IntechOpen

Irrigation in Agroecosystems

Edited by Gabrijel Ondrašek

IRRIGATION IN AGROECOSYSTEMS

Edited by **Gabrijel Ondrašek**

Irigation in Agroecosystems
http://dx.doi.org/10.5772/intechopen.73607
Edited by Gabrijel Ondrašek

Contributors

Isaac Fandika, Michele Greco, Gaganpreet Kour, Jian Liu, Hongbin Liu, Ruliang Liu, M G Mostofa Amin, Limei Zhai, Hongyuan Wang, Xubo Zhang, Yitao Zhang, Ying Zhao, Xiaodong Ding, Adalberto Café-Filho, Mauricio Rossato, Carlos Alberto Lopes, Timothy Coolong, Luke Miller, George Vellidis, Tsugihiro Watanabe, Anabela Afonso Fernandes-Silva, Manuel T. Oliveira, Teresa Paço, Isabel Ferreira, Constanze Buhk, Jens Schirmel, Rebekka Gerlach, Oliver Frör, Megersa Olumana Dinka, Kassahun Birhanu Birhanu Tadesse, Gabrijel Ondrasek

First published in London, United Kingdom, 2019 by IntechOpen
eBook (PDF) Published by IntechOpen, 2019
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, The Shard, 25th floor, 32 London Bridge Street
London, SE19SG – United Kingdom
Printed in Croatia

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Additional hard and PDF copies can be obtained from orders@intechopen.com

Irrigation in Agroecosystems
Edited by Gabrijel Ondrašek

p. cm.

Print ISBN 978-1-78984-923-3

Online ISBN 978-1-78984-924-0

eBook (PDF) ISBN 978-1-83881-743-5

Meet the editor

Prof. Ondrasek is employed at the University of Zagreb, Faculty of Agriculture (UZFA), Croatia, and is currently a full professor and head of the Department of Soil Amelioration. His academic and scientific opus is orientated towards sustainable soil and water management in agroecosystems. He coordinates three MSc and two BSc study courses at UZFA, and has been a supervisor of 24 students and four visiting scientists. He has published more than 30 scientific papers, 13 book chapters, and edited one academic book. During his professional career he spent almost three years abroad at eminent Australian, European, and Latin American research and academic institutions and centers of excellence. At the national level he participated in the creation of the national master plan for irrigation (NAPNAV, 2005). He also participated in master plans for irrigation in almost all counties (17/20) and in more than 20 irrigation system projects in Croatia.

Contents

Preface XI

Chapter 1 **Introductory Chapter: Irrigation after Millennia - Still One of the Most Effective Strategies for Sustainable Management of Water Footprint in Agricultural Crops 1**
Gabrijel Ondrasek

Chapter 2 **Informational Entropy Approach for Rating Curve Assessment in Rough and Smooth Irrigation Ditch 5**
Greco Michele

Chapter 3 **Irrigation Management Practices and Their Influence on Fruit Agroecosystem 21**
Gaganpreet Kour and Parshant Bakshi

Chapter 4 **Using Smartphone Technologies to Manage Irrigation 37**
Timothy Coolong, Luke Miller and George Vellidis

Chapter 5 **Deficit Irrigation in Mediterranean Fruit Trees and Grapevines: Water Stress Indicators and Crop Responses 51**
Anabela Fernandes-Silva, Manuel Oliveira, Teresa A. Paço and Isabel Ferreira

Chapter 6 **Water Footprint Differences of Producing Cultivars of Selected Crops in New Zealand 87**
Isaac R. Fandika, Peter D. Kemp, James P. Millner and Davie Horne

Chapter 7 **Water Quality in Irrigated Paddy Systems 105**
Jian Liu, Hongbin Liu, Ruliang Liu, MG Mostofa Amin, Limei Zhai, Haiming Lu, Hongyuan Wang, Xubo Zhang, Yitao Zhang, Ying Zhao and Xiaodong Ding

Chapter 8 **Management of Plant Disease Epidemics with Irrigation Practices 123**
Adalberto C. Café-Filho, Carlos Alberto Lopes and Maurício Rossato

Chapter 9 **Paddy Fields as Artificial and Temporal Wetland 143**
Tsugihiro Watanabe

Chapter 10 **Traditional Water Meadows: A Sustainable Management Type for the Future? 159**
Constanze Buhk, Jens Schirmel, Gerlach Rebekka and Oliver Frör

Preface

Agroecosystem is defined as an interrelated functional unit of (a)biotic components (crops, livestock, microbes, soil particles/solutions/gases) with the principal aim of food production, underpinned either by natural precipitations (rain-fed agriculture) and/or artificially added water (irrigated agriculture). Rain-fed agroecosystems are experiencing more frequent and pronounced water imbalances such as water deficit (stress) as a consequence of global climate change. Besides the substantial reduction in yield and quality, water stress in arable agricultural areas often additionally underpins numerous other environmental constraints such as salinization, desertification, soil organic matter depletion, compaction, etc. Thus, ensuring a stable and balanced water relationship in the soil/crop route is important for the sustainability of the whole (agro)ecosystem.

Implementation of irrigation practice in agriculture is one of the most effective approaches to overcome crop water stress and ensure stable and quality food production. Irrigated cropping is conducted on about 20% of cultivated land areas and generates about 40% of global food production. However, due to increasing demands and continuous competition for high-quality water resources in the agricultural/industrial/domestic triangle, it is unrealistic to expect further expansion of agricultural irrigation. Adaptations to modern challenges of irrigated cropping (e.g., more frequent droughts, global warming) aim to improve water use efficiency, and are therefore more likely.

This book presents a collection of 10 chapters focused of irrigation planning, designing and management, irrigation systems, and improvement of water use efficiency across the irrigated agroecosystems. The book is thus mostly dedicated to all those scientists, students, and professionals dealing with irrigated agriculture and sustainable natural (principally water and soil) resource management, as well to those who can find an interest in elaborated subtopics.

The editor is grateful to all contributors for their collaboration, notably on considerations and acceptance of all suggestions and comments. Finally, great thanks go to Ms. Romina Skomersic from the publishing service office on her support and help.

Prof. Gabrijel Ondrasek
University of Zagreb, Croatia

Chapter 1

Introductory Chapter: Irrigation after Millennia - Still One of the Most Effective Strategies for Sustainable Management of Water Footprint in Agricultural Crops

Gabrijel Ondrasek

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.81189

1. Introduction

Water is an essential component of the Earth's (agro) ecosystems with direct influence on global food production. As a renewable resource, water fluctuates over its phases in the global water cycle and replenishes the root zones (rhizospheres) of cultivated croplands in agro-ecosystems. Agroecosystem can be defined as a very complex functional unit of biotic (agricultural crops/varieties, animal breeds, uncultivated weeds and accompanied macro/micro biota) and abiotic (minerals, organics, fluids, gasses, water) components with the primary goal of food/feed production. Agroecosystems orientated to cultivated crop production have the major contribution in human food supply given that about 80% of human nutrition represent plant-derived foodstuffs (cereals, vegetables, fruits), while the rest are those of animal origin. Therefore, agroecosystems are the world's principal food supplier, as well as the predominant user of renewable freshwater (*blue water*) resources, consuming globally per year ~7 trillion m^3 of water, either in rain-fed (~60%) or irrigated (~40%) conditions. Thus, water resources and their management in agroecosystems are of crucial importance for stability and security of global food production.

However, from the last several decades, water resources exploited in (agro) ecosystems have been started to be overexposed to different human-induced pressures (pollution by modern in/organic contaminants) and non-sustainable management practices (uncontrolled water abstractions, lacking of purification, recycling and/or reusing of *grey waters*). Such pressures accompanied with ongoing global climate changes and processes (more frequent and intensive droughts, deruralisation, human growth in water-stressed areas) imbalance water cycling and reduce availability of fresh hydro-resources for increased food demands.

Agroecosystems, especially those rain-feed, are experiencing more frequent and pronounced water imbalances (water stress) on the soil-plant-atmosphere route. Besides the substantial reduction in yield and quality, water stress in arable areas often additionally underpins numerous other environmental constraints such as salinisation, desertification, soil organic matter depletion, biodiversity reduction, eutrophication, etc. Thus, ensuring a stable and balanced water relationship in the soil-crop route is important for the sustainability and stability of the whole (agro) ecosystem.

Implementation of irrigation practice in agroecosystem is one of the most effective approaches to overcome crop water stress and ensure stable and quality food supply. It was confirmed that application of irrigation systems can substantially reduce the *water footprint* (i.e. a measure for the water volume needed for the realisation of goods and/or services), notably in horticultural and fruit crops more responsive to irrigation. Irrigated agroecosystems are overspread at nearly 20% of cultivated land areas but they generate even ~40% of global food supplies. For more than 50 years (1961–2009), irrigation was one of the widely accepted and fast-growing global strategies for overcoming water stress in agroecosystems and generator of continuous stable crop yields. In the same period, irrigated areas grew almost linearly by 120% and occupied about 300 Mha worldwide. However, due to increasing demands and continuous competition for high-quality water resources in the agricultural-industrial-domestic triangle, it is quite unrealistic to expect further expansion of agricultural irrigation on the expanse of rain-feed cropping. Adaptations to modern challenges of irrigated agroecosystem (e.g. more frequent and pronounced draughts and extreme heat strikes) aim to improve water use efficiency (WUE), and are therefore more likely. Namely, most of the modern sustainable irrigation (agricultural) management strategies are focused on using hydro-/land-resources more effectively (avoiding/reducing losses and quality deterioration) and more efficiently (maximally increasing food production) which are encompassed by the concept of WUE.

Among traditional irrigation methods and systems (which dominate at nearly 95% of irrigated area) and modern ones (distributed at nearly 5% of irrigated land) existing many significant differences in WUE along with their different operational (technological) and environmentally related characteristics. For instance, traditional surface gravity-flow irrigation systems (furrows, basins, contours, *muang fai*) in comparison to modern ones (drip irrigation, low-energised/-pressurised sprinklers) can obtain and up to two-fold lower WUE. Consequently, there is a significant potential for improvement of WUE in irrigated agroecosystems over shifting from traditional to modern irrigation systems and/or upgrading particular sections and their elements (from the water source over conveyance system to the irrigated paddocks) of traditional systems.

Finally, improved irrigation management (scheduling, timing, frequency, depth) was confirmed as one of the most feasible approach of achieving large increases in WUE. Current soil-water regime, detected either on real-time *in situ* approach (with precise sensors, probes) or calculated based on nearby weather recordings (to obtain reference evapotranspiration, crop coefficients, effective rainfalls), may significantly optimise irrigation timing and consequently improve WUE. Processing of such instantly collected data over modern information technologies (smartphone/PC applications) represents some of the most novel approaches in irrigation agroecosystems management.

http://dx.doi.org/10.5772/intechopen.81189

Author details

Gabrijel Ondrasek

Address all correspondence to: gondrasek@agr.hr

Department of Soil Amelioration, Faculty of Agriculture, University of Zagreb,
Zagreb, Croatia

Chapter 2

Informational Entropy Approach for Rating Curve Assessment in Rough and Smooth Irrigation Ditch

Greco Michele

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.78975

Abstract

The assessment of water discharge in open channel flow is one of the most crucial issues for hydraulic engineers in the fields of water resources management, river dynamics, eco-hydraulics, irrigation, hydraulic structure design, etc. Recent studies state that the entropy velocity law allows expeditive methodology for discharge estimation and rating curve development due to the simple mathematical formulation and implementation. A lot of works have been developed based on the entropy velocity profile supporting measurements in lab for rating curve assessment in regular ditch flows showing a good performance. The present work deals with the use of entropy velocity profile approach in order to give a general framework of threats and opportunities related to robust operational application of such laws in the field of rating curve assessment. The analysis has been carried on a laboratory flume with regular roughness under controlled boundary conditions and different stages generating an exhaustive dashboard for the better appraisal of the approaches. Finally, entropy model may represent a robust and useful tool for the water discharge assessment in rough ditches.

Keywords: entropy velocity ratio, relative submergence, aspect ratio, water discharge

1. Introduction

Water discharge assessment in open channel still represents a fundamental aspect for hydraulic engineer in several operative and technical fields like water resources management, ecological flow assessment and control, drainage and irrigation system as well as runoff and flood routing model calibration and implementation. Nevertheless, the water discharge evaluation in generic open channel is heavily affected by local fluid dynamics and geometric conditions, which well arise once flow velocity measurements and morphological boundaries are available at the same site. On the other hand, the drainage and irrigation channel present a regular cross section which might provide facilities in water discharge assessment and control, inducing also reduction in time and operative costs. That is, the implementation of operative procedures enabling operative charges simplifying the commitment of field activities, indeed, plays a fundamental role in channel monitoring for natural flow and manmade hydraulic structures. The main idea is related to the definition of expeditive procedures for flow field assessment and water discharge evaluation capable to optimize the surveying resources in time and efforts. Thus, the opportunity to manage with a simple and straightforward velocity law, different from the classical logarithm formulation but capable to provide suitable results is all the more technically fruitful. That is, an operative tool for expeditive velocity distribution assessment basing on simple and immediate parameters.

Recent theoretical and experimental studies endorse the informational content hold into the distributed velocity measurements following an entropy-probabilistic approach. That is, Chiu [1, 2] drew the correlation between the mean flow velocity and maximum flow velocity defining the entropy parameter, M introducing the velocity ratio Φ(M). Considering the important implication that this finding could have for monitoring of high flows in rivers, many authors investigated the reliability of this relationship using field data [3–7]. Overall, they found M as a river site depending and not influenced by the flood intensity both in terms of amount and duration. Thus, M should be considered a specific factor of the gauged cross section as outlined by Moramarco and Singh [7] exploring the dependence of M on the hydraulics and geometries of the river cross sections.

The study was able to explain the constancy of M value on the ground that M is not depending on the dynamic of flood, such as expressed by the energy or water surface slope, Sf and to identify a formula expressing M as a function of the hydraulic radius, Manning's roughness and the location, y_0, where the horizontal velocity is hypothetically equal to zero. For the latter, it was preliminarily found that if y_0 was assessed by distinguishing low flows from high flows, then a better estimation of M would have been obtained across a gauged river site. However, considering that the y_0 location is not of simple assessment and then might have high uncertainty, the assessment of M should be addressed, mainly for ungauged river sites, using hydraulic and geometric variables easy to acquire. Such a thought might be discussed introducing the relative submergence D/d (in which, D = average water depth and d = roughness dimension). That is, the velocity distribution in natural rivers depends on several variables like channel geometry, bed and bank roughness, and the vertical velocity distribution generally increases monotonically from 0 at the channel bed, to the maximum at the water surface and can be assumed 1-D flow dominant. Moreover, whenever the channel cannot be considered "wide", that is the aspect ratio (B/D with B channel width and D water depth) is less than 6, besides the presence of the boundary, the velocity varies even transversely and a two-dimension distribution occurs, leading G as the 2D entropy parameter. The maximum velocity places below the water surface inducing dip-phenomenon and the position of maximum velocity is also influenced by the aspect ratio [8], which is of simple assessment once channel cross-section geometry is known. Thus, investigating the influence of bed roughness and cross section geometry on medium and maximum velocity ratio at the global scale assumes a relevant interest in the field of open channel flow.

Therefore, M might represent an intrinsic parameter of the gauged site and this insight led several authors to explore the dependence of M on hydraulic and geometric characteristics of the flow site [3, 7]. In the case of river flows, Greco [9] enlightened a different behavior of Φ(M) depending on the roughness dimension: the velocity ratio is heavily influenced by the magnitude of relative submergence if large or intermediate scale [10]. Finally, the results support and validate a robust and fruitful operative chain to be implemented for expeditive water discharge assessment in rough and smooth irrigation ditch.

2. Entropy velocity profiles in open channels

The concept of informational entropy as a measure of uncertainty associated to a probability distribution was formulated for the first time in the field of hydraulics by Shannon [11]. The principle of maximum entropy introduces the least-biased probability distribution of a random variable constrained by defined information system as well as the theorem of the concentration for hypothesis testing, introducing the informational entropy theory [12]. A direct evaluation of uncertainty related to the probability distribution of a continuous random variable expressed in terms of entropy, H, is defined as follows

$$H = -\int_{-\infty}^{+\infty} p(x) \log p(x) dx \quad (1)$$

where, p(x) is the continuous probability density function of random variable x.

Using POME, entropy can be maximized through the method of Lagrange multiplier as follows:

$$L = -\frac{1}{m-1}\int_{-\infty}^{+\infty} p(x)\left\{1 - [p(x)]^{m-1}\right\}dx + \sum_{i=1}^{N} \lambda_i g_i(x) \quad (2)$$

in which, $m > 0$, $g_i(x)$ is the ith constraint function and λ_i is the constrain Lagrange multiplier as a weight in the maximization of entropy.

Chiu [1, 2] applied the concept of entropy to open-channel analysis to model velocity and shear stress distribution as well as sediment concentration. In such a way, the velocity distribution in the probability domain allows to obtain the cross-sectional mean velocity and the momentum and energy coefficients disregarding the geometrical shape of cross sections, which is generally complex in natural channels [2, 13].

Further, an assumption on the probability distribution in the space domain is needed to relate the entropy-based probability distribution to the spatial distribution. Therefore, defining u by the time-averaged velocity placed on an isovelocity curve with the assigned value ξ, the value of u is almost 0 at ξ_0, which corresponds to the channel boundary, while u reaches U_{max} at ξ_{max}, which generally occurs at or below the water surface, depending on the dip-phenomenon. Thus, the velocity u monotonically increases from ξ_0 to ξ_{max} and for each value of the spatial coordinate greater than ξ, the velocity is greater than u, and the cumulative distribution function can be written as

$$\mathrm{F(u)} = \frac{\xi - \xi_0}{\xi_{\max} - \xi_0} \tag{3}$$

Thus, the Shannon entropy of velocity distribution can be written as:

$$H = -\int_0^{U_{max}} p(u)\, log\, p(u) du \tag{4}$$

Through a similar procedure, the probability density function of the velocity distribution is obtained by maximizing the Shannon entropy equation

$$L = \int_0^{U_{max}} \frac{f(u)}{m-1} \left\{1 - [f(u)]^{m-1}\right\} du + \lambda_0 \left[\int_0^{U_{max}} f(u) du - 1\right] + \lambda_1 \left[\int_0^{U_{max}} u f(u) du - \overline{u}\right] \tag{5}$$

in which, λ_0 and λ_1 are the Lagrange multipliers and the following constraint equations

$$C_1 = \int_0^{U_{max}} f(u) du = 1 \tag{6}$$

$$C_2 = \int_0^{U_{max}} u f(u) du = \overline{u} \tag{7}$$

$$f(u) = exp\,(\lambda_0 - 1 + \lambda_1 u) \tag{8}$$

Thus, Chiu's 1D velocity distribution results as:

$$u = \frac{U_{max}}{M} ln \left[1 + \left(e^M - 1\right) F(u)\right] = \frac{U_{max}}{M} ln \left[1 + \left(e^M - 1\right) \frac{\xi - \xi_0}{\xi_{max} - \xi_0}\right] \tag{9}$$

where M is the dimensionless entropy parameter introduced in the entropy-based derivation [14, 15]. Hence, M can be used as a measure of uniformity of probability and velocity distributions. The value of M can be determined by the mean, Um, and the maximum velocity values are derived from the following equation:

$$\Phi(M) = \frac{U_m}{U_{max}} = \left(\frac{e^M}{e^M - 1} - \frac{1}{M}\right) \tag{10}$$

Φ(M) is a relevant parameter which contains relevant information about the flow field asset: the mean velocity value, the location of the mean velocity [14–16], and the energy coefficient [14, 16] can be obtained from *M*. That is, once known the mean velocity, the flow discharge, sediment transport, and pollutant transport can be derived. Furthermore, mean vs. maximum velocity assumes linear relationship as discovered by Xia collecting velocity data in several cross-sections of the Mississippi River [17].

Eq. (10), in fact, represents the fundamental relationship, from an applied point of view, of the entropy velocity distribution and the assessment of the entropy parameter passing through the knowledge of the ratio between mean and maximum velocities, *Φ(M)*.

In order to identify the dependence of *M* from the hydraulic and geometric characteristics of channels, that is, the relative submergence and aspect ratio, respectively, the formulation proposed by Greco [9] for U_m is considered:

$$\frac{U_m}{u_*} = \frac{1}{k} ln\, \frac{D}{d} + \frac{1}{k} ln\, C_0 \tag{11}$$

where u_* is the shear velocity, d is the bed roughness height (i.e., d_{50}), k is the Von Karman constant, and C_0 is the dimensionless coefficient.

