungar, 1992). The scientific theories were now backed up by concrete extreme weather events, and the wide-scale debate was triggered by the testimony of Dr James Hansen in the US Congress. The weather anomalies in the North America and elsewhere were reported as signs of global warming by the Finnish media as well (Kantola, 1996).

4. Coverage of climate change during 1990–2010

Between January 1990 and December 2010, almost 5,500 news stories mentioning climate change appeared in the pages of HS (Fig. 1). Generally, the news coverage was characterised by short-term ups and downs and a relatively low level of attention to climate change until the mid 2000s. Between 1990 and 2005, only 7.5 news stories mentioning climate change appeared per month. This was partly because climate issues were largely treated under the label of "greenhouse effect" especially in the 1990s (Suhonen, 1994). In 2006, the monthly average increased to 34.3, and during 2007–2009, the monthly average reached 84.2. In 2010, the monthly average dropped to 46.2. The development of climate news in other Finnish broadsheet newspapers has generally followed the same pattern (Lyytimäki, 2011).

About a fourth of the HS news items mentioning climate change were published in the letters to the editor pages (16.8%) or in the editorial section (10.1%). In addition to editorials by the newspaper staff, viewpoint articles by external expert writers are published in the editorial section. Domestic news pages (15.2%) and foreign news pages (15.4%) hold almost identical share of the news. Despite the global perspective inherent to climate issues, 6.9% of the news items appeared in sections focusing on local issues.

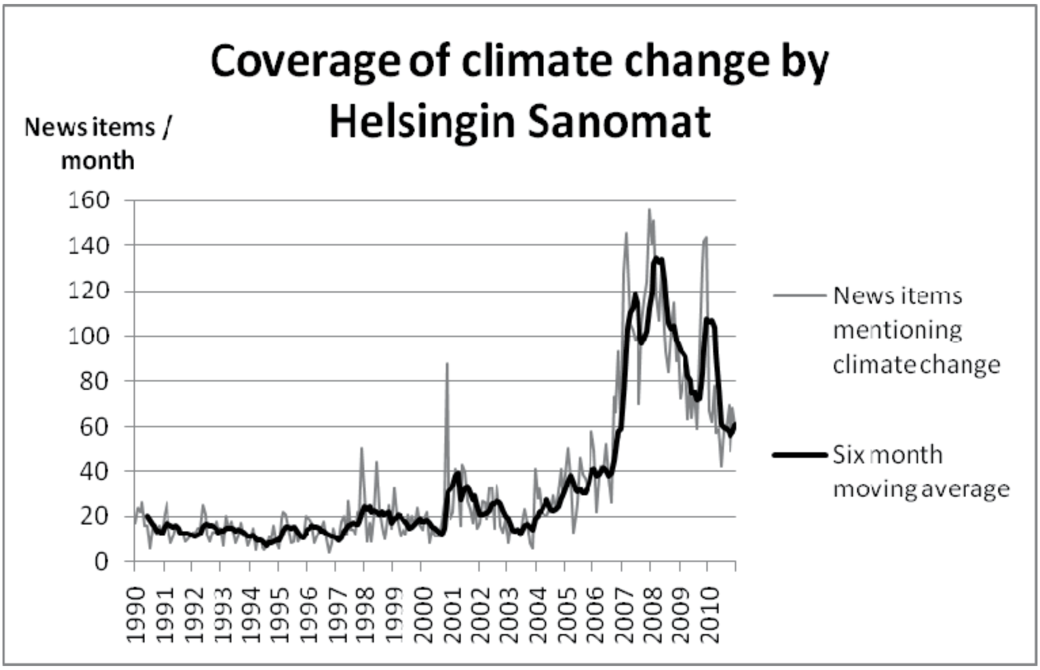

Fig. 1. Overall development of the climate news. Monthly number of news items mentioning climate change and a 6-month moving average, 1990-2010 (Modified from Lyytimäki & Tapio 2009; Lyytimäki, 2011).

Internationally, the media coverage of environmental issues was on a relatively high level in the late 1980s but the coverage receded in the early 1990's (Mazur, 1998; Carvalho & Burgess, 2005; Boykoff, 2009). One of the key events of the period was the 1992 UN Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil. Outcomes of the conference included the UN Framework Convention on Climate Change (UNFCCC) that formed the basis for the subsequent international climate policies. However, the conference concentrated on a variety of environmental and sustainability topics and it did not show as a clear peak in the Finnish climate coverage.