Even the maximum velocity plays an important role in the flow dynamics, and more than it magnitude, a relevant aspect is related to the position of the maximum velocity inside the flow domain. That is, the location of maximum velocity from the channel bottom, y_{max}, does not always occur at water surface, but a "velocity-dip" may occur as an indicator of *secondary currents* [18], which represents the circulation in a transverse channel cross section, while the longitudinal flow component is called the *primary flow.*

In this context, Moramarco and Singh [7] identified the ratio between U_{max} and u_* as:

$$\frac{U_{max}}{u_*} = \frac{1}{k} ln \left(\frac{D}{y_0(1+\alpha)} \right) + \frac{\alpha}{k} ln \left(\frac{\alpha}{1+\alpha} \right) \tag{12}$$

with $\alpha = (D/y_{max}-1)$.

y_0 can be assumed proportional to the characteristic bottom roughness height, d, as suggested by Rouse [19] through the experimental parameter $C_\xi = y_0/d$. Therefore, Eq. (12) turns into:

$$\frac{U_{max}}{u_*} = \frac{1}{k} ln \left(\frac{D}{d} \right) + \frac{1}{k} ln \left(\frac{\alpha^\alpha}{C_\xi (1+\alpha)^{1+\alpha}} \right) \tag{13}$$

Unlike Moramarco and Singh [7], here the ratio between Eq. (11) and Eq. (13), based on logarithm properties, explicitly proposes *Φ(M)* as a function of the relative submergence *D/d*:

$$\Phi(M) = \frac{U_m}{U_{max}} = \frac{ln\left(\frac{C_0 D}{d}\right)}{ln\left[\frac{D}{d}\frac{\alpha^\alpha}{C_\xi(1+\alpha)^{1+\alpha}}\right]} \cong A_\Phi ln\, \frac{D}{d} + B_\Phi \tag{14}$$

where A_Φ and B_Φ are the numerical coefficients. Eq. (14) follows under the hypothesis of linear interpolation between the pairs $\left[\ln\left(\frac{C_0 D}{d}\right)/\ln\left(\frac{D}{d}\frac{\alpha^\alpha}{C_\xi(1+\alpha)^{1+\alpha}}\right); \ln\left(\frac{D}{d}\right)\right]$ [13].

Eq. (14) highlights, indeed, a possible effect of bed roughness on the entropy velocity distribution in open channel flows, which depends on the roughness scale according to [1]. The dependence between the ratio Φ(M) and the relative submergence, D/d, has been widely studied by Greco [9] using a wide volume of data collected in the field on several cross sections along different rivers and in the laboratory [20–22], showing values of Φ(M) ranging in the [0.5–0.9] interval.

3. Laboratory measurements in rectangular smooth and rough ditch

The experimental tests were carried out in the Hydraulics Laboratory of Basilicata University, on two free surface rectangular flumes of 9 m length and with a cross section of 0.5×0.5 and 1×1 m, whose slope can vary from 0 up to 1%. **Figure 1** shows pictures about the flume, one of the bed configuration and the flow-meters.

The bed roughness (d) has been modulated between smooth surfaces, with 0.0005 m roughness height, and a rough bottom, obtained with both a sand bed, with a characteristic diameter of 0.002 m and standard deviation $\sqrt{d_{84}/d_{16}} = 1.67$, and a set of wood spheres of 0.035 m in diameter.

The measurement reaches were placed at the distance of 4 m from the beginning of the flumes, in order to damp large-scale disturbances and allow a quasi-uniform water depth. In the end section of the flume, a grid was installed to regulate the water depth for each assigned discharge or rather to obtain a small longitudinal variation of the flow depth. The experiments were performed in steady flow conditions for different values of discharge (0.015–0.100 m^3/s) and slope (0.05–1%). The measurement cross section was located in the middle of the rough reach in order to observe a fully developed flow, avoiding edge effects. The flow depth was measured by two hydrometers placed at both the beginning and the end

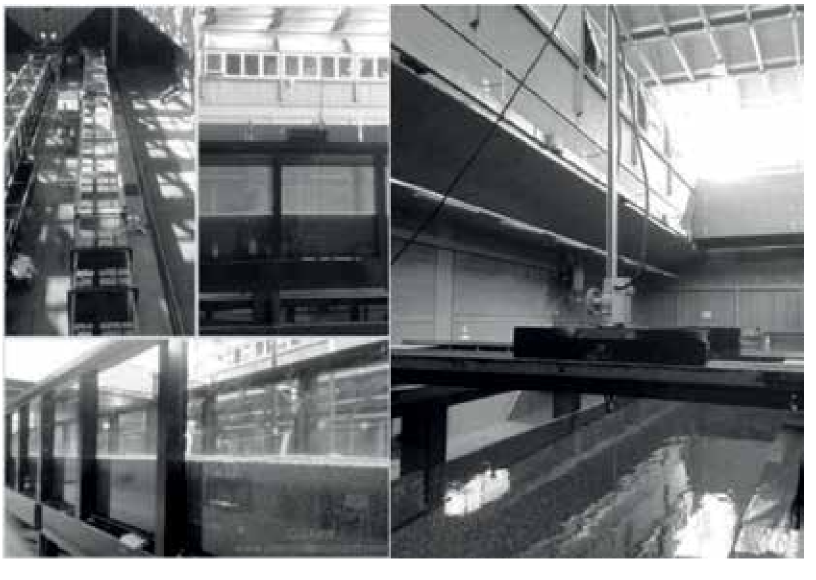

Figure 1. The experimental apparatus for laboratory measures.

of the measurement reach, and the water depth, D, was assumed as the average value. The velocity was acquired through a micro current-meter with a measuring head diameter of 0.01 m, while the water discharge was measured with a concentric orifice plate installed in the feed pipe and on a laboratory weir placed at the end of the flumes, and compared to the value calculated according to the velocity-area method [23], with a maximum error of around 1–2%. In particular, the adopted velocity-area method must be applied dividing the cross section into a fixed number of verticals and thus, on each vertical, a fixed measurement points are selected. In each point along the vertical, the velocity is acquired in order to compute the mean velocity of the flow along each vertical. Furthermore, the number of measures on each vertical was chosen with respect to the criterion that the difference in velocity between two consecutive points was less than 20%, of the higher measured velocity value, and the points close to the channel bottom and the water surface was fixed according to the size of the micro-current meter.

In such a way, two roughness configurations were enabled:

- RRF: rough rectangular flume, with relative submergence ranging in between 1.89 and 6.43; and
- SRF: smooth rectangular flume, with relative submergence greater than 50.

Table 1 synthetically reports the ranges of variation of the main parameters observed during the experiments for the RRF and SRF configuration, while Q is the water discharge, D is the water depth, D/d is the relative submergence, B/D is the aspect ratio, and $\Phi(M)$ is the ratio between the mean and maximum velocities.

For each configuration and for all the stages explored, a relevant bulk of velocity measurements was collected in order to provide a detailed reconstruction of the flow field allowing to obtain mean, U_m, and maximum, U_{max}, cross section velocities.

Figure 2 shows the linear relationship existing between the pairs (U_{max}; U_m) for the two configurations investigated, RRF and SRF.

From **Figure 2**, some useful issues arise. Even if the correlation among homogeneous data is very strong in both cases with R^2 greater than 0.95, it is immediately realized a slight different behavior between rough and smooth channels. That is, for the smooth rectangular flow, $\Phi(M)$ assumes the value 0.9, while for the rough condition, the value decreases to 0.67. That is, in other terms, it seems to be evident and sufficiently confirmed, the dependence of the velocity ratio on the roughness here represented by the relative submergence D/d as discussed in the previous section for Eq. (14).

Type	Q (mc/sec)	D (m)	D/d	B/D	Φ(M)
RRF	0.007–0.076	0.07–0.23	1.89–6.43	2.22–7.58	0.52–0.73
SRF	0.025–0.100	0.06–0.40	50–298	2.50–10	0.7–0.93

Table 1. Range of variation for the main parameters of the laboratory experiments.

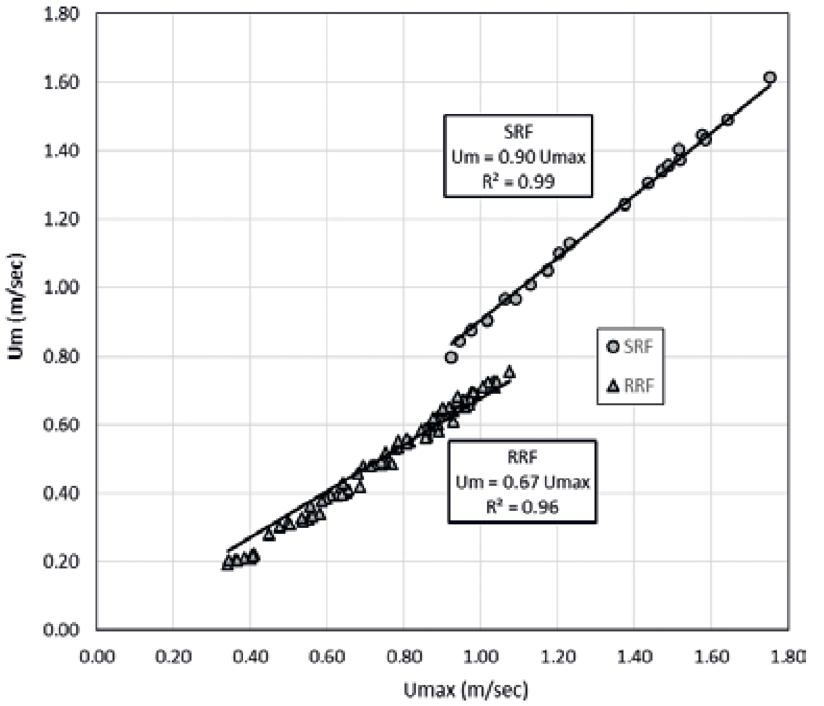

Figure 2. Average vs. maximum velocities observed for rough and smooth channel.

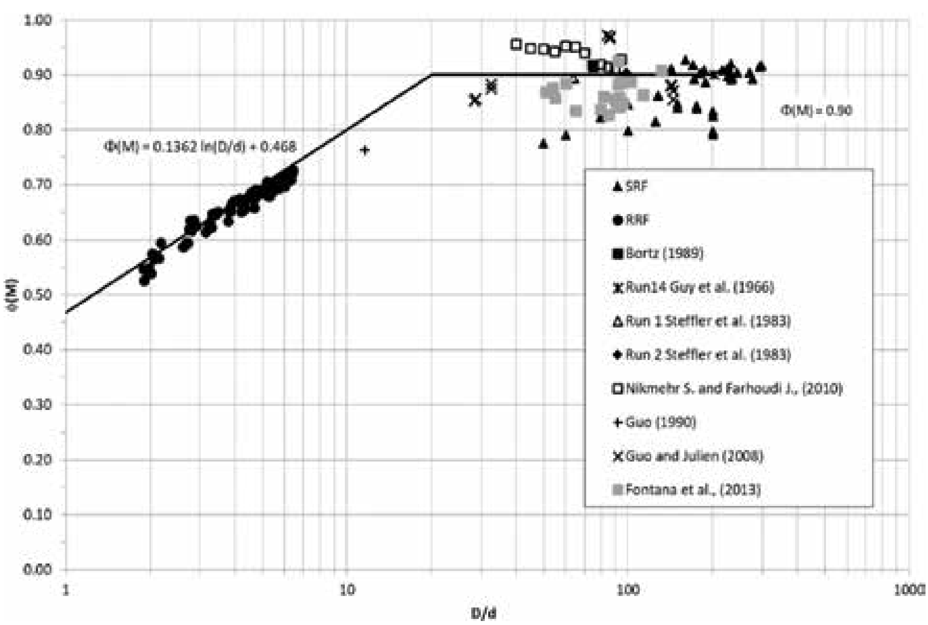

Figure 3. Velocity ratio vs. relative submergence.

Figure 3 clearly outlines such an outcome, showing how the velocity ratio is austerely dependent on relative submergence in case of rough flows, while it is sufficiently uniform for values of D/d > 20. Furthermore, the same picture proposes several literature data collected by other authors during experimental laboratory campaigns carried on smooth and rough flumes [22, 24–27], plotted and compared to those arising from the here presented research activity. The same **Figure 4** immediately deals with the robust correspondence between data sets related to the low rough/smooth flow conditions for which the hypothesis of the constant value of mean-to-maximum velocities ratio might be assumed consistent, at least from an operative point of view for D/d > 20. At the same time, Eq. (14) still remains compelling for D/d < 20, but it needs to be recalibrated and the coefficients A_Φ and B_Φ can be assumed 0.136 and 0.468, respectively ($R^2 = 0.95$).

Such a result can be immediately implemented in the operative chain of water discharge assessment, in order to derive the rating curve in a ditch or artificial channel. Furthermore, such knowledge allows us to assess the level of integrity of the channel in terms of sensitive changes in the bottom roughness, may be due to the local deposition of sediment or vegetation.

Furthermore, in case of $D/d > 20$, typical of concrete channels, the setting of rating curve is quite direct collecting few measures of velocity, in a little volume of the flow field mainly located in the center of the upper part of the cross section where is generally located at the maximum

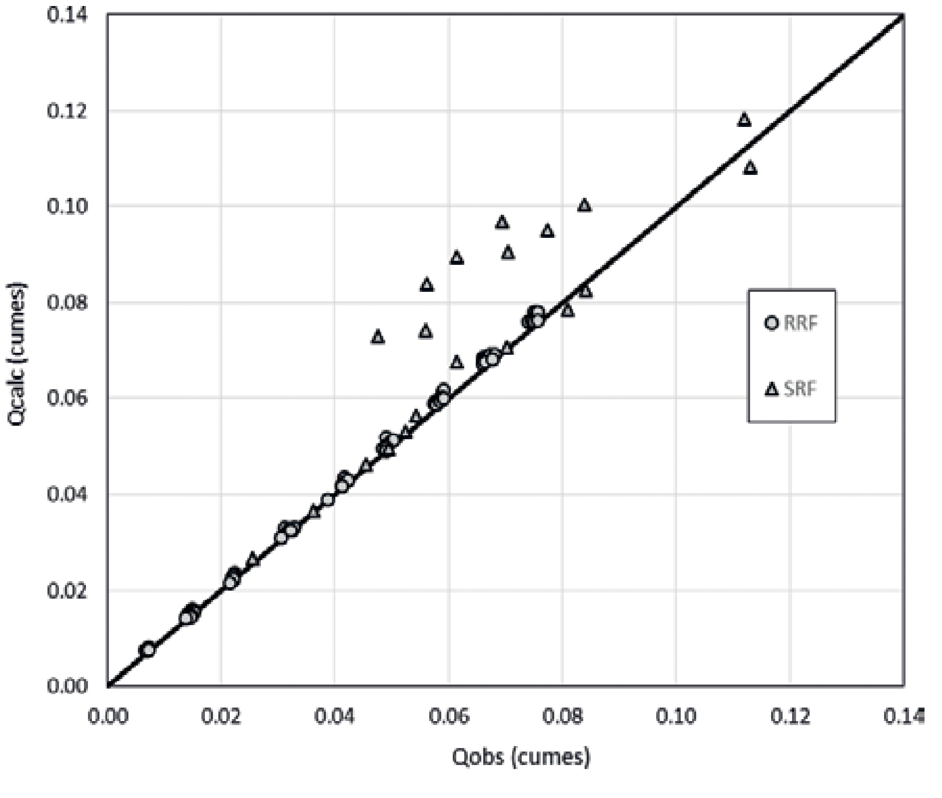

Figure 4. Comparison between the computed (Q_{calc}) and observed (Q_{obs}) discharges.

velocity. Thus, assuming the value of *Φ(M)* equal to 0.9, the mean velocity can be computed and the water discharge as well. The benefit even deals with the reduction of measurement time and costs. On the other side, once performed velocity measurements in a cross section following the above mentioned procedure, the observed value of *Φ(M)* can suggest whether or not some changes in bed roughness occurred.

Finally, the use of the entropy velocity profile gives a robust feedback in terms of operative assessment of water discharge, due to the easy and immediate evaluation of the *M* parameter.

4. Entropy velocity profile approach for rating curve assessment

The wide bulk of measurements obtained through the laboratory experiments allows us to perform a robust analysis in order to obtain suitable information for the use in the operative chain of water discharge assessment as well as in numerical flow dynamics modeling in regular open channel flow.

In Eq. (10), the mean velocity can be evaluated using Manning's formula:

$$U_m = \frac{1}{n} R^{2/3} \sqrt{S_f} \tag{15}$$

where n is the Manning's roughness, R is the hydraulic radius, and Sf is the energy slope.

To determine the maximum velocity of the cross-section, U_{max}, along the y-axis assumed perpendicular to the bottom, the dip-modified logarithmic law for the velocity distribution in a smooth uniform open channel flow, proposed by Yang et al. [8], is considered:

$$u(y) = u_* \left[\frac{1}{k} ln \frac{y}{y_0} + \frac{\alpha}{k} ln \left(1 - \frac{y}{D} \right) \right] \tag{16}$$

where $u^* = \sqrt{g\, R\, S_f}$ is the shear velocity (g = gravity acceleration); k is the von Karman constant equal to 0.41; y_0 is the distance at which the velocity is hypothetically equal to zero; α is the dip-correction factor, depending only on the ratio between the relative distance of the maximum velocity location from the river bed, y_{max}, and the water depth, D, along the y-axis, where U_{max} is sampled.

The location of the maximum velocity, supporting the dip-phenomenon hypothesis, can be obtained by differentiating Eq. (16) and equating d$u/dy = 0$, which gives:

$$\frac{y_{max}}{D} = \frac{1}{1+\alpha} \tag{17}$$

Experimental studies [2–9] have shown that, for channels at different shapes of the cross-section, the velocity maximum is below the free surface around the 20–25% of the maximum depth. Thus, considering y_{max} equal to ¾ of the maximum depth, D, according to Eq. (17), α becomes equal to 1/3. Replacing the value of α in Eq. (16), and after a few algebraic manipulation, the maximum flow velocity can be expressed as:

$$U_{max} = \frac{u_*}{k}\left[ln\left(\frac{3}{4}\frac{D}{y_0}\right) - 0.4621\right] \tag{18}$$

Therefore, inserting Eqs. (15) and (18) in Eq. (10), *Φ(M)* can be expressed in terms of hydraulic and geometric characteristics of a river:

$$\Phi(M) = \frac{\frac{1}{n}R^{2/3}\sqrt{S_f}}{\frac{\sqrt{gRS_f}}{k}\left[ln\left(\frac{3}{4}\frac{D}{y_0}\right) - 0.4621\right]} \tag{19}$$

From this latter equation, a new formulation of Manning's roughness, n_e, based on *Φ(M)* is derived:

$$n_e = \frac{R^{1/6}/\sqrt{g}}{\frac{\Phi(M)}{k}\left[ln\left(\frac{3}{4}\frac{D}{y_0}\right) - 0.4621\right]} \tag{20}$$

Therefore, if *Φ(M)* is available, then Eq. (20) allows us to estimate the *n* value in the cross-section. Replacing Eq. (20) in Eq. (15), the modified form of the Manning's equation is obtained:

$$U_m = \frac{\Phi(M)}{k}\left[ln\left(\frac{3}{4}\frac{D}{y_0}\right) - 0.4621\right]\sqrt{gRS_f} \tag{21}$$

which takes into account the variation of a flow hydraulic and geometric characteristics following the change of the water discharge. Eq. (20) computes Manning's roughness once the values of *Φ(M)* are known and the values of y_0 are calibrated. Once the Manning's coefficient, *ne*, was evaluated, the mean velocity was recalculated according to Eq. (21).

Figure 4 shows the correspondence between *Qcalc*, computed through the Eq. (21), and those observed *Qobs*, for both cases RRF and SRF. The result shows the perfect correlation between the observed and computed values and enforces the use of the proposed Manning's Eq. (20), derived by the entropy velocity theory and the assumption of a constant value of the dip velocity. The approach leads to get water discharge assessment by integrating the information about hydraulic and geometric characteristics of the flow.

Finally, the following **Figures 5** and **6** report the theoretical rating curves obtained by the modified Manning's equation and the experimental data collected for both cases rough and smooth channel.

Defining the standard error, S_e, as suggested by the ISO 1100-2 [28], through the following relationship:

$$s_e = \left[\frac{\sum\left(\ln Q_{obs} - \ln Q_{calc}\right)^2}{N - 2}\right]^{0.5} \tag{22}$$

where N is the number of available measures, the computed S_e is permanently less than 5% for the rectangular rough flow (RRF), while increases up to 15%, with a generalized

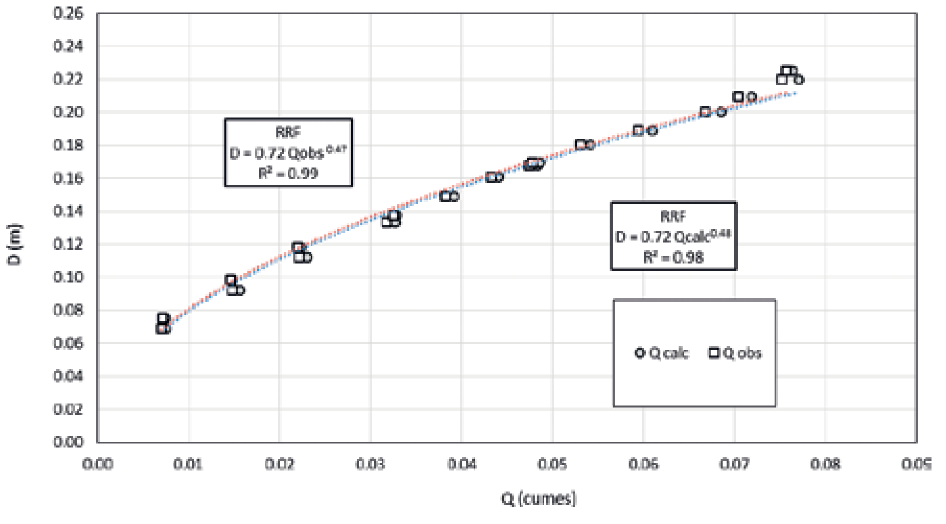

Figure 5. Observed data and calculated rating curves for roughness rectangular flow.

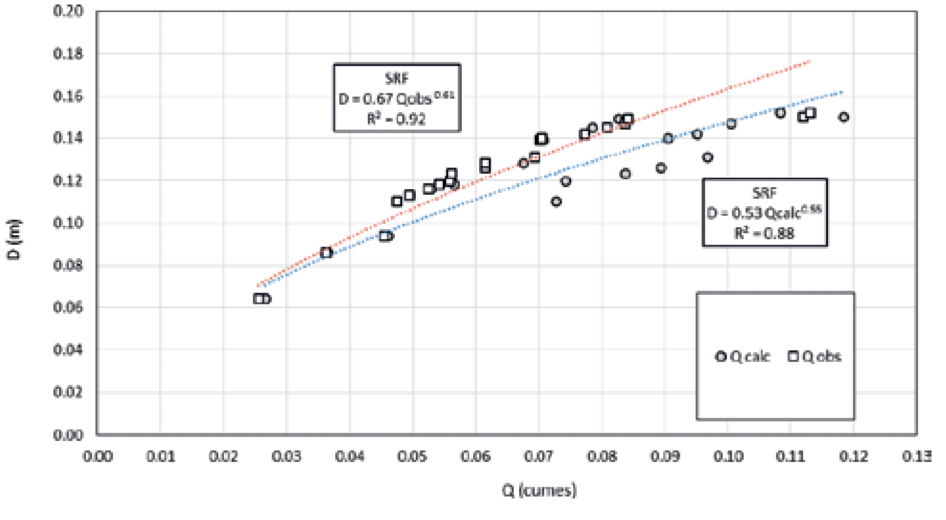

Figure 6. Observed data and calculated rating curves for smooth rectangular flow.

overestimation, in case of smooth rectangular flow. In both cases, the results support the use of this expeditive methodology in the chain of operative procedures leading a good assessment of the rating curve.

5. Conclusion

The use of a rating curve formulation derived from the entropy velocity theory complained to the assumption of a constant value of the dip velocity and taking into account the variables describing the geometric and hydraulic characteristics of a rectangular ditch, should allow us the improvement of water discharge assessment.

This approach was tested, in a first phase, on a suitable data set of water discharge measures collected in the laboratory on both rough and smooth rectangular cross section proposing practical and common flow conditions.

The rating curve evaluation, derived for the rough rectangular flow, underlines a standard error less than 5%, generally, favoring an expeditive assessment of the flow stage with a sufficient level of reliability, while such an error increase up to 15% in case of smooth cross section.

Author details

Greco Michele

Address all correspondence to: michele.greco@unibas.it

1 Engineering School, University of Basilicata, Potenza, Italy

2 Regional Environmental Observatory Research Foundation of Basilicata, Italy

References

[1] Chiu C-L. Entropy and probability concepts in hydraulics. Journal of Hydraulic Engineering, ASCE. 1987;**113**(5):583-600

[2] Chiu C-L. Velocity distribution in open channel flow. Journal of Hydraulic Engineering, ASCE. 1989;**115**(5):576-594

[3] Greco M, Mirauda D, Volpe Plantamura A. Manning's roughness through the entropy parameter for steady open channel flows in low submergence. Procedia Engineering, ISSN 1877-7058, Published by Elsevier Ltd. 2014;**70**:773-780. DOI: 10.1016/j.proeng.2014.02.084. 2-s2.0-84899680421

[4] Greco M, Mirauda D. An entropy based velocity profile for steady flows with large-scale roughness. In: Lollino G, Arattano M, Rinaldi M, Giustolisi O, Marechal JC, Grant G, editors. Engineering Geology for Society and Territory. Vol. 3. Cham: Springer International Publishing; 2015. pp. 641-645. Print; ISBN: 9 978-331909054-2; 978-331909053-5, DOI: 10.1007/978-3-319-09054-2_128, WOS: 000358990300128, EID: 2-s2.0-84944599725

[5] Mirauda D, Greco M, Moscarelli P. Practical method for flow velocity measurements in fluvial sections. WIT Transactions on Ecology and the Environment. 2011;**146**:355-366. ISBN:978-1-84564-516-8 e ISSN 17433541. DOI: 10.2495/RM110301

[6] Moramarco T, Saltalippi C, Singh VP. Estimation of mean velocity in natural channels based on Chiu's velocity distribution equation. Journal of Hydrologic Engineering, ASCE. 2004;**9**(1):42-50

[7] Moramarco T, Singh VP. Formulation of the entropy parameter based on hydraulic and geometric characteristics of river cross sections. Journal of Hydrologic Engineering. 2010; **15**(10):852-858

[8] Yang SQ, Tan SK, Lim SY. Velocity distribution and dip-phenomenon in smooth uniform open channel flows. Journal of Hydrologic Engineering, ASCE. 2004;**130**(12):1179-1186

[9] Greco M. Effect of bed roughness on 1-D entropy velocity distribution in open channel flow. Hydrology Research. 2015;**46**(1):1-10. ISSN 1998-9563, EID: 2-s2.0-84926637541. DOI: 10.2166/nh.2013.122

[10] Bathurst JC, Li RM, Simons DB. Resistance equation for large-scale roughness. Journal of the Hydraulics Division. 1981;**107**(HY12):1593-1613

[11] Shannon CE. A mathematical theory of communication. The Bell System Technical Journal. 1948;**27**:623-656

[12] Tsallis C. Possible generalization of Boltzmann-Gibbs statistics. Journal of Statistical Physics. 1988;**52**(1–2):479-487

[13] Greco M, Moramarco T. Influence of bed roughness and cross section geometry on medium and maximum velocity ratio in open-channel flow. Journal of Hydraulic Engineering. 2016;**142**(1):06015015. DOI: 10.1061/(ASCE)HY.1943-7900.0001064. Article number 0601501 EID: 2-s2.0-84950267443

[14] Chiu C-L, Said CA. Maximum and mean velocity and entropy in open channel flow. Journal of Hydraulic Engineering, ASCE. 1995;**121**(1):26-35

[15] Luo H, Singh V. Entropy theory for two-dimensional velocity distribution. Journal of Hydrologic Engineering. 2011;**16**(4):303-315

[16] Chiu CL, Tung NC. Maximum velocity and regularities in open-channel flow. Journal of Hydraulic Engineering. 2002;**128**(8):803-803

[17] Xia R. Relation between mean and maximum velocities in a natural river. Journal of Hydrologic Engineering, ASCE. 1997;**123**(8):720-723

[18] Nezu I, Nakagawa H. Turbulence in open-channel flows. In: Balkema. The Netherlands: Rotterdam; 1993

[19] Rouse H. Critical analysis of open-channel resistance. Journal of the Hydraulics Division. 1965;**91**(4):1-23

[20] Greco M, Mirauda D. Entropy parameter estimation in large-scale roughness open channel. Journal of Hydrologic Engineering. 2015;**20**(1–2). DOI: 10.1061/(ASCE)HE.1943-5584.00010 09. ISSN: 1084-0699 eISSN: 1943-5584, Article number 04014047, EID 2-s2.0-84921442470

[21] Greco M. Entropy-based approach for rating curve assessment in rough and smooth irrigation ditches. Journal of Irrigation and Drainage Engineering. 2016;**142**(3):04015062. DOI: 10.1061/(ASCE)IR.1943-4774.0000986. EID 2-s2.0-84958758546

[22] Nikmehr S, Farhoudi J. Estimation of velocity profile based on Chiu's equation in width of channels. Research Journal of Applied Sciences, Engineering and Technology. 2010;**2**(5): 476-479

[23] ISO 748. 2007 Hydrometry—Measurement of liquid flow in open channels using current-meters or floats-ISO/TC 113/SC 1 Velocity area methods

[24] Guy HP, Simons DB, Richardson EV. Summary of Alluvial Channel data from flume experiments, 1956–1961, Geological Survey Professional Paper, 1966, 462-I. US Government Printing Office, Washington, DC

[25] Steffler PM, Rajaratnam N, Peterson AW. LDA Measurements of Mean Velocity and Turbulence Distribution in a Smooth Rectangular Open Channel. Edmonton: Department of Civil Engineering., University of Alberta; 1983

[26] Bortz K. Parameter estimation for velocity distribution in open channel flow [M.S. Thesis]. Department of Civil Engineering, University of Pittsburgh: Pittsburgh, PA; 1989

[27] Guo ZR. Personal communication in Chiu and Hsu, 2006. In: Southeast China Environmental Science Institute. China: Yuancun; 1990

[28] ISO 1100-2: 2010 Hydrometry—Measurement of liquid flow in open channels—Part 2: Determination of the stage-discharge relation-ISO/TC 113/SC 1 Velocity area methods

Chapter 3

Irrigation Management Practices and Their Influence on Fruit Agroecosystem

Gaganpreet Kour and Parshant Bakshi

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79569

Abstract

Annual crops are highly sensitive to water stress, so efficient water management in orchards enhance the production and sustainability of fruit cultivation. The performance of fruit tree in terms of fruit yield, fruit size and quality and long term productivity is highly dependent on irrigation and different species respond to it differently, It is known fact that the amount of fresh water available for agriculture use is decreasing and there is a need to use water efficiently either by using water saving irrigation techniques or by scheduling irrigation as per the plant's need. The scheduling of irrigation in fruit crops has gained significant importance for last one decade due to viewed rise in temperature, changing pattern of rainfall and reduction of fresh water for irrigation purposes especially for farmers indulged in fruit culture. The recent research phenology and physiology of the fruit trees in orchard management with major emphasis on water management practices e.g. deficit irrigation can influence an optimal nutrient equilibrium in soil, improve irrigation efficiency and prevent soil erosions. On this basis, work on irrigation scheduling based on evapotranspiration demand was studied in fruit agroecosystem to maintain high yield and quality of fruit crop.

Keywords: peach, fruit crops, evapotranspiration, irrigation intervals and rainfed

1. Introduction

Irrigation is one of the major agricultural activities because the plant production is proportional to water use. It is becoming a limiting factor not only in Indian subtropics but its reduction has been observed globally. The current decrease of predicted water resources are leading to urgent need to adopt a strategy which could be applied to efficiently utilize water without affecting the growth, yield and quality of a plant in agroecosystem. In fruit agroecosystem, sometime introduced plants have different water needs than the ability of ecosystem provide for naturally. The water need of the fruit tree is governed by the annual phenological and soil-water-plant relationship. Fruit trees require frequent irrigation during fruit development and mismanagement of water supply to trees at critical stages leads to fruit drop, reduced fruit size and quality. So, proper irrigation is essential in maintaining a healthy and productive fruit orchard. Whereas over irrigation slow root growth, increases the potential for iron chlorosis in alkaline soils, and leaches nitrogen, sulfur and boron out of the root zone leading to nutrient deficiencies. It can also induce excessive vegetative vigor. Excessive soil moisture also provides an ideal environment for crown and collar rots in peach. On the other hands applying insufficient irrigation water results in drought stress and reduced fruit size and quality [1]. Many studies on irrigation management under different agroecological system on fruit crops e.g. peach [2–4], cherry [5], pummelo [6], olive [7, 8] and mango [9] reported that moderate water restriction do not effect morphological and physiological processes of tree. In fact, enhance the bearing, maturation and fruit tree features.

In irrigated agroecosystem, irrigation systems have been under pressure to produce more with lower supply of water. Majority of developed/developing countries implement technological, economical and regulative irrigation strategies for efficient use of hydro-resources and reusing wastewater in agriculture sector. Decreased water due to global warming along with uneven rainfall patterns have increased the requirement of optimum and efficient use of irrigation by means deficit irrigation practices. Deficit irrigation supplies reduced water volume depending upon evapotranspiration (Et) percentage throughout fruit crop irrigation season with the minimal impact on fruit production. Evapotranspiration is key factor in irrigation scheduling as a management tool, Et (actual, potential and reference) rate either directly measured or indirectly estimated are of crucial importance for determining crop water requirement. Among numerous indirect methods for Et estimation, initial Penman equation is probably the most modified one. Modified Penman-Monteith approach is the most used mathematical approach for Et determination accepted by research as well as in practice of water management and planning. The P-M method can be successfully applied for Et calculations and water management in field conditions [10].

2. Irrigation management practices, vegetative growth and fruit productivity

Considerable changes in weather and water availability during the last decade as expected, caused increase in temperature, frequencies and durations of summer drought events with changing precipitation patterns leading to enhanced rainfall during winter and spring, thereby adversely affecting the physiological performance, growth and competitive ability of trees [11]. Thus, the aim of this study was to understand the response of peach tree's morphological and biochemical characteristics, by supplying irrigation at T1 = 20 mm potential Et (PET), T2 = 30 mm potential Et (PET), T3 = 40 mm potential Et (treatment trees mulched with straw mulch), T4 = 50 mm potential Et (PET). The maximum soil water availability of the soil was 80 mm. The growth and quality characteristics of peach cultivars cultivated under rainfed conditions (control) were also evaluated. Irrigation water requirements (IWRs) for peach crop was calculated by subtracting effective rainfall (calculated using the CROPWAT Programme, [12]) from Etc, without taking account of the variation in soil water content during both experimental year. Estimation of crop coefficients (Kc1 = 0.20, Kc2 = 0.5, Kc3 = 0.7, Kc4 = 1.0) mean values given by [13] were used. Et requirement by the crop has been computed using the equation: Etc = Kc × Eto.

2.1. Effect of different irrigation levels on vegetative growth of crop

Water stress significantly reduces trunk growth and shoot extension growth of peach tree [14], so both vegetative characters was closely linked to irrigation volume and showed significant differences when compared under different trials. Shoot extension growth was measured on weekly bases, while trunk girth development measured at 15 days intervals in all the treatments. In both the year of study maximum trunk girth and shoot extension growth was attained by plants irrigated at 40 mm PET level, whereas minimum trunk girth and shoot extension growth observed under rainfed condition (**Figures 1** and **2**). Peach shoot growth reduced in proportion to the magnitude of the water deficit and with the replacement of 12.5% of the evaporation, there was more than 75% reduction in shoot weight [15]. Shoot growth and limb diameter were limited whenever water supply was restricted in Merrill Sundance cultivar of peach [16]. Water stress affected the growth and dry matter partitioning of young peach trees, whereas total dry matter production reduced with each incremental decrease in applied water and attributed to lower leaf conductance in the unirrigated conditions. Reduction or halting of lateral branching and new leaf production soon after water stress is the major factor that contributes to differences in tree biomass production [17]. Regulated deficit irrigation applied at stage II as well as combined regulated irrigation at stage II and postharvest stage

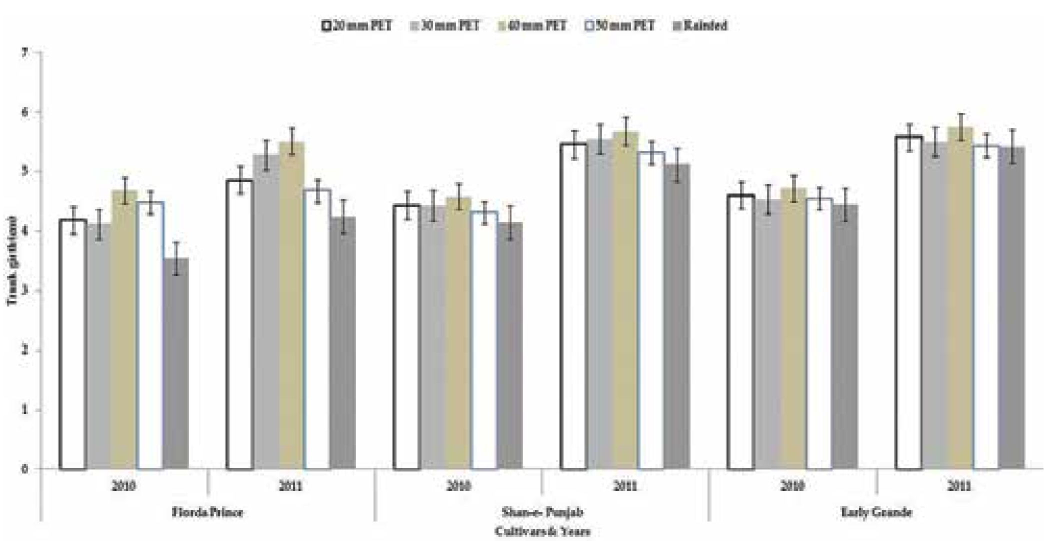

Figure 1. Effect of irrigation on trunk girth of peach cultivars.

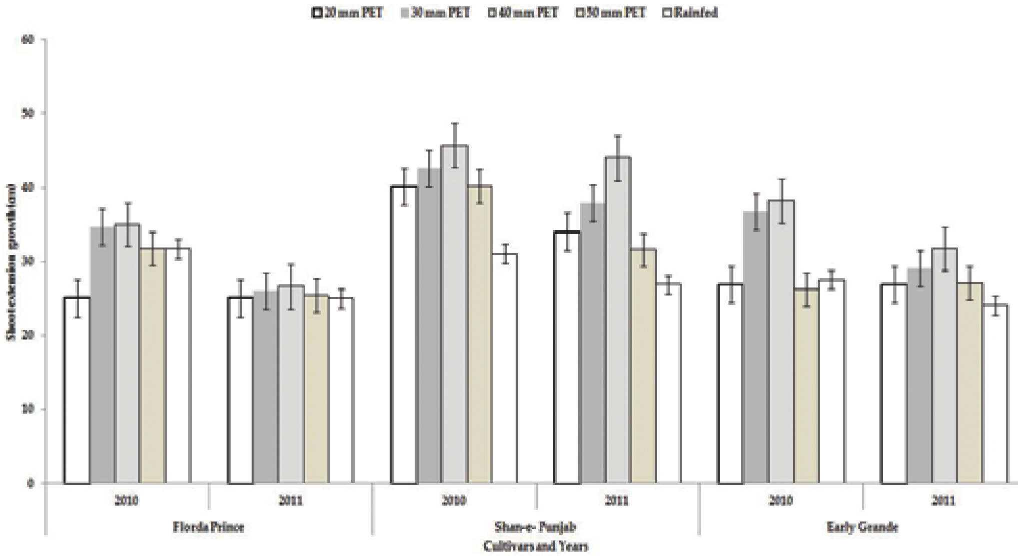

Figure 2. Effect of irrigation on shoot extension growth of peach cultivars.

reduced length of the shoots (>75 cm) inside the canopy in clingstone peaches [18]. Similarly, peach tree had reduced trunk radial growth and canopy shaded area when no irrigation was provided to the trees as compared to irrigated ones [19]. The range of maximum daily shrinkage was more pronounced in non-irrigated than the irrigated peach trees, because development of unirrigated plants was probably impaired by low values of stomatal conductance and CO_2 assimilation [20]. Trunk growth was maximum in 75% Etc based irrigation, followed by 50 and 25% Etc-based irrigation as compared to unirrigated in Larnaka pistachio [21]. Supplemental irrigation substantially increased trunk cross sectional area (TCA) of 1-year old Red Globe cultivar of peach as compared to tree supplied with no irrigation, whereas unirrigated trees were smaller than irrigated trees because of a lack of sufficient annual rainfall [22], a reduced increase in trunk diameter was observed due to limiting xylem deposition. The irrigated "Doyenne du Comice" pear trees had better trunk diameter development than water stress trees, with the intensification of water stress, there was a decrease in trunk fluctuations in non-irrigated rootstocks and related it to the low pluviometric precipitations and high ambient temperatures, which occurred at the time of experiment [23]. In grapefruit maximum relative growth of the trunk diameter at irrigation applied on 15 days with 1.00 pan evaporation (23% above the graft and 28% below the graft), whereas minimum relative growth rates, (10% above the graft and 12% below the graft), were observed in irrigation applied at 25 days interval with 1.00 pan evaporation [24]. Gemlik cv. of olive had highest trunk section area and canopy volume under full irrigation treatment at 100% evapotranspiration along with application of 400 g/tree phosphorous during initial developmental stage, potassium (500 g/tree) before endocarp hardening, and Nitrogen (40 g/tree) applied during each irrigation period. Canopy volume increased up to 10% with full irrigation treatment at 50% evapotranspiration and 25% with full irrigation at 100% evapotranspiration compared to rainfed conditions, whereas under full irrigation treatment at 50% evapotranspiration and full irrigation at 100% evapotranspiration 8 and 14% more trunk section area was recorded respectively [25]. Increased diurnal shrinkage of trunk in trees which did not get any irrigation over course of postharvest season reflected the progressive reduction in water potential. In a sub-humid climate, 'Z-900'/Gisela 5 young dwarf cherry trees had maximum values in terms of trunk cross-sectional area and volume of trees when irrigation was applied at 125% evaporation as compared to irrigation based on 75% pan evaporation wherein smallest trunk cross-sectional area was obtained [26].