A peak in climate coverage occurred in November–December 1997 due to the third Conference of the Parties (COP3) of the UNFCCC meeting in Kyoto, Japan. After heated negotiations, this meeting ended up with the Kyoto protocol that included concrete targets for global climate policies. The Kyoto meeting can be considered as a turning point in Finnish climate change policies (Tirkkonen, 2000; Perimäki, 2002). Finland signed the Kyoto protocol in 1998 and ratified it together with 14 other EU member states in 2002. The implications of the Kyoto protocol for the Finnish economy were discussed on various occasions during late 1990s. This debate was mainly connected to the so-called burden sharing between the EU Member states. The country specific target set for Finland was to freeze the emissions of major greenhouse gases at the level of 1990 for the period of 2008–2012. Since the key issues were already settled, the media attention was scarce when the Kyoto protocol entered into force on the 16 February 2005. The issue was noticed by the HS (e.g. HS February 15, 2005), but without a major discussion on the effects of the protocol.

Various policy issues related to the energy issues and global climate policies dominated the climate debate during the autumn 2000 (Kerkkänen, 2010). The most distinctive event was the failure of international climate negotiations in the COP6 meeting in Hague, the Netherlands. The November 2000 peak of coverage was also connected to the application sent to the Finnish Parliament for a permission to build the 5th nuclear reactor in Finland by the energy company TVO. International negotiations were also connected to the national level preparations of the government's climate strategy.

The climate coverage decreased during 2001–2004 (on average, 11.4 news items per month). At the start of the 2001, a disagreement between key politicians over the potential costs of climate policy received attention. At the end of 2005, a rise in coverage occurred partly related to the COP11 meeting in Montreal, Canada, followed by a temporary drop in early 2006. Growth of coverage continued later in 2006. During the autumn 2006, the focus of news was clearly on international issues. For example, a series of news labelled "changing climate" and focusing on the effects of climate change on people and nature around the world was published on the HS foreign news pages.

Two major documents that gained wide international attention were published during the autumn 2006. These were treated very differently by the HS. Release of the "Stern report" on the economics of climate change (Stern, 2007) was reported in the news front page and in the economy pages (HS October 31, 2006) in a serious tone as a well-reasoned warning of a respected economist. On the other hand, the documentary film An Inconvenient Truth by Al Gore was treated on the economy pages with a critical and even sarcastic tone as "...a kind of extended PowerPoint presentation that was awarded at the Cannes film festivals." (HS 6 September 2006). The HS presented Al Gore as the "leading preacher of global warming" and a columnist invited to evaluate Gore's presentation in Helsinki nicknamed him as "Al Bore" because he presented too many graphs (HS 6 September, 2006).

A sharp increase of coverage occurred in January 2007. No single dominant news topic can be attributed for this increase. Several letters to editor related to energy policy were published as well as various other expressions of concern related to climate risks. Domestic and foreign news pages focused on news related to research results, climate policies and weather anomalies. In the end of the January, an interview of Mr Jorma Ollila, chairman of the Nokia corporation and the Royal Dutch Shell was published (HS January 28, 2007). This interview can be considered as a distinctive turning point, since it clearly articulated the concern over climate change by a key economic actor and an opinion leader. Mr Ollila urged for fast reductions of carbon dioxide emissions and asserted that "the big European energy and oil companies have already accepted that climate change is caused by human beings".

The high level of coverage was sustained in February 2007 when the EU initially declared its climate package, introducing a target of 20% reduction of greenhouse gas emissions by 2020

(HS February 21, 2007) (see also Uusi-Rauva & Tienari, 2010). The debate was further fuelled because of the estimation by the Government's Economic Research Institute that fulfilling the EU targets would cost the loss of employment of some 60 000 Finns (HS February 20, 2007). Other key news included the publication of the IPCC summary report. The title on the front news page highlighted and dramatised the risks: "Report: The Finnish climate can get even 9 degrees warmer" (HS February 3, 2007). Furthermore, the news included a statement from the Prime Minister Matti Vanhanen that the "downplaying of the climate change has to be stopped immediately".

During the following months, the coverage began to decrease, but it increased again during the following autumn and winter. The Nobel peace prize given to Al Gore and IPCC fuelled the debate (HS October 23, 2007). Individual critical news were also published about the decision of British court on mistakes in Gore's documentary film An Inconvenient Truth (HS October 12, 2007).