2.1.1. Transpiration

Among the indicator used for monitoring water status transpiration is reliable, because transpiration and crop yield is linearly related in areas with higher solar radiations. The transpiration rates trends observed for all cultivars in 2010 and 2011 appeared to be mainly a function of the climatic factors in the different stages of growth. Rate of transpiration was low during 2010 due to moderate drought conditions (**Figure 3**). Overall transpiration rate in 2011 was higher at fruitset, maturity and post harvest in all irrigation levels as well as under rainfed conditions, whereas less transpiration rate in fruitset stage from plants irrigated at 20 mm Etc level. Similarly, the rate of transpiration was highest in well watered mango plants compared to the extremely stressed plants [27]. Small transpiration differences between control and irrigated or fertigated treatments which might be due to early season irrigation in grape Concord and Niagara vineyard observed [28]. Among various peach cultivars, Early Grande and Florda Prince transpired more at post harvest stage during both the years, whereas Shan-e-Punjab transpired more at maturity stage in 2010 and at post harvest stage in 2011. The variability was due to increased natural moisture because of rainfall during April and May.

2.1.2. Leaf area and traits

Fruit productivity is closely related to rate of leaf area development. As the amount of absorption of photosynthetically active radiation and dry matter accumulation depends on the area of leaf. Larger the leaf area, more the PAR is absorbed by plant and more dry matter accumulated, water is main factor responsible for leaf area development [29]. Thus, the purpose of study to understand the impact of irrigation on leaf area in low chilling peach cultivars. Leaf area in peach plant significantly increased with higher irrigation levels, however maximum leaf area recorded in plants irrigated at 30 mm PET level, due to better root establishment, efficient photosynthesis and production of more assimilates. Leaf area reduced in plants grown under rainfed conditions and irrigated at 50 mm PET level (**Figure 4**). Similarly, Korona cultivar of strawberry plants which received cent per cent water (100% water) supply differed significantly as compared to the water stressed plants, in terms of leaf expansion during fruit ripening [30]. The large reduction in leaf area with long term water stress is caused by a lower leaf elongation rate and earlier abscission of the old leaves. Whereas, Dashehari mango trees irrigated at 20 and 40% depletion of available soil moisture attained more spread and leaf area than those irrigated at 60% depletion of ASM and unirrigated [31]. In Thompson seedless cultivar of grape plant leaf area was higher in plants irrigated through drip irrigation followed by furrow irrigation than stressed plant [32]. Bell pepper had higher leaf area under irrigation applied after 3 days interval [33]. 16.8 laterals with leaf area of 122 cm^2/leaf, and leaf biomass

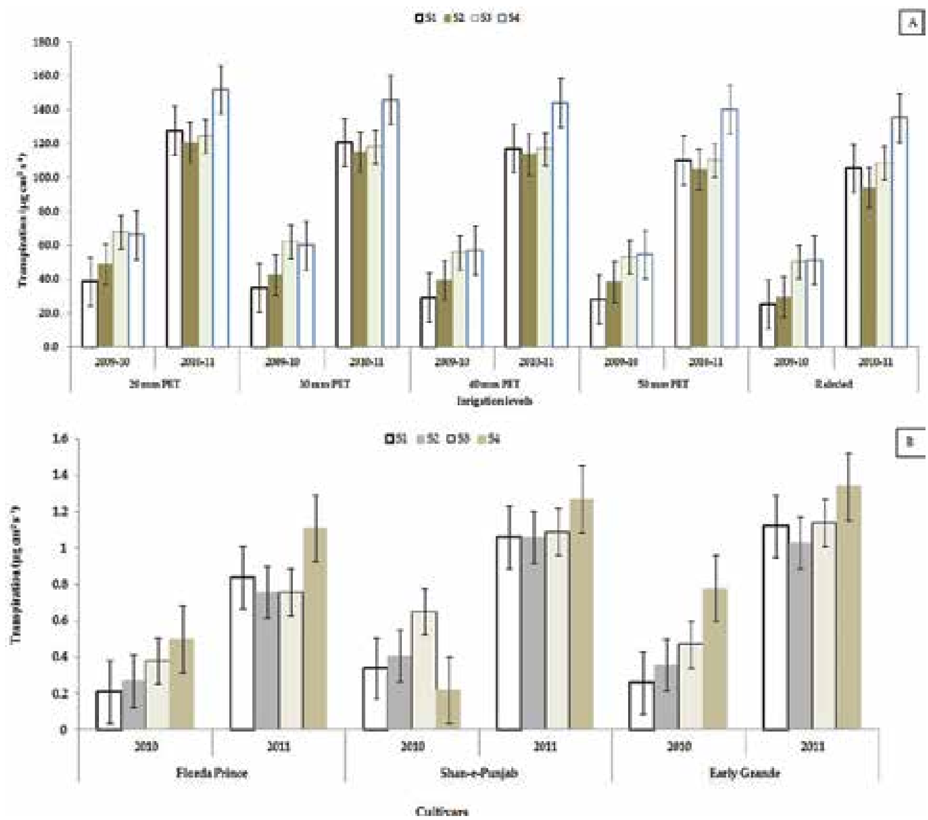

Figure 3. Graph showing average transpiration (a) in different irrigation levels (b) in three cultivars of low chilling peach at different stages of growth and development (stage 1: Fruitset, stage 2: Pit hardening, stage 3: Maturation and stage 4: Postharvest).

of 2.4 g/leaf was recorded when 20 L water was applied as compared to 2.5 L water application in purple passion fruit, wherein 11.3 laterals with leaf area of 106.5 cm^2/leaf and leaf biomass of 2.0 g/leaf was obtained [34]. Highest irrigation level of 15 m^3/tree/year increased leaf area, while lowest irrigation level of 7 m^3/tree/year decreased leaf area in 20-year old pomegranate trees [35].

2.1.2.1. Stomatal density

Stomatal features are known to affect transpiration, moderate water deficits had positive effects on stomatal number, but more sever deficits led to a reduction. The stomatal size obviously decreased with water deficit and stomatal density was positively correlated with stomatal conductance (gs), net CO_2 assimilation rate and water use efficiency [36]. Stomatal density of peach cultivars was maximum at 40 mm PET and 30 mm PET levels, whereas reduced stomatal density was recorded in plants grown under rainfed conditions as well as plants irrigated at 50 mm PET. The reduced stomatal density under stress conditions might be due to adaptation of plant to reduced water loss and cell division under certain degree of water stress, while stomatal density under surplus soil moisture conditions might be due to

http://dx.doi.org/10.5772/intechopen.79569

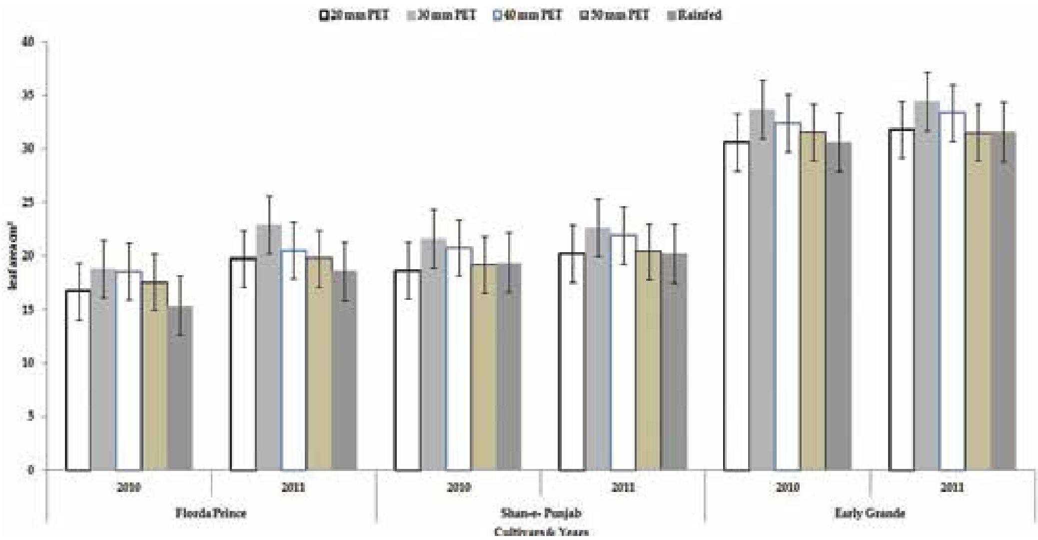

Figure 4. Leaf area development under different irrigation levels.

difference in stomatal number and size. Leaves from peach seedlings grown under both water stress and saturation conditions changed stomatal aperture and density as compared to leaves of seedling which received proper moisture [37], while water stress induced approximately 35% reductions in stomatal density in peach seedlings which is plant adaptation to water deficit conditions and lack of significant difference between stomatal density of leaves grown with excess and adequate soil moisture be caused primarily due to variation in stomatal number in each leaf. Stomatal density in 6-year-old apple was minimum under permanently irrigated trees and maximum in unirrigated trees, [38] concluded that stomatal density appeared to be predominantly affected by water status of the apple tree during vegetative growth period in spring. Hybrid peach seedling rootstocks (S-21, 42, 46, 47, 51 and 52) had highest stomatal density in soil moisture raised to 25% of the field capacity once in a week through irrigation and in saturated soil with irrigation once in a week, while lowest stomatal density was found in tree leaves when soil moisture was raised to 50 and 75% of the field capacity once in a week [39].

2.1.2.2. Chlorophyll content

Green color pigment chlorophyll is a light capturing molecule in photosystem and one of the key factors influencing photosynthetic capacity. Chlorophyll content in leaves was considered as a trait for crop production, drought stress during growth is negatively correlated with chlorophyll pigment in plants. Chlorophyll content of water-saturated grown peach leaves was minimum than that of leaves grown under stress and adequate soil moisture which attributed to the destruction or inhibition of chlorophyll synthesis in the leaves which resulted from water saturation conditions. In another study, [40] chlorophyll content of peach leaves from effluent treated watered trees was significantly higher than that of tree leaves from unirrigated, which could have been due to the significant increase in mineral contents, particularly Fe and N in effluent treated leaves. The chlorophyll content in peach leaves was another factor which was affected by the irrigation levels during the present investigation. Highest total chlorophyll content was in plants irrigated at 40 mm PET level and 30 mm PET. Reduced in plants irrigated at 20 mm PET and 50 mm PET as well as in plants under rainfed conditions. Decreased chlorophyll content under drought or water stress condition in Nectarin-8 cultivar reported [41]. Total chlorophyll content decreased with increased water stress among different rootstocks of grapes. The maximum total chlorophyll content was in 1103P leaves under water stress [42]. Similarly, in 6 months old mango rootstock seedlings, slight increase in chlorophyll content under water stress conditions, because chlorophyll A was more resistant to dehydration; it increased slightly with water stress, as compared to chlorophyll B, which remained constant, however slight increase in total chlorophyll under water stress suggest that the chlorophyll pigments in leaves were somewhat resistant to dehydration [27]. Chlorophyll A,B, and total chlorophyll reduced under drought stress conditions [43]. Leaves total chlorophyll content was higher under irrigation compared with rainfed condition in fig [44].

2.2. Fruit yield and quality

The sensitivity of fruit growth to soil water availability has been well documented, fruit growth depend on the accumulation of large quantities of osmotically active solutes and massive cell expansive growth and these processes require carbohydrates and its restriction under water-stressed crop decrease ability to accumulate water [14]. Maximum fruit size in peach was attained in the plants irrigated at 40 mm PET level as compared to fruit taken from plants provided with irrigation at different levels of evapotranspiration. However, the main contributed parameter in fruits, which was influenced by different levels of irrigation, is found to be diameter of the fruits in the present study. Bigger fruits harvested from the plant might be due to fulfillment of water requirement of that plant at that particular level of irrigation which in turn resulted into larger cell size rather than increase in the cell number and this cell expansion might have resulted in better uptake of mineral nutrient. In the present investigation, under water deficit condition, fruit size decreased probably due to reduction in availability of assimilate and lower stomatal conductance, whereas surplus water condition might have led to anaerobic conditions and reduced water and nutrient uptake, thus reduced the fruit size. Reduction observed in fruit weight of Nijisseiki Asian pear in late stress conditions compared to the well watered tree [45], whereas highest fruit weight under optimum irrigation and light water stress reported in Big-Top cv. of peach and the lowest average soluble solids percentages under water stress. When light water stress was applied; soluble solids percentages appeared to slightly decrease while peach weight remained relatively constant [46]. Peach fruit size increased with irrigation compared to no irrigation [47]. Water stress improved fruit size by 37% in low-chill peach cv. Florda Prince [48]. Nectarine fruit size distribution was shifted towards larger fruit with increased level and with decrease in crop load [49]. Larger fruit size in pear trees irrigated at amount 30% below (T 70, 1.7 × control irrigation rate) a presumed optimum rate (daily irrigated, control) of water than tree irrigated at 30% above (T130, 1.3 × control irrigation rate) or daily irrigated trees (control) [50]. Under regulated deficit irrigation, bigger average fruit size and a more favorable fruit size distribution in Chok Anan cultivar of mango was recorded [51]. In purple passion the fruit weight of 6016 g/plant was obtained from 20 L irrigation, which was greater than plants received 2.5 L water (505.5 g/plant) [34]. Pineapple fruit weight increased with irrigation volumes of 0.2, 0.3 and 0.4 pan evaporation, while irrigation volumes affected the polar and equatorial diameter of pineapple fruits with smallest fruit diameters in 0.1 pan evaporation (8.07 and 5.15 cm, respectively) as compared to other irrigation volumes [52]. The irrigation increases peach quality depending on the amount of water applied, cultivar and environmental conditions. The results of this study showed higher total soluble solids content in fruits harvested from plants under deficit water, while total soluble solids was lower in fruit from plant grown under optimum or excessive level of water and fruits from plants grown under rainfed conditions. Active increase in total soluble solids in the fruit by osmotic adjustment in low water level might be the mechanism through which the plant could have compensated for decrease in turgor potential and consequently attenuated the decrease in fruit growth, whereas decreased Total soluble solids under increased soil moisture might be due to dilution of the soluble solids under higher water content in fruit. Further studies on deficit irrigation and stress conditions revealed increased total soluble solids at harvest in 'O' Henry peaches as compared to optimum or fully irrigated trees [53–55, 65]. Increased level of total soluble (TSS) in Mihowase Satsuma under deficit irrigation compared to fruit grown under normal irrigation level with slight influence on peel color, titratable acidity (TA) and TSS/TA ratio was observed [56]. On other hand higher total soluble and glucose and fructose concentration obtained in the irrigated vines of Tempranillo grapes than in the unirrigated vines [57]. Andross cv. of peach had higher soluble solid content (12^{o}Brix) under regulated deficit irrigation during stage II of fruit growth [2, 58], and also increased fruit firmness and total soluble solid under deficit irrigation during stage 3rd of growth observed [59] with higher total soluble solids and titratable acidity, coupled with small decreases in maturity index in citrus under deficit irrigation [60]. Total soluble solids in peach fruit increased under high water restriction as compared to control and light water restriction [61].

Relationship between water and yield demonstrated that in well watered cv. Ëlegant Lady "peach plants, tree water status is independent of crop load, whereas drought stress level increased with increasing crop load in trees receiving reduced irrigation [14]. The experiment conducted determine the yield response of the crop to different irrigation intervals. On an average maximum yield/plant was recorded when irrigation was applied at 40 mm PET level, in comparison to all treatment yield/plant was recorded lowest under rainfed condition. However, a significant decrease was noticed during the second year of the experimentation. Similarly strawberry yield reduced in water stressed plants because of a decreased mean fruit weight mainly caused by the reduction in individual fruit size [30]. Water restriction at stage III in peach reduced yield [20]. Pear-jujube yield under moderate and sever water deficit treatments at bud burst to leafing and fruit maturation stages increased fruit yield. Fruit yield under low water deficit at fruit growth and fruit maturation stages was similar to that of full irrigation treatment [62]. Yield comparison in case of variety Shan-e-Punjab had similar yield under different irrigation levels including rainfed treatment. Rainfall pattern in the second season is optimal for this cultivar needing least irrigation. Rainfall during sprouting phase gave positive response and rainfall during flowering phase gave negative response to yield and quality [63]. **Figure 5** represents yield (kg/plant) response of three peach cultivars to seasonal water use under different irrigation levels. Seasonal Etc (mm) of peach cultivars treatment wise in season first (2010) T1 = 202 mm, T2 = 168 mm, T3 = 127 mm, T4 = 121 mm & season second (2011) T1 = 216 mm, T2 = 173 mm, T3 = 158 mm, T4 = 152 mm.

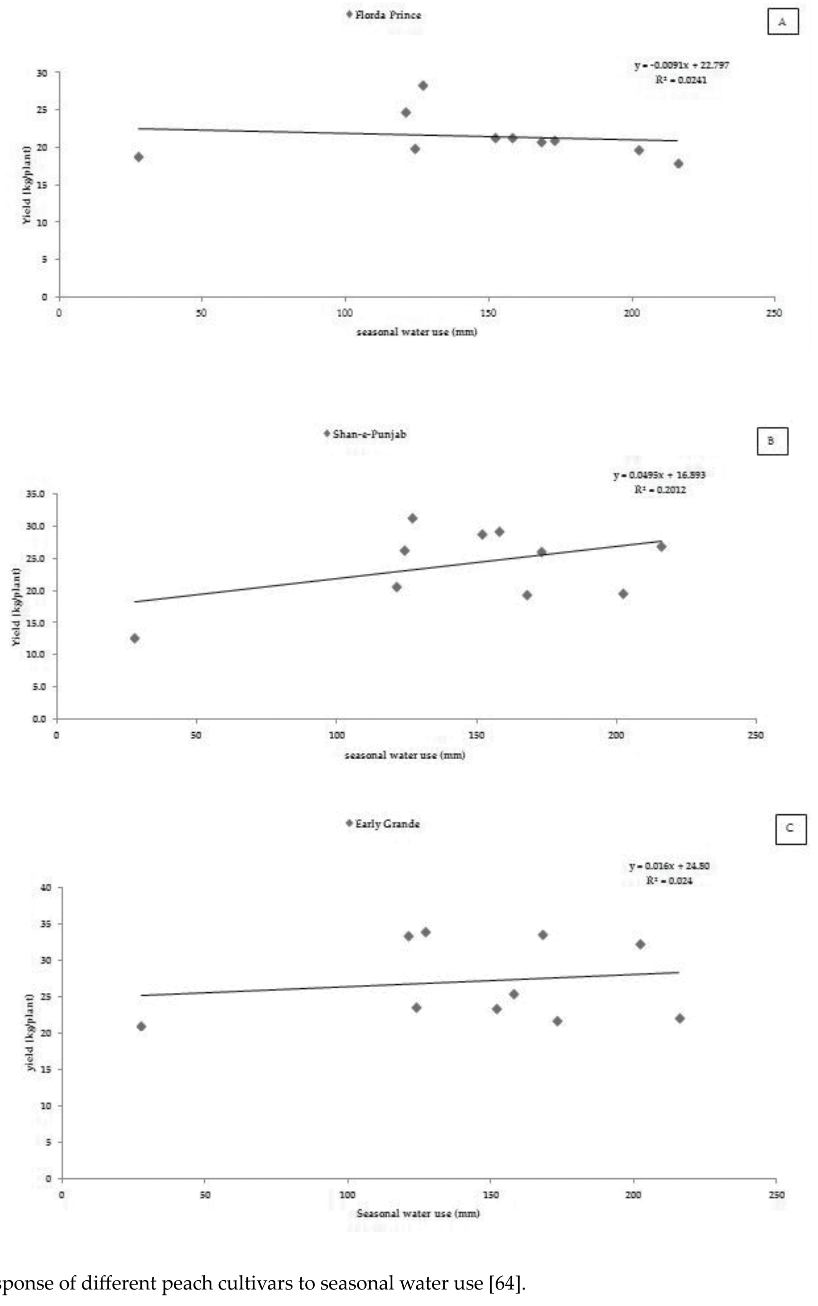

Figure 5. Response of different peach cultivars to seasonal water use [64].

3. Conclusion

Irrigation water is costly to farmers in most of the agroecosystem nowadays. The increasing environmental emergencies related to water scarcity, severely affected the performance of fruit plants in term of growth, yield, quality, storability and long term productivity. With an innovative and sustainable irrigation management, the effect of these environmental emergencies can be reduced. In fruit growing areas of world, environmental vagaries causes conditions like reduction of soil organic matter, groundwater contamination, soil deficiency of mineral elements (in particular phosphorus and nitrogen), alkalinization/salinization and nutritional imbalances in plants. As experimental works highlighted in this chapter, on morphological and biochemical characters (directly affected by water shortage) of fruit trees in orchards have revealed that sustainable and innovative irrigation management, with a particular emphasis on reduce irrigation, allow to obtain an optimal plant nutritional equilibrium, reduce nutrients leaching risks, improve irrigation efficiency and prevent soil erosion. The deficit irrigation technique based on reference evapotranspiration in fruit orchards are indispensable need for preserving tree quality and maintaining high yield and quality. With these information a fruit farmer can be informed of the field water loss occurring after the last rain or irrigation and taking into consideration the expected advised on the timing and quantum of irrigation. Optimization and innovation of sustainable irrigation technique with a low negative environmental impact, represent a major change in fruit agroecosystem by reducing needs or increase efficiency of water use and also enhance the value of water within ecosystem.

Acknowledgements

I express deep sense of gratitude to Dr. M.K. Khushu (Chief Scientist) and Dr. Mahendra Singh, (Associate Professor), Agrometeorology for their valuable suggestion and providing weather station and laboratory facilities at Agrometeorology Centre during the entire course of my research work.

Author details

Gaganpreet Kour* and Parshant Bakshi

*Address all correspondence to: gaprit05@gmail.com

Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu,
Jammu and Kashmir, India

References

[1] Black B, Hill R, Cardon G. Orchard Irrigation: Peach. Horticulture/Fruit/2008-02pr

[2] Gelly M, Recasens I, Girona J, Mata M, Arbones A, Rufut J, Marsal J. Effect of stage II and post harvest deficit irrigation on peach quality during maturation and after cold storage. Journal of the Science of Food and Agriculture. 2004;**84**:561-568. DOI: 10.1002/isfa.1686

[3] Larson KD, Dejong TM, Johnson RS. Physiological and growth responses of mature peach trees to post harvest water stress. Journal of the American Society for Horticultural Science. 1988;**113**(3):296-300

[4] Sofo A, Palese AM, Casacchia T, Dichio B, Xiloyannis C. Sustainable fruit production in Mediterranean orchards subject to drought stress. In: Ahmad P, Parsad M, editors. Abiotic Stress Responses in Plants. New York, NY: Springer; 2012. pp. 105-129. DOI: 10.1007/987-1-0635-1_6

[5] Yazgan S, Buyukcangaz H, Demirtas C, Candogan BN. Evapotranspiration for young cherry trees (*Prunus avium*) and growth responses to irrigation. Pakistan Journal of Biological Sciences. 2006;**9**(1):39-44

[6] Halder NK, Shaha MK, Fazlul Kabir AHM, JillurRahman MD, Zahurul Islam MD. Effect of lime and irrigation on the yield performance of pummelo (*Citrus grandis*) in the hilly region. Pakistan Journal of Biological Sciences. 2003;**6**(3):246-248

[7] Inglese P, Barone E, Gullo G. The effect of complementary irrigation on fruit growth, ripening pattern and oil characteristics of olive (*Olea europaea* L.) cv. Carolea. Journal of Horticultural Science. 1996;**71**(2):257-263. DOI: 10.1080/14620316.1996.11515404

[8] Proietti P, Antognozzi E. Effect of irrigation on fruit quality of table olives (*Olea europaea*) cultivar 'Ascolana tenera'. New Zealand Journal of Crop and Horticultural Science. 1996;**24**:175-181. DOI: 10.1080/01140671.1996.9513950

[9] Nasir MA, Mian IUH. Mango yield and quality as affected by irrigation intervals. Pakistan Journal of Agricultural Research. 1993;**14**(4):324-328

[10] Ondrasek G. Water scarcity and water stress in agriculture. In: Ahmad P, Wani MR, editors. Physiological Mechanism and Adaptation Strategies in Plant under Changing Environment. Vol. 1. New York/Dordrecht/Heidelberg/London: Springer; 2014. pp. 75-96

[11] Kreuzwieser J, Gessler A. Global climate change and tree nutrition: Influence of water availability. Tree Physiology. 2010;**30**:1221-1234. DOI: 10.1093/treephys/tpq055

[12] Smith M. CROPWAT—A computer program for irrigation planning and management. FAO Irrigation and Drainage; Paper 46, Rome; 1992. 126pp

[13] Dorenbos J, Pruitt WO. Crop water requirements-guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24. 1984 FAO, Rome

[14] Berman M, Dejong TM. Water stress and crop load effects on fruit flesh and dry weight in peach (*Prunus persica*). Tree Physiology. 1996;**16**:859-864

[15] Chalmers DJ, Mitchell PD, Jerie PH. The relation between irrigation, growth and productivity of peach trees. Acta Horticulturae. 1985;**173**:283-288. DOI: 10.17660/Acta Horti. 1985. 173.32

[16] Li SH, Huguet JG, Schoch PG, Orando P. Response of peach tree growth at various phonological stages of fruit development. Journal of Horticultural Science. 1989;**64**(5): 541-552

[17] Steinberg SL, Miller JC, Mcfarland MJ. Dry matter partitioning and vegetative growth of young peach trees under water stress. Australian Journal of Plant Physiology. 1990; **17**(1):23-36. DOI: 10.1071/PP9900023

[18] Sotiropoulos T, Kalfountzo D, Aleksiou I, Kotsopoulos S, Koutinas N. Response of a clingstone peach cultivar to regulated deficit irrigation. Scientia Agricola (Piracicaba, Braz). 2010;**67**(2):164-169. DOI: 10.1590/s0103-90162010000200006

[19] Johnson RS, Handly DF, Dejong TM. Long term response of early maturing peach trees to post harvest water deficits. Journal of the American Society for Horticultural Science. 1992;**117**(6):881-886

[20] Remorini D, Massai R. Comparison of water status indicators for young peach trees. Irrigation Science. 2003;**22**:39-46. DOI: 10.1007/s00271-003-0068-4

[21] Monastra F, Avanzato D, Martelli S, Dascanio R. Pistachio trial under different volumes of irrigation in Italy. Acta Horticulturae. 1995;**419**:249-252. DOI: 10. 17660/Acta Hortic.1995.419.40

[22] Layne DR, Cox DB, Hitzler EJ. Peach systems trail: The influence of training system, tree density, rootstock, irrigation and fertility on growth and yield of young trees in South Carolina. Acta Horticulturae. 2002;**592**:367-375. DOI: 10.17660/Acta Hortic.2002.592.51

[23] Giacobbo CL, Fachinello JC, Massai R, Remorini D, Loreti F. Growth and productive behavior of 'Doyenne du Comice' pear trees grown on two rootstocks and two regimes. Acta Horticulturae. 2008;**800**:785-792. DOI: 10.17660/Acta hortic.2008.800.107

[24] Kanber R, Koksal H, Yazar A, Ozekici B, Onder S. Effects of different irrigation programmes on fruit, trunk growth rates, quality and yield of grapefruit trees. Turkish Journal of Agriculture and Forestry. 1999;**23**:401-411

[25] Toplu C, Onder D, Onder S, Yildiz E. Determination of fruit and oil characteristics of olive (*Olea europaea* L. cv. Gemlik) in different irrigation and fertigation regimes. African Journal of Agricultural Research. 2009;**4**(7):649-658

[26] Candogan BN, Yazgan S. The effects of different irrigation levels on vegetative growth of young dwarf cherry trees in a sub-humid climate. Pakistan Journal of Botany. 2010; **42**(3):3399-3408

[27] Luvaha E, Netondo GW, Ouma G. Physiological responses of mango (*Mangifera indica*) rootstock seedlings to water stress. Journal of Agricultural and Biological Science. 2007; **2**(4-5):6-12

[28] Reynolds AG, Lowrey WD, Savigny CD. Influence of irrigation and fertigation on fruit composition, vine performance and water relations of Concord and Niagara grapevines. American Journal of Enology and Viticulture. 2005;**56**(2):110-128

[29] Gigova A, Moteva M, Mitova T, Kostadinov G. Irrigation impact on leaf area and net photosynthetic productivity of Canola. In: Proceedings of the 5th International Conference on Trends in Agricultural Engineering (TEA-2013); 3-6 September, 2013; Prague Czech Republic; 2013. pp. 173-180

[30] Gehrmann H. Growth, yield and fruit quality of strawberries as affected by water supply. Acta Horticulturae. 1985;**171**:463-469. DOI: 10.17660/ActaHortic.1985.117.44

[31] Chandel JS, Singh R. Effect of different irrigation levels on growth, cropping and mineral composition of mango (*Mangifera indica* Linn.). Acta Horticulturae. 1992;**321**:561-565. DOI: 10.17660/Acta Hortic.1992.321.64

[32] Araujo F, Walliams LE, Matthews MAA. Comparative study of young 'Thompson Seedless' grapevines (*Vitis vinifera* L.) under drip irrigation and furrow irrigation II. Growth, water use efficiency and nitrogen partitioning. Scientia Horticulturae. 1995; **60**:251-265. DOI: 10.1016/0304-4238(94)00711-w

[33] Khan MUH, Chattha TH, Saleem N. Influence of different irrigation intervals on growth and yield of bell pepper (*Capsicum Annuum* Grossum Group). Research Journal of Agriculture and Biological Sciences. 2005;**1**(2):125-128

[34] Gaturuku JK, Isutsa DK. Irrigation and mulch significantly enhance yield but not quality of purple passion fruits. ARPN Journal of Agricultural and Biological Science. 2011; **6**(11):47-53

[35] Khattab MM, Shaban AE, El-Shrief AH, El-Deen Mohamed AS. Growth and productivity of pomegranate trees under different irrigation levels I: Vegetative growth and fruiting. Journal of Horticultural Science & Ornamental Plants. 2011;**3**(2):194-198

[36] Xu Z, Zhou G. Response of leaf stomatal density to water status and its relationship with photosynthesis in a grass. Journal of Experimental Botany. 2008;**59**(12):3317-3325. DOI: 10.1093/jxb/ern185

[37] Basiouny FM. Response of peach seedlings to water stress and saturation conditions. Proceedings of the Florida State Horticultural Society. 1977;**90**:261-263

[38] Elias P. Stomata density and size of apple trees growing in irrigated and non-irrigated conditions. Biologia Bratislava. 1995;**50**(1):115-118

[39] Sharma N, Sharma SD, Kumar D. Selection of stone fruit rootstock for drought tolerance and amenability to clonal multiplication. Biological Forum: An International Journal. 2009;**1**(1):36-46

[40] Basiouny FM. The use of municipal treated effluent for peach tree irrigation. Proceedings of the Florida State Horticultural Society. 1984;**97**:345-347

[41] Kaynas N, Eris A. The effects of soil water deficits on biochemical changes of some nectarine cultivars. Turkish Journal of Agriculture and Forestry. 1998;**22**:35-41

[42] Kadam JH, Tambe TB, Kaledhonkar DP. Effect of irrigation regimes on chlorophyll content and chlorophyll stability index in different grape rootstock. Indian Journal of Horticulture. 2005;**62**:3293-3295

[43] Javadi T, Arzani K, Ebrahimzadeh H. Study of proline, soluble sugar and chlorophyll A and B changes in nine Asian and one European pear cultivar under drought stress. Acta Horticulturae. 2008;**769**:241-246. DOI: 10.17660/ActaHortic.2008.769.34

[44] Al-Desouki MI, Abd EL-Rheman IE, Sahar AF. Effect of anti-transpiration and supplementary irrigation on growth, yield and fruit quality of 'Sultani' fig (*Ficus Carica*) grown

in the Egyptian western coastal zone under rainfed conditions. Research Journal of Agriculture and Biological Sciences. 2009;**5**(6):899-908

[45] Behboubian MH, Lawes GS. Fruit quality in Nijisseiki Asian pear under deficit irrigation: Physical attributes, sugar and mineral content and development of flesh spot decay. New Zealand Journal of Crop and Horticultural Science. 1994;**22**:393-400. DOI: 10.1080/01140671.1994.9513851

[46] Besset J, Genard M, Girarda T, Serrab V, Bussia C. Effect of water stress applied during the final stage of rapid growth on peach trees (cv. Big-Top). Scientia Horticulturae. 2001;**91**(3-4):289-303. DOI: 10.1016/So304-4238-4238(01)00272-2

[47] Huslig SM, Smith MW, Brusewitz GH. Irrigation schedules and annual ryegrass as a ground cover to conserve water and control peach tree growth. Hortscience. 1993; **28**(9):908-913

[48] George AP, Nissen RJ. Effects of water stress, nitrogen and paclobutrazol on flowering, yield and fruit quality of low chill peach cultivars, 'Flordaprince. Scientia Horticulturae. 1992;**49**:197-209. DOI: 10.1016/0304-4238(92)90157-8

[49] Naor A, Klein I, Hupert H, Grinblat Y, Peres M, Kuafman A. Water stress and crop level interaction in relation to nectarine yield, fruit size distribution and water potential. Journal of the American Society for Horticultural Science. 1999;**124**:189-193

[50] Marsal J, Mata M, Arbone's A, Rufat J, Girona J. Regulated deficit irrigation and rectification of irrigation scheduling in young pear trees: An evaluation based on vegetative and productive response. European Journal of Agronomy. 2002;**17**:111-122. DOI: 10.10 16/S1161-0301(02)00002-3

[51] Spreer W, Ongprasert S, Hegele M, Wunsche JN, Muller J. Yield and fruit development in mango (*Mangifera indica* L. cv. Chok Anan) under different irrigation regimes. Agricultural Water Management. 2009;**96**:574-584. DOI: 10.1016 /j.agwat.2008.09.020

[52] Ojeda M, Pire R, Perez de Camacaro M, Mogollon N. Effects of irrigation on growth, flowering and fruit quality of pineapple 'Red Spanish'. Acta Horticulturae. 2012;**928**: 171-178. DOI: 10.17660/Acta Hortic.2012.928.20

[53] Crisosto CH, Johson RS, Luza JG, Crisosto GM. Irrigation regimes affect fruit soluble solids concentration and rate of water loss of 'O' Henry peaches. Hortscience. 1994;**29**:1169-1171

[54] Crisosto CH, Johson RS, Dejong TM, Day KR. Orchard factors affecting post harvest stone fruit quality. Hortscience. 1997;**32**(5):820-823

[55] Johnson RS. Water use and water management of mid to late season stone fruit. CTFA Annual Report. 1994:1-6

[56] Peng YH, Rabe E. Effect of differing irrigation regimes on fruit quality, yield, fruit size and net CO_2 assimilation of Mihowase Satsuma. The Journal of Horticultural Science and Biotechnology. 1998;**73**(2):229-234. DOI: 10.1080/14620316.1998.11510969

[57] Estenban MA, Villanueva MJ, Lissarrague JR. Effect of irrigation on changes in berry composition of Tempranillo during maturation, sugars, organic acids and mineral elements. American Journal of Ecology and Viticulture. 1999;**50**:4418-4434

[58] Pascual M, Domingo X, Rufat J, Villar JM. Water productivity of peach for processing in a soil with low available water holding capacity. Acta Horticulturae. 2011;**889**:189-195. DOI: 10.17660/Acta Horticulturae. 2011.889.21

[59] Rufat J, Arbones A, Villar P, Domingo X, Pascual M, Villar JM. Effects of irrigation and nitrogen fertilization on growth, yield and fruit quality parameters of peaches for processing. Acta Horticulturae. 2010;**868**:87-93. DOI: 10.17660/Acta Hortic.2010.868.7

[60] Garcia-Tejero I, Romero-Vicente R, Jimenez-Bocanegra JA, Martinez-Garcia G, Duran-Zuazo VH, Muriel-Fernandez JL. Response of citrus trees to deficit irrigation during different phonological periods in relation to yield, fruit quality and water productivity. Agricultural Water Management. 2010;**97**:689-699. DOI: 10.1016/j.agwat.2009.12.012

[61] Mercier V, Bussi C, Lescourret F, Genard M. Effects of different irrigation regimes applied during the final stage of rapid growth on an early maturing peach cultivar. Irrigation Science. 2009;**27**:297-306. DOI: 10.1007/s00271-009-0146-s

[62] Cui N, Du T, Kang S, Li F, Zhang J, Wang M, Li Z. Regulated deficit irrigation improved fruit quality and water use efficiency of pear-jujube trees. Agricultural Water Management. 2008;**95**(4):489-497. DOI: 10.1016/j.agwat.2007.11.007

[63] Kumar S, Singh JB, Ram SN. Influence of pruning and weather on productivity of ber based horti-pastoral system in rainfed conditions. Indian Journal of Horticulture. 2006;**63**(3):260-263

[64] Kour G, Wali VK, Khushu MK, Bakshi P, Sharma A, Sharma C. Studies on the irrigation scheduling in low chilling cultivars of peach under subtropical conditions. Journal of Agrometeorology. 2013;**15**:194-198

[65] Lopez G, Behboudian MH, Vallverdu X, Mata M, Girona J, Marsal J. Mitigation of severe water stress by fruit thinning in 'O' Henry peach: Implications for fruit quality. Scientia Horticulturae. 2010;**125**:294-300. DOI: 10.1016/j.scientia.2010.04.003

Using Smartphone Technologies to Manage Irrigation

Timothy Coolong, Luke Miller and George Vellidis

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77304

Abstract

Numerous tools have been developed with the aim of improving irrigation scheduling. Some methods involve using soil moisture sensors and irrigating based on soil moisture thresholds. Others may be based on evapotranspiration models. More novel techniques include irrigating based on the water status within the target crop. However, growers have been reluctant to adopt many of these irrigation scheduling methods because they may be too cumbersome to use, require specialized equipment, or are perceived as too risky compared to traditional methods. Recently, smartphone applications have been developed that schedule irrigation based on crop coefficients and real-time weather data. Called the SmartIrrigation™ application (smartirrigationapps.org), these tools have the potential to aid farmers in conserving water and nutrients, while maintaining crop yields. These applications were developed by the University of Florida and include such crops as citrus (*Citrus spp*.), cotton (*Gossypium hirsutum*), turfgrass, blueberries (*Vaccinium darrowii*), and several vegetables. These applications can be downloaded for free by the public and utilize real-time data from nearby weather stations in Georgia and Florida. To determine the efficacy of the new SmartIrrigation™ applications for watermelons and tomatoes, trials were conducted over 2 years in southern Georgia, USA.

Keywords: drip irrigation, plasticulture, soil moisture sensor, evapotranspiration

1. Introduction

Fruit and vegetable farmers in the USA rely on irrigation to produce high-value crops. Though drip irrigation is perceived to be efficient compared to other forms of irrigation, mismanagement can result in excessive water applications with water migrating through macropores (worm holes, cracks, root channels) to below the root zone. Previous experiments have demonstrated that water used for irrigation can be detected in a pan lysimeter within 20 min of drip irrigation initiation on tomatoes [1]. When the water used for irrigation migrates below the root zone, there may be associated leaching of fertilizer and pesticides [2]. Efficient irrigation scheduling requires that farmers manage the timing and duration of irrigation in a manner that maintains yield and quality, while efficiently using water. Many irrigation scheduling methods exist including: the water balance (WB) method, soil moisture monitoring, hand feel and soil appearance, and crop phenology observations. Water balance-based irrigation scheduling relies on reference (ET_o) measurements to estimate water losses from a given area [3].

A majority of vegetable growers use traditional methods of measuring soil moisture, by observing soil dryness and through feeling the soil itself. Recent surveys conducted in Georgia (US) found that this method accounts for over 40% of the irrigation scheduling occurring on farms. In addition, an estimated 88% of growers in Georgia may allow crops to be visibly stressed before watering [4]. Other methods of soil moisture-based irrigation may utilize tensiometers, granular matrix probes, or resistance-based sensors to determine thresholds for irrigation management [5, 6]. While soil moisture sensor (SMS)-based irrigation has been shown to be more efficient than a time-based system [7–9], proper placement of sensors to accurately reflect conditions experienced by the plant can be challenging [10]. Furthermore, placement of sensors within an irrigation zone can be problematic for growers with heterogeneous soils or topography within a field. Irrigation thresholds may also be impacted by factors such as soil type and depth of drip tubing [11].

2. Determining irrigation scheduling

2.1. Evapotranspiration

Evaporation and transpiration are two important processes involved in the removal of water from soil and plants into the atmosphere. These processes occur simultaneously and are inherently connected to each other [12]. While transpiration and evaporation occur simultaneously, evaporation is based on the availability of water in topsoil and the amount of solar radiation reaching the soil surface [13]. Transpiration is a function of crop canopy density and soil water status. Evaporation accounts for the majority of crop evapotranspiration (ET_c) during early stages of crop growth in bare-ground plantings, while transpiration contributes to nearly 90% of the ET_c for a mature crop [14].

Evapotranspiration can be separated into ET_o and ET_c. Crop evapotranspiration is calculated from ET_o of a given area and the crop coefficient (K_c) of the crop being measured. Factors affecting ET_c include extent of ground cover, crop canopy properties, and aerodynamic resistance [12]. Reference ET_o is the amount of water exiting the soil at any time from a reference surface covered by grass at a 0.12 m height that is adequately watered, actively growing, and with a fixed surface resistance [14]. Weather conditions are also important to quantify as they affect the amount of energy available for ET_o to occur. The four most important conditions to measure are solar radiation, wind speed, temperature, and humidity, with the most important factor being solar radiation [15].

Crop coefficients are an adjustable constant that define the amount of transpiration occurring within a plant at a given stage of development. Crop coefficients are computed as the ratio ET_o:ET_c. Environmental and physiological factors affecting K_c include crop type, crop growth stage, climate, and soil type [14]. Plant developmental stage encompasses the relative activity of the plant. Plant size is also impacted by the crop development stage, thus affecting leaf area and canopy density, which in turn impacts transpiration. Accounting for environmental and management factors that influence the rate of canopy development is also important in calculating K_c. Climatic factors that significantly affect K_c are rainfall frequency, wind speed, temperature, and photoperiod [14]. Soil profile characteristics that affect K_c development are water table depth and soil porosity. Therefore, regional K_c estimates from several seasons are important to account for the variability in weather, irrigation, drainage, and runoff [16, 17].