In December 2007, the COP13 meeting in Bali, Indonesia, received considerable international news coverage (Eide et al., 2009). The HS summarised the meeting with the title "Vaulting drama ended with climate concord in Bali" (HS December 16, 2007). However, this meeting did not cause a major shift in the Finnish climate debate although the news coverage remained at a high level during the following months. Importantly, the mild winter weather and the lack of snow gave journalists a convenient passage for presenting climate issues connected with various news topics (Lyytimäki & Tapio, 2009).

The most dramatic monthly decrease of coverage occurred during January 2010. This can be explained by the preceding peak of coverage caused by the COP15 meeting held in Copenhagen, Denmark. Unusually high expectations directed to the meeting created a sense of drama, increasing journalistic interest in the meeting. As measured by the number of journalists attending, the Copenhagen meeting was more popular than the Rio de Janeiro UNCED meeting in 1992 or the Kyoto COP3 meeting in 1997 (Painter, 2010). The aim of the Copenhagen meeting was to agree on the global climate policies after the Kyoto protocol. However, in Finland the COP15 peak of coverage appears to be substantially lower than in several other countries (Boykoff & Mansfield; 2010; Painter, 2010). During the COP15 meeting, the climate coverage of HS reached about the same level than in January-February 2007 and January 2008.

Despite the peak related to the COP15 meeting, the yearly amount of climate news decreased in 2009. This can partly be explained by the global financial crisis and economic slowdown that spread to the Finnish economy and reduced public interest in environmental issues. After the two mild winters, there was also more normal weather during the winter of 2009–2010, as the whole of Finland was covered in snow (Lyytimäki & Tapio, 2009). Only one small news item (HS February 16, 2010) noted that despite the cold weather in Europe and eastern parts of North America, globally the weather was exceptionally warm in January 2010 (National Oceanic and Atmospheric Administration [NOAA], 2010).

The summer of 2010 was record-breaking hot, and November and December 2010 were unusually cold in Finland. However, these weather anomalies were not strongly connected to the climate change by the HS.

5. Discussion

Recent decline of climate change news coverage can be understood as an outcome of several intertwined factors. The two unusually snowy winters suggested no warming and made it easy for journalists to ignore research results and policy processes related to climate change. Furthermore, the global economic crisis that hit also the Finnish economy was perceived as a more serious and immediate problem.

The economic slowdown and cold winters were presented as possible explanations for the results of an opinion poll showing that 48% of the Finns considered that the effects of climate change had been exaggerated (YLE, 2010). This opinion poll (N=1007) was conducted in March 2010. Another opinion poll, reported by the HS in April 14, 2010, indicated that the share of the Finns who fully agree that the climate change is the greatest environmental threat requiring rapid actions dropped from 51% in winter 2009 to 32% in winter 2010 (Haavisto, 2010). Yet another opinion poll indicated that the willingness of the Finns to pay for climate actions decreased already in 2009 (HS October 8, 2009). The Finnish Science Barometer indicated that the share of the people who fully agree that the continuation of climate change is a real and serious threat that requires efficient actions from the decision makers dropped from 59% in 2007 to 42% in 2010 (Kiljunen, 2010).

Lack of progress of climate policies showed the difficulties of finding the solutions to climate problems and perhaps contributed to a sense of helplessness and apathy (Sairinen et al., 2010). Additional possible explanation is the decrease of interest of both journalists and the public – a climate fatigue – following the period of intense debate. For example, in a letter to the editor (HS April 21, 2009), the author rearticulated a deeply rooted popular belief of the beneficial warming by asserting that "people are getting fed up with the one-sided doomsday predictions. Common sense tells us that the warming of climate is a good thing in the Nordic countries."

From the November 2009 onwards, scepticism towards climate change increased due to the so-called "climategate" and "Himalayagate" episodes (Berkhout, 2010; Nerlich, 2010; Painter, 2010). However, despite some critique presented especially in the letters to the editor, the news coverage of HS was dominated by views favourable to IPCC and other actors stressing the seriousness of climate change and general trustworthiness of climate science. For example, when reporting on the forthcoming review of the IPCC reports, HS (April 12, 2010) mentioned the critique only briefly and gave more space to the UN Secretary-General Ban Ki-moon who assured that "Let me be clear - the threat posed by climate change is real ... None of the recent accusations or disclosures by the media alters the scientific consensus on climate change." Thus, the Finnish coverage appear to resemble other European countries, such as Sweden (Olausson, 2009), Germany (von Storch and Krauss, 2005) and France and the Netherlands (Dirikx & Gelders, 2009) where the visibility of so called climate sceptics has been low, in contrast with the US climate debate (Armitage, 2005; Boykoff & Boykoff, 2007).