Several WB-based methods exist to calculate ET_o rate, such as the Priestley-Taylor method and Hargreaves method. The Priestly-Taylor equation is a modification of the Penman-Monteith equation that approximates parameters established by the Penman-Monteith, using solar radiation to determine ET_o. However, calculations at a research site in the humid Southeastern USA found that Priestley-Taylor could overestimate ET_o for the region [18]. Priestly-Taylor has also been reported to overestimate the cumulative ET_o for the Georgian Coastal Plain area during months with significant rainfall, corresponding to peak early summer vegetable production [18]. Another method that has been used to estimate ET_o has been the Hargreaves method. This equation is an empirical model that considers incoming solar energy, evaporation, monthly maximum and minimum temperature, and a temperature coefficient [19]. This method has a high correlation with the Penman-Monteith model for estimates of average weekly ET_o in humid regions [19]. These methods of calculating evapotranspiration are easier to use than the Penman-Monteith method; however, this can also result in reduced precision over the course of a season.

2.2. Current recommendations

Current recommendations for drip-irrigated tomatoes in Georgia and Florida are based on variations of the WB method [20]. The WB method estimates daily crop water use based on historical theoretical ET_o values for the region adjusted with a K_c [14]. An advantage of using the WB method is that it allows growers to anticipate crop water requirements at certain times during the growing season and plan irrigation based on anticipated ET_o. However, irrigating solely based on predicted ET_o values may be inaccurate due to changes in annual weather patterns as well as differences in production practices for which crop coefficients were developed [21].

Regulated deficit irrigation is another method of irrigation management performed by imposing water deficits only at certain crop development stages [22]. Progressive or sustained deficit irrigation is the systematic application of water at a constant fraction of ET_c throughout the season. Reducing irrigation based on deficit ET_c levels may not result in optimal yields or quality in some crops as reducing ET_c has been shown to result in a concomitant decrease in yield of many crops [22].

2.3. Smartphone irrigation technologies

Recently, a suite of smartphone-based irrigation scheduling tools, which use real-time ET_o data from statewide weather station networks, were developed [24]. Called SmartIrrigation™ Apps [24], these tools use meteorological parameters to determine irrigation schedules based on ET_c calculated using K_c and ET_o in the following relationship: $ET_c = ET_o \times K_c$. The suite includes applications for avocado (*Persea americana*), citrus, strawberry (*Fragaria × ananassa*), cotton, turfgrass, and several vegetables. Prior studies have reported that the applications have performed well for citrus in Florida and cotton in Georgia [23, 25]. Migliaccio et al. [25] reported up to a 37% reduction in water use for growers using the SmartIrrigation™ Citrus App. in Southern Florida. SmartIrrigation™ applications developed for turfgrass management evaluated in Southern Florida were found to improve water savings of up to 57% compared to traditional methods [26]. The use of SmartIrrigation™ Cotton App resulted in the reduction of water used for irrigation by 40–75% with concomitant 10–25% increases in yield in Georgia when compared to the WB-based method recommended for cotton by the University of Georgia Cooperative Extension Service. The SmartIrrigation™ Cotton App also performed well when compared to SMS-based methods [25].

The SmartIrrigation™ Vegetable App (VegApp) generates irrigation recommendations based on real-time weather for vegetables. The VegApp currently can be used to schedule irrigation for multiple crops including tomato (*Solanum lycopersicum*), cabbage (*Brassica oleracea var. capitata*), squash (*Cucurbita pepo*), and watermelon (*Citrullus lanatus*). The weather data are retrieved from the Florida Automated Weather Network or the University of Georgia Automated Environmental Monitoring Network and are used to calculate ET_o from air temperature, solar radiation, wind speed, and relative humidity measurements using the FAO Penman-Monteith Equation [23]. Each new field registered in the VegApp by a user is automatically associated with the closest weather station; however, the user has the option to select any of the other available weather stations. The VegApp uses ET_o from the prior 5 d to calculate an average ET_o. Then ET_c is estimated using K_c curves developed by The University of Florida based on a weeks-after-planting model of crop maturity [27, 28]. The K_c curve for tomato is based on a drip-irrigated crop grown on plastic mulch [27, 28]. The VegApp may then provide an irrigation schedule for the subsequent 2 weeks. The user can recalculate requirements at any time to devise a weekly or even daily irrigation schedule. The irrigation schedule is provided to the user as an irrigation run time per day. Additional model variables used by the VegApp to schedule irrigation include crop, row spacing, irrigation rate, irrigation system efficiency, and planting date. The VegApp differs from other applications in the SmartIrrigation™ suite, in that it does not account for precipitation or soil type as it is designed for use with vegetables grown in a drip irrigation and raised-bed plastic mulch production system [23].

3. Evaluating the SmartIrrigation™ vegetable application in tomatoes and watermelons

3.1. SmartIrrigation™ vegetable application performance in tomatoes

Studies conducted during the 2016 and 2017 spring growing seasons in Georgia compared the new VegApp to currently recommend WB-based methods as well as an SMS-based system.

Total water use, yield, irrigation water use efficiency (IWUE), soil moisture status, and plant macronutrient content in tomato "Red Bounty" (HM Clause, Davis, CA) were measured.

Results of studies conducted with tomatoes in Georgia over 2 years suggested that the weather conditions during the growing season can influence the relative performance of the VegApp. Results from the 2016 growing season showed that the WB-based method of irrigation used the most water, followed by plants grown using the VegApp and SMS-based irrigation (**Table 1**). The SMS irrigation method used the least amount of water in 2016, which was similar to results obtained in other studies evaluating the impact of tensiometers for irrigation scheduling [29]. In 2016, plants grown with the VegApp utilized less water than the WB method, suggesting that applying real-time ET_o values obtained by nearby weather stations may be more efficient than using historic ET_o values [28] in some seasons. Irrigation volumes in the second year of the study were lower than the first year levels for WB and VegApp-based irrigations. There were two likely causes for the increase in water use for the SMS-based and VegApp methods relative to the WB method in 2017. In 2017, the VegApp accounted for higher levels of ET_c in the earlier growing season than historic ET_o values. In addition, there were several significant rain events late in the 2017 growing season, which resulted in irrigations in the VegApp and WB being discontinued for a period of several days. During the time period when irrigation was turned off, the WB method would have called for more water than the VegApp based on historic ET_o values.

Discontinuing irrigation led to relatively less water being used by the WB method in 2017. The contribution of rainfall has not been incorporated into the VegApp due to limited information regarding the impact of rain on soil moisture levels under raised beds covered with plastic mulches and the potential for significant spatial variability in precipitation [23]. Soil water tension readings (data not shown) suggested that levels of soil moisture were not significantly affected by rainfall. This suggests that the assumption that the VegApp does not incorporate rainfall into irrigation recommendations for crops grown on raised beds with plastic mulch is appropriate.

Irrigation treatment	**Irrigation volume**	**Daily water use**
	($L \cdot ha^{-1}$)	**($L \cdot ha^{-1} \cdot d^{-1}$)**
	2016	
VegApp	3306,000^z	39,380
WB	4,526,000	53,880
SMS	1,935,000	23,010
	2017	
VegApp	1,895,000	29,180
WB	1,684,000	25,910
SMS	2,339,000	36,010

^{z}Mean separation could not be performed between treatments as water meters were not replicated in individual treatments.

Table 1. Season irrigation volume and daily water use for tomatoes grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

When averaged over the two study years, the VegApp used 16% less water than the WB method, though much of this was due to the 2016 growing season. The SMS-managed plots utilized 31% less water than the WB method. This suggests that the VegApp and SMS-based irrigation can reduce water use when compared to methods relying on historic ET_o to manage irrigation. This may be expected as numerous studies have demonstrated the efficiencies of a microclimate and SMS-based irrigation when compared to historical ET-based methods [30].

While tomatoes grown using the VegApp utilized less water than the currently recommended WB irrigation method, yields were comparable among the three treatments (**Table 2**). In both study years, plants grown using the VegApp had the highest numerical total yield, but this was not significantly different than the other treatments.

In 2016, plants grown using the SMS-based irrigation method had a significantly higher IWUE when compared to those grown using the VegApp and WB-based methods (**Table 2**). While the yield of the SMS-managed plots was numerically lower than the other irrigation treatments in 2016, the SMS plots used substantially less water than the VegApp and WB-based plots, resulting in a significantly greater IWUE. In 2017, the VegApp had a significantly greater IWUE than the SMS-based irrigated plants. The increased IWUE in 2017 for VegApp and WB-grown plants was due to the decrease in irrigation volume used (**Table 1**). During this study, the SMS-grown plants had the most consistent IWUE, with 25.2 $g \cdot L^{-1}$ and 24.0 $g \cdot L^{-1}$ in 2016 and 2017, respectively, which were similar to those reported for fresh market tomato in North Florida [7]. The IWUE of the other irrigation treatments were more variable. This variability was the result of fluctuations in water used with no significant difference in yield (**Table 2**). However, when averaged over both study years, the IWUE of the VegApp and SMS-based irrigations were numerically similar. DePascale et al. [30] reported real-time microclimate-based irrigation to

Irrigation treatment	**($kg \cdot ha^{-1}$)**			**($g \cdot L^{-1}$)**
	Total	**Extra large**	**Large**	**IWUE**[z]
	2016			
VegApp	58,490a[y]	36,310a	17,180a	18.0b
WB	57,500a	35,280a	17,490a	13.2b
SMS	48,740a	30,350a	14,160a	25.2a
	2017			
VegApp	57,990a	51,130a	5560a	31.1a
WB	50,620a	43,660a	5840a	30.0ab
SMS	54,590a	46,370a	6970a	24.0b

[z] IWUE = total marketable yield divided by seasonal irrigation volume.

[y] Values in the same column and year followed by the same letter are not significantly different at $P \leq 0.05$ according to Tukey's honest significant difference test.

Table 2. Marketable yields of total, extra-large, and large fruit and irrigation water use efficiency (IWUE) for tomatoes grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

be slightly more efficient than tensiometer-based irrigation scheduling. The automated SMS-based system has the ability to deliver water at a high frequency with short-duration (pulsed) irrigation events, which have been shown to reduce water use while maintaining yields of tomato [31]. Pulsed irrigation typically results in a shallower wetting front shortly after the irrigation event, increasing application efficiencies [32, 33]. The VegApp and WB-based irrigations were scheduled for two events per day to simulate optimal grower practices, suggesting that the twice-daily irrigations with the VegApp tool may be as efficient in some years as a more complex SMS-based system.

Foliar concentrations of macronutrients were measured during this 2-year trial. While there were no significant differences among treatments for most macronutrients in either study year, plants grown with the VegApp had significantly higher nitrogen (N) levels than the WB- and SMS-grown plants in 2017 (**Figure 1**). In 2017, the VegApp had foliar N concentrations of 5.56% when compared to 5.04% and 4.61% in the WB and SMS-treated plants, respectively. In 2017, less water was applied to WB-grown plants, yet these plants had lower leaf N concentrations. However, during periods of sampling (fruit formation), the historic ET_o values used in the WB-based irrigation methods were higher than those generated using the VegApp. This additional application of water during the sampling period may have resulted in leaching of some fertilizer during fruit formation.

3.2. SmartIrrigation vegetable application performance in watermelon

Watermelons were also grown in order to evaluate the performance of the VegApp when compared to WB-based and SMS-managed irrigation regimes. Water usage, fruit yield, quality, and nutrient content were measured in plasticulture-grown “Melody” seedless watermelons over 2 study years. Results in the watermelon trial were similar to those of the tomatoes.

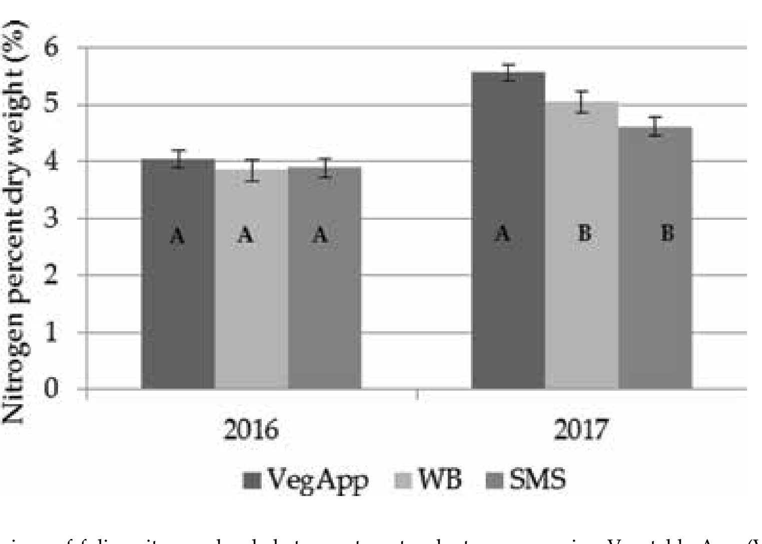

Figure 1. Comparison of foliar nitrogen levels between tomato plants grown using Vegetable App (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA in 2016 and 2017.

The SMS irrigation method used the least amount of water in 2016, which was similar to results found in tomatoes in 2016 (**Table 3**). Likewise, irrigation volumes in 2017 were lower than 2016 in watermelons. This is not unexpected as ET_c was 29% lower in 2017 than in 2016. As with tomatoes, in 2017, the VegApp accounted more appropriately for lower levels of ET_c in late May and June for watermelons when compared to the WB method using historic ET_o values. This resulted in a larger relative reduction in water use in the VegApp plots when compared to plants grown using the WB method in 2017.

When averaged over the 2 years of the study, the VegApp used 15% less water than the WB method, and the SMS-based regime utilized 29% less water than the WB method. Unlike tomatoes, the VegApp used less water than the WB-grown plants in both study years. The cumulative water use data suggests that the VegApp was more conservative in scheduling water than the current recommended WB method.

The performance of the VegApp when compared to the SMS-based system was more variable over the 2 study years. Several studies have reported improved irrigation efficiencies using SMS-based or real-time ET_c data when compared to historic ET_o-based methods [30, 31]. Nonetheless, in both study years, the VegApp utilized less water than the WB method, again suggesting that applying real-time ET_o values obtained by nearby weather stations may be more efficient than historic ET_o values.

As with tomatoes, total yields of watermelon were not impacted by irrigation treatment in either study year (**Table 4**). There were differences between first harvest yields in 2016, with plants grown using the SMS-based irrigation regime having a significantly lower first harvest than the other treatments. This may be due to the lower irrigation volume used by the SMS-grown plants in the hot and dry 2016 growing season. In 2017, there were differences in yields of 45-ct fruit among the treatments, with WB-grown plants having the lowest yields of this size category of melon.

Irrigation treatment	**Irrigation volume**	**Daily water use**
	(L·ha^{-1})	**(L·ha^{-1}·d^{-1})**
	2016	
VegApp	2892,000^{z}	26,570
WB	3,024,000	27,780
SMS	1,997,000	18,330
	2017	
VegApp	1,438,000	16,000
WB	2,067,000	23,010
SMS	1,629,000	17,960

^{z}Mean separation could not be performed between treatments as water meters were not replicated in individual treatments.

Table 3. Season irrigation volume and daily water use for watermelon grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

Irrigation treatment	**(kg·ha⁻¹)**			
	Total	**45 ct**[z]	**36 ct**	**First harvest**
	2016			
VegApp	55,640a[x]	12,100a	22,750a	30,350a
SMS	55,190a	11,400a	23,150a	22,960b
WB	48,600a	7990a	21,290a	31,990a
	2017			
VegApp	56,310a	23,730ab	10,180a	20,440a
SMS	65,430a	28,970a	12,870a	23,510a
WB	66,580a	16,720b	16,020a	23,770a

[z] 45 ct = 6.2 to 7.9 kg, 36 ct = 8.0 to 9.7 kg.

[x] Values in the same column and year followed by the same letter are not significantly different at $P \leq 0.05$ according to Tukey's honest significant difference test.

Table 4. Total marketable yields, first harvest yields, and yield of 45 and 36 count (ct) fruit for watermelons grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

Similar to tomatoes, there were differences in IWUE among treatments and study years. However, there were no interactions between the study year and the treatment. Analysis of main effects indicated that IWUE in the VegApp was not significantly different than either the SMS or WB irrigation systems (**Table 5**). In addition, results of foliar nutrient analysis in the watermelons were similar to those in tomatoes. Foliar N concentrations were significantly higher in the VegApp-treated plots than the SMS-grown plants (**Table 5**). In this instance, the increase in foliar N levels in VegApp-grown plants compared to SMS-managed plants may not be due to differences in leaching, as the SMS-grown plants utilized less water than those managed using the VegApp. A shallower wetting front that may be associated with pulsed-type irrigations in the SMS system may have resulted in a shallower root system in

	IWUE[z]	**N**
Irrigation treatment	(g·L⁻¹)	(%)
VegApp	28.8ab[y]	4.54a
SMS	33.6a	4.21b
WB	24.0b	4.30ab

[z] IWUE = season irrigation volume divided by total marketable yield.

[y] Values in the same column and year followed by the same letter are not significantly different at $P \leq 0.05$ according to Tukey's honest significant difference test.

Table 5. Effects of treatment for irrigation water use efficiency (IWUE) and foliar nitrogen (N) concentrations for watermelons grown using the vegetable app (VegApp), water balance (WB), and soil moisture sensor (SMS) methods in Tifton, GA, in 2016 and 2017.

those plants reducing nitrogen uptake by those plants. Alternatively, the VegApp, through improved early-season irrigation management, may improve root growth and the ability for crops to remove nutrients from the soil profile [34].

4. Conclusions

The rapid incorporation of smartphones into the daily lives of individuals has opened new avenues for data delivery. A 2015 survey indicated that 69% of farmers owned smartphones, and this number was expected to increase to 87% by 2016 [35]. As access to smartphone technology increases, dispersal of precise irrigation scheduling methods may also increase. Using real-time weather data to schedule irrigation is not a new concept; however, previously, it would have involved directly downloading data from a weather station or, more recently, accessing data from the Internet-based site and entering it into a fairly complicated equation to develop irrigation recommendations. This process was generally too time-consuming for growers who may be managing dozens if not hundreds of irrigation zones. By linking to nearby weather stations and generating automated recommendations that are sent directly to a smartphone in the field, these new SmartIrrigation™ applications bypass the cumbersome data transfer and calculations previously required for scheduling irrigation. Our data suggest that the VegApp is more efficient in terms of water use than a well-managed irrigation program developed from historic Et_o data and, in most cases, just as efficient as a relatively complicated SMS-based system, while maintaining similar yields. In addition, our data suggest that some of the assumptions incorporated into the VegApp (e.g., rainfall not accounted for when using raised beds covered with plastic mulch) are indeed appropriate. Because these trials were conducted on a loamy sand soil, we could not confirm how soil type would affect the efficiency of the VegApp. Nonetheless, our findings suggest that the SmartIrrigation™ applications represent an easily accessible tool that growers and managers can use to produce vegetables by an efficient irrigation management system.

Acknowledgements

We would like to thank the Georgia Department of Agriculture for funding this research through a Specialty Crop Block Grant titled: *SmartPhone Apps for Scheduling Irrigation in Six Specialty Crops*. We would also like to thank the University of Florida for developing the SmartIrrigation™ used in these experiments.

Author details

Timothy Coolong*, Luke Miller and George Vellidis

*Address all correspondence to: tcoolong@uga.edu

The University of Georgia, Tifton, Georgia, USA

References

[1] Malone RW, Ma L, Wauchope D, Ahuja L, Rojas K Ma Q, Warner R, Byers M. Modeling hydrology, metribuzin degradation, and metribuzin transport in macroporous tilled and no-till silt loam soil using RZWQM. Pest Management Science. 2004;**60**:253-266

[2] Tindall JA, Vencil W. Transport of atrazine, 2-4 D and dicamba through preferential flowpaths in an unsaturated claypan soil near Centralia, Missouri. Journal of Hydrology. 1995;**166**:37-59

[3] Andales AA, Chavez JL, Bauder TA. Irrigation scheduling: The water balance approach. Colorado State University Cooperative Extension Bulletin. 2015;**4**:707

[4] United States Department of Agriculture. Methods used in deciding when to irrigate. In: Farm and Ranch Irrigation Survey 2013. Vol. 3. Washington, DC: USDA; 2014. p. 87

[5] Cardenas-Lailhacar B, Dukes MD, Miller GL. Sensor-based automation of irrigation on bermudagrass, during dry weather conditions. Journal of Irrigation and Drainage Engineering. 2010;**136**:184-193

[6] Munoz-Carpena R, Dukes MD, Li YCC, Klassen W. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. HortTechnology. 2005; **15**:584-590

[7] Zotarelli L, Scholberg JM, Dukes MD, Munoz-Carpena R, Icerman J. Tomato yield, biomass accumulation, root distribution, and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agricultural Water Management. 2009;**96**:23-34

[8] Zotarelli L, Scholberg JM, Dukes MD, Munoz-Carpena R, Icerman J. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agricultural Water Management. 2009;**96**:1247-1258

[9] Zotarelli L, Dukes MD, Scholberg JM, Femminella K, Munoz-Carpena R. Irrigation scheduling for green bell peppers using capacitance soil moisture sensors. Journal of Irrigation and Drainage Engineering. 2011;**137**:73-81

[10] Dabach S, Shani U, Lazarovitch N. Optimal tensiometer placement for high-frequency subsurface drip irrigation management in heterogeneous soils. Agricultural Water Managment. 2015;**152**:91-98

[11] Coolong T. Evaluation of shallow subsurface drip irrigation for the production of acorn squash. HortTechnology. 2016;**26**:436-443

[12] Shukla S, Jaber F, Srivastava S, Knowles J. Water use and crop coefficient for watermelon in Southwest Florida. University of Florida Institute of Food and Agricultural Sciences Report. 2007; WRP-LY-009

[13] Pereira LS, Perrier A, Allen RG, Alves I. Evapotranspiration: Review of concepts and future trends. Journal of Irrigation and Drainage Engineering. 1999;**125**:45-51

[14] Allen RG, Pereira LS, Raes D, Smith M. Crop Evapotranspiration, Irrigation and Drain-age. Paper No. 56. Rome: United Nations FAO; 1998. p. 300

[15] Brown P. Basics of Evaporation and Transpiration. Tuscon, Arizona, USA: The University of Arizona Cooperative Extension Publication; 2000. p. 4

[16] Rana G, Katerji N. Measurements and estimation of actual evapotranspiration in the field under Mediterranean climate: A review. European Journal of Agronomy. 2000;**13**:25-153

[17] Shukla S, Jaber FH, Goswami D, Srivastava S. Evapotranspiration losses for pepper under plastic mulch and shallow water table conditions. Irrigation Science. 2012;**31**:523-536

[18] Suleiman AA, Hoogenboom G. Comparison of Priestley–Taylor and FAO-56 penman–Monteith for daily reference evapotranspiration estimation in Georgia, USA. Journal of Irrigation and Drainage Engineering. 2007;**133**:175-182

[19] Hargreaves GH, Samani ZA. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture. 1985;**1**:96-99

[20] Harrison K. Irrigation Scheduling Methods. Vol. 974. Univ. Georgia Coop. Ext. Bul.; 2009. p. 8

[21] Amayreh J, Al-Abed N. Developing crop coefficients for field-grown tomato (Lycopersicon esculentum mill.) under drip irrigation with black plastic mulch. Agricultural Water Managment. 2005;**73**:247-254

[22] Fereres E, Goldhamer DA, Parsons LR. Irrigation water management of horticultural crops. Historical review compiled for the American Society of Horticultural Science's 100th anniversary. Hortscience. 2003;**38**:1036-1042

[23] Migliaccio KL, Morgan KT, Vellidis G, Zotarelli L, Fraisse C, Zurweller BA, Rowland D, Andreis JH, Crane JH. Smartphone apps for irrigation scheduling. Transactions of the ASABE. 2016;**59**:291-301

[24] University of Florida. Smart Irrigation Applications. 2012. Available from: www.smartirrigationapps.org [Accessed 2016-01-12]

[25] Vellidis G, Liakos V, Perry C, Roberts P, Tucker M, Barnes E. Field evaluation of a smartphone app for scheduling irrigation in cotton. In: Proceedings of the 2015 Beltwide Cotton Conference; 5-7 January. Vol. 2015. New Orleans. Memphis, Tennessee: National Cotton Council of America; 2015. pp. 913-918

[26] Migliaccio KL, Morgan KT, Vellidis G, Zotarelli L, Fraisse C, Rowland D, Andreis JH, Crane JH. Smartphone apps for irrigation scheduling. In: Emerging Technologies for Sustainable Irrigation: A Joint ASABE/IA Irrigation Symposium; 10-12 November, 2015 Long Beach California. St. Joseph, MI. 2015. pp. 1-16

[27] Stanley CD, Clark GA. Water Requirements for Drip Irrigated Tomato Production in Southwest Florida. University of Florida Institute of Food and Agricultural Sciences Publication; 2009. p. SL213

[28] Simonne EH, Dukes MD, Zotarelli L. Principles and practices of irrigation management for vegetables, p. 17-26. In: Olson SM, Simonne E, editors. Vegetable Production Handbook for Florida 2010-2011. Gainesville, FL: University of Florida Institute of Food and Agricultural Sciences; 2010. pp. 17-26

[29] Smajstrla AG, Locascio SJ. Irrigation scheduling of drip-irrigated tomato using tensiometers and pan evaporation. Proceedings of the Florida State Horticulture Society. 1990;**103**:88-91

[30] DePascale S, Costa D, Vallone S, Barbieri G, Maggio A. Increasing water use efficiency in vegetable crop production: From plant to irrigation systems efficiency. HortTechnology. 2011;**21**:301-308

[31] Munoz-Carpena R, Dukes MD, Li YCC, Klassen W. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. HortTechnology. 2005; **15**:584-590

[32] Assouline S, Ben-Hur M. Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. Catena. 2006;**66**:211-220

[33] Coolong T, Surendan S, Warner R. Evaluation of irrigation threshold and duration for tomato grown in a silt loam soil. HortTechnology. 2011;**21**:466-473

[34] Dukes MD, Zotarelli L, Morgan KT. Use of irrigation technologies for vegetable crops in Florida. HortTechnology. 2010;**20**:133-142

[35] Potter B. 87% of Farmers Will Own a Smartphone by 2016 [Internet]. 2015. Available from: https://www.agweb.com/article/87-of-farmers-will-own-a-smartphone-by-2016-naa-ben-potter/ [Accessed 2016-11-20]

Chapter 5

Deficit Irrigation in Mediterranean Fruit Trees and Grapevines: Water Stress Indicators and Crop Responses

Anabela Fernandes-Silva, Manuel Oliveira,
Teresa A. Paço and Isabel Ferreira

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80365

Abstract

In regions with Mediterranean climate, water is the major environmental resource that limits growth and production of plants, experiencing a long period of water scarcity during summer. Despite the fact that most plants developed morphological, anatomical, physiological, and biochemical mechanisms that allow to cope with such environments, these harsh summer conditions reduce growth, yield, and fruit quality. Irrigation is implemented to overcome such effects. Conditions of mild water deficit imposed by deficit irrigation strategies, with minimal effects on yield, are particularly suitable for such regions. Efficient irrigation strategies and scheduling techniques require the quantification of crop water requirements but also the identification of pertinent water stress indicators and their threshold. This chapter reviews the scientific information about deficit irrigation recommendations and thresholds concerning water stress indicators on peach trees, olive trees, and grapevines, as case studies.

Keywords: olive, peach, vine, irrigation management

1. Introduction

Mediterranean climate is characterized by hot dry summers, mostly rainy winters, and partially wet autumns and springs. Rainfall occurs mostly throughout the dormant season of fruit trees, hence vegetative and fruit growth and production are dependent on stored soil water and on irrigation during summer. Precise knowledge on when to irrigate and the amount of water to apply are essential to attain sustainable management and environmentally sound water management, since this natural resource is increasingly scarce and expensive. Projected global warming will enhance this problem as climate change scenarios forecast reductions in the total amount of precipitation and changes in its seasonal distribution, up surging the problem of water scarcity for agricultural use [1]. Agricultural water management comprehends different features related to irrigation, for instance, water productivity index (WP), that is, ratio yield/marketable product or yield/net income, to water used by the crop [2]. Optimization of irrigation strategy is necessary to increase WP and minimize yearly fluctuations of crop production. Irrigation is also essential to ensure the productivity increase and therefore meet the rising food needs in a world with an ever larger population, which is expected to augment by 30% in 2050 [3]. Overall, food production from the irrigated agriculture accounts for 40% of the total output, using only 17% of the land area devoted to food production [4]. The agriculture uses correspond to more than two-thirds of the total of freshwater uses [5, 6]. In many parts of the world, irrigation water has been over-exploited and over-used and freshwater shortage is becoming critical mainly in the arid and semiarid areas, such as some of the Mediterranean region. Freshwater allocation between agriculture and other economic sectors is a source of conflict, claiming to a constant need to improve WP of crops. Thus, precise irrigation scheduling, combining plant and/or soil water stress indicators, is one of the tools that can help growers to achieve this goal [7, 8]. The combination of these indicators with modeling has been defended by several authors [9].

In the last decades, extensive research in fruit crops has shown that they respond positively to conditions of mild water deficit imposed by deficit irrigation (DI) strategies [10]. Under this agronomic practice, the amount of water applied is reduced to a value below maximal crop irrigation requirements allowing the development of a mild water deficit with minimal effects on yield [11, 12]. In fact, several studies have demonstrated that DI is particularly suitable for regions where water is scarce, and improving WP is a critical goal [13, 14]. The increase of WP when DI is applied to woody crops is explained by: (i) DI efficiently reduces plant transpiration (T) by stomatal closure in fruit trees and vines as tall, rough canopies are well coupled to the atmosphere [15]; (ii) in most woody crops, net incomes are not linearly linked to biomass accumulation, but to fruit yield and fruit quality [4] and DI normally enhances the quality of fruits and derived products [16–18], eventually increasing the net income of the grower; and (iii) DI increases WP by the control of excessive growth that reduces pruning frequency and intensity. In fact, the control of plant vigor has a particular importance in orchards with high-plant densities, also called super intensive orchards [19, 20], thus DI may increase their productive life through decreasing the competition between trees for solar light [21]. Scheduling DI in commercial orchards usually requires knowledge of the soil water capacity, the actual plant water requirements, plant water relations, and plant stress sensitivity according to their phenological stages.

Fruit orchards and vineyards constitute an integral and significant part of the Mediterranean environment and culture, with a great economic, ecological, and social support in different countries [22]. Therefore, it is easy to understand that the study of the response of fruit trees and vineyards to deficit irrigation is of key importance for the agriculture and the economy of the Mediterranean countries. Based on our own experimental results and also on information from the literature, the aim of the present chapter is to provide criteria to enable the sustainable management of irrigation at farm level in agricultural areas, where water is scarce. Three of the most important productive fruit species of the Mediterranean basin are addressed: peach, olive, and grapevines.

2. Concept and strategies of deficit irrigation

According to Fereres and Soriano [4], the term DI should be defined in terms of the level of water supply in relation to maximum crop evapotranspiration (ETc) and the terms deficit or supplemental irrigation are not interchangeable, because in the latter, a maximum yield is not sought. It is widely known that conditions that limit water use usually decrease crop evapotranspiration (ETc) and crop growth by the limitation of its main component, transpiration (T), and therefore carbon assimilation. Thus, it is of remarkable concern to be aware of the maximum reduction of ETc with the minimum impact on the economic return of production and quality on mature fruit trees, as compared to those obtained when ETc is fully replaced. In young fruit trees, it is not desirable to practice water deficit irrigation once in this stage of development, the main objective is to maximize vegetative growth leading to reach the mature phase as faster as possible to attain full production [23]. The correct application of DI requires precise knowledge on the crop response to water stress at different phenological stages, to identify the periods when fruit trees are less sensitive [24] and in order to define the level of DI to be applied.

This work focuses on the main strategies of DI since they have been studied and applied in olive, peach orchards, and grapevines. They can be depicted as: (i) sustained deficit irrigation (SDI), with a deficit throughout the season; (ii) regulated deficit irrigation (RDI), with periods when the irrigation can be stopped or reduced to a minimum level, based on physiological aspects of the response of plants to water deficit, and (iii) partial rootzone drying (PRD), see Section 2.3 for definition. All these practices aim at maximizing the efficiency of water use and WP [25, 26] with minimum impact on yield, which can be attained if precision tools are used to manage DI [27, 28].

2.1. Sustained deficit irrigation

Sustained deficit irrigation is an irrigation strategy based on the distribution of a reduced water volume, controlled by a water stress indicator or as a percentage of the full water requirements for a crop throughout the whole irrigation season, so that the water deficit is intended to be uniform over the whole crop cycle to avoid the occurrence of severe water stress at any particular moment that might have unfortunate results [29]. At the end of the 1970s, field experiments on irrigation below the ETc demand, but at very frequent intervals, have shown very promising results [30].

2.2. Regulated deficit irrigation

To our knowledge, the concept of regulated deficit irrigation (RDI) was first presented in the 1980s [31, 32] with the aim of controlling excessive vegetative growth in peach orchards. They founded that water deficit limited shoot growth, when shoots and fruits were competing for photo-assimilates. It is important to bear in mind that fruit tree sensitivity to water deficit is not constant during the whole growing season, and a water deficit during a phenological stage less sensitive might benefit WP, as it increases irrigation water savings, and minimizes negative impacts on yield and crop profits [31, 33, 34]. So, when a RDI strategy is applied, it may be necessary to supply full irrigation during the drought sensitive phenological stages and irrigation may be stopped or restricted during the non-critical periods, less sensitive to drought [31, 35]. The crucial constraints of RDI are: (i) difficulty in keeping plant water status within tight limits of water deficit during noncritical phenological periods; (ii) depending on management, unexpected variation in evaporative demand may result in severe losses of yield and fruit [36]; (iii) need to define precise criteria for the water deficits, in different growth conditions, related to species, weather, soil depth, fruit load, and rootstock [37, 38]; and (iv) lack of precise knowledge in the effect of water deficit during bud development [38, 39].

2.3. Partial root drying system

Partial rootzone drying (PRD) is a strategy of DI that consists in irrigating only one half of the rootzone in each irrigation event, while the other half is allowed to dry. For this, both halves are watered alternately [40]. This technique was first developed in Australia for vineyards and relies on root-to-leaf signaling induced by a rootzone that is in a drying process [41], decreasing stomatal aperture and leaf growth, preventing water loss [42, 43] with a little effect on photosynthesis, hence increasing transpiration efficiency [41]. At the same time, the wet portion of the root system receiving water enables the plant to maintain a favorable plant water status, such that yield is not significantly compromised and quality may even improve [42]. The PRD performance is based on the assumption that photosynthesis and fruit growth are less sensitive to water deficit than transpiration, and besides, water deficit induces the production of chemical signals, like ABA in the root, that can be translocated to leaves [44] inducing stomatal closure. As demonstrated in a recent meta-analysis, the advantages of PRD in relation to RDI are highly controversial and also depend on the soil texture, a success or enhanced yield performance with RDI and PRDI occurring most likely in deep and finely textured soils [45].

3. Water stress indicators and thresholds

3.1. Water status indicators: use in research and in irrigation scheduling practices

The use of water status indicators has been enhanced not only by the increasing importance of DI, but also due to the increased possibilities of automatically recording of some of those variables. This requires the selection of the appropriate variables and their threshold values, for different objectives concerning marketable yields. In the perspective of this contribution, the question is how to select a water status variable and how to transform it in a useful stress indicator for DI scheduling. The requirements of a water stress indicator include the consideration of a consistent answer (similar response in similar circumstances), low cost, and easiness of use, reliability with reasonable low sampling, and possibility to define thresholds that facilitate a decision. Above all these requirements, it is necessary to measure or derive an indicator that depends much more on the water stress affecting yield, then on other variables independent from water stress (such as atmospheric demand).

Stomatal conductance (g_s), which decreases as soil water deficit develops, is a primary mechanism in regulation of plant transpiration; therefore, a potential indicator of water stress [46]. Stomatal opening is not only affected by the soil water status, but also by external factors not related to water stress, such as meteorological conditions at leaf level, mainly vapor pressure deficit (VPD) [47]. Consequently, it makes more sense to use g_s taken in relative, which is the value in a stressed crop divided by the correspondent value in a well-watered one. Such measurements are time consuming, due to the required sampling, consequence of the high scattering in the canopy and instability with clouds or gusts of wind. It is very difficult to automate g_s measurements and the sensors used (porometers) are delicate and expensive. Therefore, its use is limited to research.

Due to the buffer role of the soil, soil water potential and soil water content (θ_s) have the advantage of being almost independent from diurnal atmospheric variations. Soil water potential measurements (with tensiometers) are easy and cheap, they can be, in principle, easily automated, but there are limits concerning the range of soil water status in which tensiometers operate well. The changes in θ_s (volumetric fraction) have the advantage of being a direct component of the soil water balance equation. The relative extractable water (REW) is a very useful concept that relates the actual volume of water available for plants to the total available water capacity, between the so-called field capacity and permanent wilting point (TAW) [48].

Leaf water potential (Ψ_{leaf}) is also related to stomatal closure. Even if, for different reasons, reductions in stomatal opening can occur without changes of Ψ_{leaf} [47, 49], this indicator has been broadly used for irrigation scheduling purposes.

The use of stem water potential at noon (Ψ_{stem}) has the advantage of being less disturbed by environmental conditions than Ψ_{leaf} [50] but it loses its relevance in the case of isohydric behavior, as such plants close stomata so effectively that they avoid important decreases in noon Ψ_{leaf} [51, 52]. In such cases, the difference between irrigated and stressed plants can be higher at predawn than at noon and predawn leaf water potential (Ψ_{pd}), being independent from diurnal oscillations can better represent water status in both cases: isohydric or anisohydric behavior.

The difficulties in finding meaningful correspondence between gas exchange and plant water balances impose limitations on accurate measurement of plant water stress in field conditions. It is largely demonstrated however that, in spite of such limitations, Ψ_{pd} or Ψ_{stem} are variables considered reliable as water status indicators for irrigation scheduling purposes and have been almost unavoidable in research studies [53, 54].

Several variables have been derived from stem diameter variations (SDVs) [55, 56], with the advantage of being cheap and easily continuously recorded. The most used are the organ (stem or fruits) growth rate (OGR), the daily trunk shrinkage (DTS), or the relative DTS

(RDTS), where the relative value of daily amplitude in diameter is divided by the correspondent in well-watered plants, obtaining an indicator practically independent from atmospheric variations, as required. Sometimes, maximum and minimum trunk diameters are used individually (MXTD and MNTD).

The success of SDV-derived variables depends on plants' behavior. Its application seems to be more successful when applied to conditions of anisohydric behavior [57]. Unfortunately, the outputs often are of difficult interpretation [56, 58], sometimes being the use based on visual and qualitative analysis.

Also, as diameter changes, sap flow rate can be continuously and automatically recorded with high resolution across large temporal scale. Sap flow sensors became popular in last decades, and by measuring fluxes, for the same reasons of independence from atmospheric demand, they only can be directly linked to water status indicators, provided relative transpiration (RT) [48] and the absolute values are not used. The inconvenience of requiring well-watered plants as reference limits its use to research.

As the stomatal conductance is reduced to prevent excessive transpiration, the temperature of leaves and canopy rises. Therefore, the temperature of the canopy in relation to the air is linked to the level of water stress, due to the effect of transpiration evaporative cooling. Several indexes have been proposed and applied in different conditions, space and temporal scales, mainly following the work of Jackson et al. in early 1980s [59], to derive the crop water stress index (CWSI). Measuring canopy temperature is a simple procedure using inexpensive infrared thermometers or any other optical devices that can take many observations rapidly without disturbing the plant. However, canopy temperature is affected by multiple factors, namely VPD, turning it complex to relate with soil water availability.

Overviews and results on remote sensing approaches have been presented [60, 61]. The "advantages and pitfalls" of plant-based methods in the perspective of irrigation scheduling have been discussed by Jones [36]. Fernández [57] recently presented a review of soil or plant water status and other variables used as other water stress indicators for irrigation scheduling. In general, technologies have greatly improved over the years, sensors are more affordable but sampling is still a limitation. In all cases where the relative independence from daily variations in atmospheric demand requires well-watered plants as a reference, this represents a practical disadvantage, limiting its use to the field of research. Unfortunately, these affects many possible indicators and the number of those remaining that are not excessively time consuming, is reduced to a few.

Therefore, the combination of these indicators with models for water balance is advisable [48]. In fact, the most popular variables in irrigation scheduling practices, used at present, either by farmers or enterprises, providing irrigation scheduling services, often include soil moisture quantification, sometimes as a complement to water balance models based on estimated ETc, for example, Ondrasek [1]. This is related to easiness, cost, rapidity to obtain the outputs, simplicity of data treatment/interpretation, and significance. Furthermore, the advantage of directly linking θ_s with the outputs from water balance is crucial. The problems of spatial heterogeneity and the quality of the measurements are often disregarded, meaning that a qualitative use of these outputs is often accepted and considered useful.

Experience and knowledge of varieties, environmental conditions, and technical and financial capabilities of the growers will ultimately determine the most adequate method or combination of methods to use for evaluation of the status of their crops and how to better manage them.

3.2. Olive

In general, plant water potential seems to be a better indicator than the SDV-derived variables, when full irrigation scheduling is applied. Moriana et al. [62] suggested that values of Ψ_{stem} > −1.65 MPa in field conditions provide the maximum g_s and when Ψ_{stem} > −1.8 MPa, maximum yield was obtained [63]. Pérez-López et al. [64] suggested that a threshold value Ψ_{stem} of −2.0 MPa (moderate water deficit) may be used to DI. Nevertheless, Ψ_{stem} in DI trees was affected by crop load and environmental conditions. Indeed, Moriana and Fereres [65] reported that VPD produced a variation on Ψ_{stem} from −0.8 to around −1.4 MPa in fully irrigated olive trees of different ages and fruit load. A threshold value of Ψ_{pd} > −0.9 MPa was often proposed to FI [66–68].