The decrease of the climate change coverage suggests a shift to some kind of post-problem stage. One of the most widely applied models that aim to explain the fluctuation of news coverage is the Issue-Attention Model (Downs, 1972; Brossard et al., 2004). The model assumes an initial pre-problem stage where environmental problem exists but has yet to capture public attention. The second stage is characterised by dramatic events that make the public both aware of the problem and alarmed about it. The "gradual-realization-of-the-cost stage" is the third phase where key actors acknowledge costs that will be incurred in dealing with the problem. This phase is followed by gradual decline of interest as actors become discouraged at the prospect of appropriately dealing with the issue, and finally a post-problem stage of low attention to the issue.

However, this model fails to address the fact that despite the decrease of coverage after the peak(s), climate issues are still featured more extensively than in the 1990s and early 2000s. The current Finnish debate can hardly be described as a post-problem phase where the issue once elevated to national prominence may sporadically recapture public interest (Downs, 1972). Instead, it appears that the relatively large-scale treatment of climate issues continue and climate issues are also treated under other topics such as energy policies (Teräväinen, 2010) or traffic (Rinkinen, 2010). Climate issues are also widely addressed in culture and lifestyle pages of the HS and arguments related to the climate change are used in advertisements, as well (Reineck, 2009).

Theories and models focusing on shifts between alternative states of a system with different qualitative properties appear to provide useful additional tools to understand the changes of the Finnish climate debate. The changes between the stages of public discourse as described by the Issue-Attention Model may be the result of a punctuation processes (Holt & Barkemeyer, 2010). Punctuated Equilibria Model focuses on systems that are characterised by a period of stasis, which are later punctuated by sudden shifts. The model has been widely applied. It has been suggested to describe the biological evolution in geological time scales (Eldredge & Gould, 1972) as well as the evolution of US policy agenda (Baumgartner & Jones, 1993). As Holt and Barkemeyer (2010) note, most explorations of punctuated equilibrium associate some form of an exogenous shock that affect the system.

Critical discourse moments can be understood as manifestations of shocks affecting a system. The most distinctive critical discourse moment identified from the Finnish climate coverage occurred in January 2007. The driving forces behind this moment of increased interest included a combination of national and international factors. On a national level, key factors were the mild and snowless winter weather and the expression of concern of an opinion leader. International factors included the publication of the IPCC report that continued the discussion on the recently published Stern report and other international and national level studies related to climate change. After this period of heightened coverage, the climate change was widely accepted as a serious policy concern.

To summarise, it any model explaining the increases and decreases of environmental coverage should take into account both ecological socio-economic factors influencing the coverage, and combine local contexts with relevant global processes. Humility is needed since it is unlikely that any single model is able to take into account all relevant variables and the wide variation of contributing factors in different contexts. For example, while the issue-attention model appears to hold in some contexts, it does not hold in others (Brossard et al. 2004). Instead of aiming for one universal model, the fruitful approach for future research is to aim at case-specific combination of different models that can best explain the global-local interactions affecting the evolution of environmental media coverage in their unique contexts.

6. Conclusion

Largely because of the heightened media coverage, the global climate change has emerged as the key environmental concern of the early 21st century. The media reporting on environmental issues is a part of a complex web of global and local social, economic, cultural, and ecological processes. It can reflect changes in ecological environment, but only rarely in a linear fashion; ecological changes usually do not result in corresponding changes of news coverage (Ader, 1995; Lyytimäki, 2007; Mazur, 2009).

In most countries, such as Finland, the news coverage of climate change has been characterized by considerable increases and decreases. Based on the Finnish case, it is suggested that the climate debate has shifted to a new phase, where the coverage has fallen from peak levels but remains at a relatively high level and where climate issues are increasingly treated under other topics than environmental ones. These changes are likely to have profound implications to climate policy.

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Edited by Juan Blanco and Houshang Kheradmand

This book shows some of the socio-economic impacts of climate change according to different estimates of the current or estimated global warming. A series of scientific and experimental research projects explore the impacts of climate change and browse the techniques to evaluate the related impacts. These 23 chapters provide a good overview of the different changes impacts that already have been detected in several regions of the world. They are part of an introduction to the researches being done around the globe in connection with this topic. However, climate change is not just an academic issue important only to scientists and environmentalists; it also has direct implications on various ecosystems and technologies.

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