It has been observed that SDVs are affected by seasonal growth patterns, crop load, plant age and size, and other factors, apart from water stress [58]. So, the use of SDV needs expert interpretation, which limits their potential for automating the calculation of irrigation depth (ID). Despite this, they refer that, when combined with aerial or satellite imaging, SDV measurements are useful for scheduling irrigation in large orchards with high crop-water-stress spatial variability.

Alcaras et al. [69] reported that the increase in MXTD showed strong relationships with REW, Ψ_{stem} and g_s. Trunk growth rate (TGR) showed a very early response to water-withholding and it decreased along with Ψ_{stem} until it reached a constant negative growth rate, at Ψ_{stem} of −2.7 MPa. In their study, DTS was much less responsive to irrigation than either MXTD or TGR. They suggest the use of automated soil moisture sensors if reliable soil moisture values can be obtained, and indicate that a continuous recording of trunk diameter has some potential, but further investigation of MXTD and TGR is warranted.

3.3. Peach

For peach, the use of Ψ_{stem} for defining thresholds under DI conditions is referred by Girona et al. [70], who found the value −1.5 MPa, the limit over which the impairing of bloom fertility appears. Naor et al. [39] have observed that the value of −2.0 MPa for SWP was a threshold for the occurrence of double fruits, while Lopez et al. [71] suggest a threshold of −1.05 MPa to obtain fruits with positive effects on consumer acceptance, without significant impacts on fruit composition and yield, as they have observed that a threshold of −1.25 MPa would reduce fruit size and yield, even if advantageous for consumer acceptance.

Other authors, using relative transpiration (RT), have observed that a minimum value of 0.7 has to be observed to avoid yield and quality losses [72].

Using the relationship between (RT) and $\Psi_{pd,}$ it was observed [73] that the Ψ_{pd} threshold corresponding to RT equal to 0.7 is −0.33 MPa. Using CWSI, based on the temperature differences between canopy and air, a threshold of 0.5 was found to trigger irrigation [74]. It was also found that it is possible to identify a threshold in the relationship between g_s and Ψ_p, corresponding to a change in the plant behavior, equal to Ψ_{pd} = −0.45 MPa [75].

3.4. Grapevines

A number of indicators related to plant water status of grapevines have been discussed in the literature such as g_s [76, 77], Ψ_p, or Ψ_{stem} [78–81], sap flow and SDV-derived variables. Being very sensitive to transient meteorological conditions, g_s at the time of measurement performed poorly in detecting grapevine water stress in Alto Douro vineyards in Portugal [82]. This can be eventually explained by the fact that either the cultivar displayed an anisohydric behavior [51] or the relative conductance was not used. According to Acevedo-Opazo et al. [83] and Lanari et al. [84], Ψ_{leaf} or Ψ_{stem} are reported to correlate well with both soil water content and net photosynthesis, and they are suitable to perform irrigation scheduling on grapevines under DI. In other studies, a better performance was obtained by using this variable measured at predawn [56, 79, 85]. According to Silvestre (2018, personal communication), there is some experimental evidence that Ψ_{stem} is not a good indicator in vineyards under high VPD.

Measurements of vegetative growth, when applied to grapevines, can offer simplicity, sensitivity to water stress over extended periods [86], as tissue expansion underlying vegetative growth responds to water status, and are interrelated with crop yield and quality. The stage development of shoot tips can be used reliably to estimate vineyard water status and manage irrigation, given that moderate water stress is primarily affected by soil water content [86]. An experiment to evaluate the visual assessment of shoot tip stage as a method to estimate the water status of vineyards and its utility in vineyard management showed that calculation based on the tip stage [87] is fast, nondestructive, and does not require special skills or equipment and it is independent of prevailing weather conditions [86].

Brillante et al. [80] observed that canopy temperature was an important predictor in determining the water stress experienced by grapevine, especially at midday. These positive results are not always observed: due to excessive wind and turbulence in SW of Portugal, the significant differences in DI treatments could not be identified using proximal radiative canopy temperature [88]. Bellvert et al. [89] emphasized the influence of VPD in using airborne thermal imagery in vineyards. Canopy temperature and derived parameters such as the empirical CWSI [59] have also been used in vineyards by Grant et al. [90] and King and Shellie [91] to monitor plant water stress.

Sap flow performed satisfactorily in detecting grapevine water stress in Alto Douro [82], and in a study developed by Selles et al. [92], diameter changes proved more sensitive than water potentials. Again, many different results were obtained in South Portugal, where differences in DI could not be distinguished using SDV, but were quite clear regarding sap flow records for different treatments [56]. If a single indicator based on sap flow or SDV did not reflect the grapevine response, according to Oliveira et al. [93], their combination could provide more detailed information.

In general, threshold values for DI in vineyard based on water potential have been abundantly suggested, but in the case of vine production, the quality issues are crucial; therefore, information is quite complex and scattered. Classical recommendations often include the use of leaf water potential [94]; a new water stress index based on a water balance model was proposed and tested by Gaudin et al. [95] as a tool for classifying water stress experienced by grapevines in vineyards.

4. Responses to deficit irrigation regarding agronomic aspects and quality

4.1. Olive

4.1.1. Vegetative growth and production cycle

Shoots growth and fruits development are cyclical and both are repeated on an annual basis, but only vegetative growth is completed in the same year, while olives production needs two consecutive seasons [96]. In the first one, the formation of the buds and their floral induction take place. In the following year, flower development occurs as well as flowering, fruit set, growth, and oil accumulation. In Mediterranean climate conditions of northern hemisphere, shoot growth takes place from March until the middle of July, although a second flow of growth can occur in late August, when olive trees are fully irrigated, or at the beginning of autumn rainfall [97]. Water deficit reduces shoots growth and has a negative effect on the potential production of the following year. Flowering occurs at the end of spring, and it is very sensitive to water deficit [63], or at high temperatures. Fruit set is very sensitive to water deficit and fruit growth has a double sigmoid behavior [96, 98] with three main stages, as follows. Phase I is the fast-growing, when both the cell division and expansion contribute to the size increase, the endocarp being the main tissue in development, reaching 80% of the volume of the olives [98] with full expansion about 8 weeks after full bloom [99]. The occurrence of water deficit in this stage results in a small endocarp and extreme water stress can compromise the viability of the fruit. Phase II, of slow-growth, is less sensitive to water deficit [100], when the endocarp progressively hardens and both the embryo and the endocarp reach their final size [98]. During phase III, of fast growing, parenchyma cells of the mesocarp experience a large increase in size, entirely due to cell expansion, and the oil biosynthesis begins [98]; so water availability for the fruit determines its size and the accumulation of oil. Thus, water deficit may produce small fruits and the mesocarp/endocarp ratio is reduced due to decreased weight of the mesocarp.

4.1.2. Olive response to water deficit

Many studies had showed that high soil water availability increments yield components such as fruit number, fruit fresh weight, fruit volume, pulp:stone ratio, and oil content; therefore, increasing fruit and oil yields [12, 63] and that water scarcity can have a negative effect, depending on its level. In addition, irrigation regime can influence the relationship between vegetative and reproductive growth [101].

Hernandez-Santana [102] observed that olive trees prioritize fruit growth and oil content accumulation over vegetative growth, suggesting a higher sink strength for reproductive growth than vegetative growth. In the initial years of orchard establishment, when rapid vegetative growth is desirable in order to quickly obtain optimum tree size and canopy, as well as to begin fruit production as soon as possible, it is critical not to depress vegetative activity. For this reason, in commercial orchards, DI is commonly implemented only once, trees are fully grown to avoid negative effects on the formation of tree structure during the training period [102]. DI at early stages of tree development may result useful not only for water saving but also for controlling vigor in super high-density (SHD) orchards, in particular in regions where local conditions lead to excessive vegetative growth, such as in northern Argentina [103]. The choice and success of DI strategy is conditioned by tree density and rootzone size. It seems that SDI is more interesting when trees explore large volumes of soil, as in low-density orchards that maximize the availability of stored soil water per tree, compared to higher densities [97, 104]. Moreover, the success of SDI as compared to FI depends on the crop load of olive. About this issue, Martín-Vertedor et al. [105, 106] conducted a long term studied in "Morisca" orchard (417 trees ha^{-1}), in the Southwest of Spain. They observed that SDI (75% ETc) reduced yield in "on" years. Nevertheless, they reported that this DI could be advisable during "off" years, when a lower water use is observed, and trees are less sensitive to water deficit with low-crop load. There is still uncertainty about which DI strategies are better, regarding SDI or RDI [58, 101].

Lavee et al. [107] suggested that the most efficient schedule for RDI irrigation was to withhold water till the end of endocarp hardening and then to apply full irrigation from that stage till 2 weeks prior to harvest.

The literature provides results, for low-density orchards (300–600 trees ha^{-1}) under FI [63], SDI [12], RDI [11], and PRD [108] and for SHD olive orchards >1500 trees ha^{-1} [109].

Often, DI strongly reduces vegetative growth, but only slightly reduces the final fruit volume. Water stress caused a higher reduction in fresh fruit yield than oil yield due to a higher oil concentration in DI irrigated trees "in Picual" (Spain), without differences between SDI and RDI [11]. Moreover, Iniesta et al. [11] observed that WP for oil production has tripled for a 25% decrease in total water applied. They conclude that both irrigation strategies may be used with moderate reductions (about 15%) in oil yield. Similarly, Fernandes-Silva et al. [12] ("Cobrançosa," Portugal) reported that for a SDI at 30% ETc, WP for oil is higher or very close to FI, depending on the year, and is more than double the one obtained in rainfed conditions; oil yield is reduced only 35% as compared to FI, while saving 60% of water applied. Nevertheless, oil concentration on a dry matter basis (DM) in SDI was 7–19% higher as compared to FI, hence oil yield reduction was lower than yield of fruit (DM). The higher oil yield observed in FI is mainly due to higher number of fruits, although under SDI, fruits have slight higher values of mesocarp (>3–5%) as compared to FI olives, mainly attributed to a higher crop load in FI olive trees. Fernandes-Silva et al. [12] founded a good relationship between the oil amount per mesocarp dry mass (g) ($y = 0.83 \times -0.17$, $r^2 = 0.97$). This may be useful in supporting the decision of the most suitable time for harvest to optimize oil productivity.

Irrigation is particularly an important component in SHD orchards as the trees are expected to have more reduced volume of the rootzone. There is not a consensus on the best irrigation approach for SHD olive orchards. A reduction in water applied up to 16% in July did not affect oil production [110], while a reduction of 72% (30 RDI) resulted in 26% less oil yield and a best balance between water saving, tree vigor, and oil production was achieved [19].

Fernández et al. [19] and Padilla-Díaz et al. [111] applied RDI in a SHD olive orchard using a strategy of 45% of the total irrigation requirements (IN) in total distribution, according to the vegetative phase: period 1–100% IN, before and during bloom; period 2–80% IN, during the maximum rate of pit hardening (6–10 weeks after bloom) that coincide with the phase of flower induction; period 3–100% IN at the end of pit hardening until the last week of September, and 20% IN during fruit maturity. During the end of June and till the last week of August IA was 20% of IN.

Marra et al. [112] conducted a study in west of Sicily (Italy) in a SHD orchard (cv "Arbequina"), where five irrigation treatments were tested: 100% of IN, three SDI treatments with 75, 50, and 25% of IN, and a nonirrigated "rainfed" control. They found that oil yield increased with higher irrigation amounts up to a certain level (50 SDI) and a further increase in irrigation level improved crop load on the one hand, but decreased vegetative growth and increased the severity of biennial bearing. They conclude [112] that irrigation scheduling in the new SHD orchards should be planned on a 2-year basis and corrected annually based on crop load.

With regard to PRD, Wahbi et al. [108] analyzed the effect of applying PRD (50% of ETc) to "Picholine marocaine" olive trees in Marrocos in field grown conditions. They reported a yield reduction of 15–20%, achieved with 50% ETc, and that WP increased by 70% in PRD treatments. However, the lack of comparison between PRD and RDI did not clarify whether the effects observed were specifically triggered by PRD or if they were simply associated with general water deficits. Later, Aganchich et al. [113] addressed this question by comparing the effects of PRD and RDI in the same cultivars grown in spots. They reported that plant vegetative growth was substantially reduced under both PRD and RDI, more pronounced in PRD, compared with FI, as expressed by lower values of shoot length, leaf number, and total leaf area. In many cases, PRD treatment has been compared to a FI treatment, so doubt remains on whether the observed benefits correspond to the switching of irrigation or just to PRD being a DI treatment. In addition, not always a PRD treatment has been found advantageous as compared to a RDI treatment [66]. Taking into account that an irrigation system suitable for the PRD approach is more expensive and difficult to manage, the literature suggests that there are no agronomical advantages on PRD as compared to RDI [66]. It is of great importance to bear in mind that results depend mainly on cultivar, orchard characteristics, environmental conditions and agronomic practices, and to the large variability in rainfall, climate, and soil types between the various growing regions. Consequently, caution must be taken when applying the findings reported by different authors to a particular orchard.

4.1.3. Effect on fruits and olive oils quality

The concept of quality in fruit products is wide, complex, and dynamic. In the case of olive trees, two main products are obtained from olive fruits: virgin olive oil (the juice of the fruit) and table olives; both are staple foods of the Mediterranean diet. The quality attributes that are considered for each product largely differ from one another.

High irrigation rates are associated with a decrease mainly in minor compounds of virgin olive oil (VOO) as they are total polyphenols (TP), orto-diphenols (OD), tocopherols (TC) volatile compounds (VC) [16, 114] that have an important role in nutritional value, biological proprieties, and organoleptic characteristics of VOO. There is a controversy about the effect of irrigation in overall quality of VOO. In the literature, there are researchers who argue that FI lowers the quality of olive oil [115]. If this may be true for Cvs poor in TP, such as "Arbequina," FI may compromise the conditions necessary for virgin extra category and in other hand, decrease its self-live time. Nonetheless, in Cvs very rich in PT (>1000 mg/kg), such as "Cornicabra," VOO is very bitter and pungent, and therefore with poor acceptability by the consumer, FI may help to overcome this problem.

Motilva et al. [116] observed that RDI strategies applied to "Arbequina" induced a significant increase in polyphenol concentration and oil stability. Fernandes-Silva et al. [16] found a strong relation ($r^2 = 0.715$; $p = 0.033$) with TP and between water stress integral (WSI). Similarly, Pearson's correlation coefficients between oxidative stability (OS) and TP was high and significant ($p = 0.026$), but no significant correlation was found between OS and TC ($p = 0.322$). Moreover, Gómez del Campo [110] and García [117] observed that the application of RDI in summer produced a significantly higher OS, which coincided with a significantly higher content of TP derivatives. These compounds are of great interest because they influence the quality and the palatability of VOO and increase their self-life time by slowing the formation of polyunsaturated fatty acid hydroperoxides.

Irrigation regimes either equivalent to 30 or 100% of ETc, applied to olive trees, "Cobrançosa" affects significantly the activity of L-phenylalanine ammonia lyase (PAL, EC 4.3.1.5), that is considered as the key enzyme in phenolic biosynthesis, the TP and amount of individual polyphenols [17]. Higher PAL activity, TP and individual polyphenol contents were observed for the rainfed conditions in the first picking date, and decreased with maturation of the olive fruits. Also, this effect was observed for the two irrigation regimes applied. The difference in the PAL activity, TP and individual polyphenol content between the three water regimes, decreases as olives become more mature.

Olive oil fatty acid composition is often not affected by RDI strategies [118], although other studies indicate that irrigation strategies cause small variations in the oleic and palmitic acids [16, 116]. Magliulo et al. [119] reported that olive oil fatty acid composition from two different cultivars ("Frantoio"; "Leccino") was more affected by varietal factors and climatic conditions of the year than by water regimes. Curiously, when cv "Arbequina," is cultivated in warm arid valleys of North Western Argentina, produced a lower content of 18:1 acid in relation to the Mediterranean region [120] and a decrease with increasing temperature during oil accumulation of 2% per °C was found.

DI can also influence the sensory attributes of olive oil. In cultivars such as "Arbequina," which normally has low-phenolic concentrations, DI is beneficial due to the greater polyphenol concentrations. More phenolics contribute to better balanced oils with a more sophisticated pungent and bitter flavor [114].

With regard to the quality attributes of tables' olive, they are also affected by DI strategies. Cano-Lamadrid et al. [121] and Cano-Lamadrid et al. [122] evaluated the quality of table olives ("Manzanilla"), after processing that were previously submitted to three irrigation treatments: FI; RDI_1 with moderate stress during pit hardening (soft water stress) and RDI_2 with low stress at the end of flowering stage, and moderate during pit hardening. They observed that FI olives had the highest weight and size, and were rounded. Color coordinates L* and b* had the highest values in RDI_2 olives. Aldehydes and monounsaturated fatty acids predominated in FI olive fruits, while terpenes and polyunsaturated fatty acids predominated in T1 fruits, and saturated fatty acids were abundant in RDI_2 olives. Sensory evaluation indicated that global acceptance was higher for RDI_1 olives, with high satisfaction degree among consumers due to fresh olive flavor, crunchiness, and global satisfaction. They argue that both RDIs are effective and can be a good alternative irrigation practice for this cultivar. However, these authors evaluated table olives quality after processing, an evaluation after harvest, that is, before olives processing may be more interesting.

Water deficit effect could increase of PhytoPs content, chemical compounds analogs to prostaglandin, which belong to a novel family of plant effectors, may be related to the enhancement of reactive oxygen species (ROS) production under drought stress, which induce the formation of an array of lipid peroxidation products [123]. The phase II of fruit growth can be non-critical considering fruit yield or fruit size [124] but is clearly critical for PhytoPs formation. Thus, olive table trees under RDI can be considered as complementary actions to enhance the PhytoP content and hence their potential beneficial effects on human health as they play a role in regulation of immune function [125].

4.2. Peach

4.2.1. Vegetative and productive cycle

RDI is based on restraining irrigation during certain periods of the vegetative cycle of the crop, therefore implying the knowledge of the several phases and sometimes its differences between genotypes, since the length of some phases (fruit development period and ripening) varies for early-maturing or late varieties [126]. The phenological stages of peach *Prunus persica* L. Batsch) can be depicted as shown in **Figure 1**. During the fruit growth period, three phases are classically considered: phases I and III, where rapid growth occurs and a phase II characterized by a plateau [127] having the growth curve, a double sigmoid pattern [128].

4.2.2. Peach response to water stress

Several studies over the last decades have addressed the use of deficit irrigation, namely RDI, in peach. Ref. [31] have applied the method to peach during the phase of final swell and observed a significant production and fruit growth increase, if irrigation restrictions were applied while excessive vegetative vigor could be suppressed to favor fruit growth. Mitchell and Chalmers [32] have used RDI during the phase of fast vegetative growth, obtaining similar yield and fruit growth to a nonrestricted situation, while saving ca. 30% of irrigation water and controlling the vegetative growth. For the post-harvest phase, [129] observed that irrigation reduction decreased pruning requirements and increased flowering in the next season. For the same phase, and also during fruit development, [130] saved 40% of irrigation water with light implications in production and fruit size. More recently, the benefits of applying

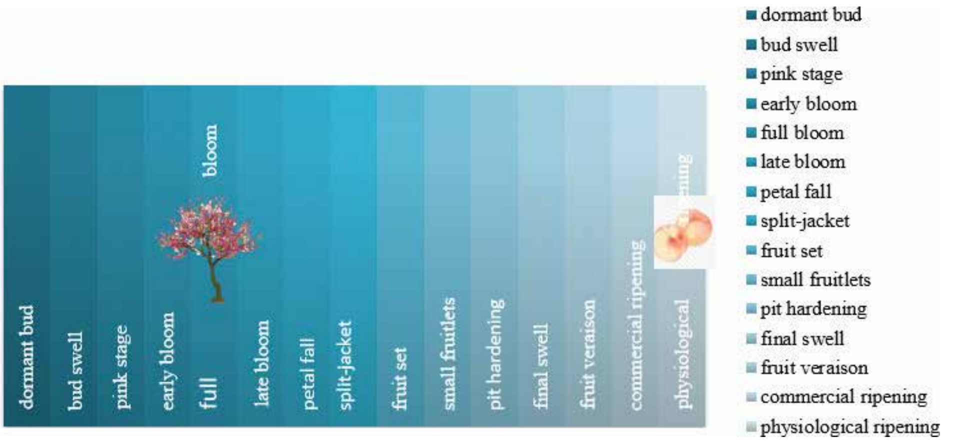

Figure 1. Phenological phases of peach (*Prunus persica*).

RDI during stage II of fruit development have also been stated [89], including beneficial reduction of tree vigor and improvement of fruit quality [71]. De la Rosa et al. [131] applied RDI after harvest, concluding that it was beneficial to control vegetative growth. Results from [70] also confirm the positive effects of RDI to control vegetative growth without a significant effect in fruit production. However, these authors recommend caution in long-term (over 3 years) application of RDI, since it gradually reduces canopy, what can affect fruit yield. The same effect was observed by [132, 133], and these last authors even advise the discontinuing of RDI after 3 years. A prevalent long-term plant adaptive response over an immediate causal effect of RDI in a single season is therefore foreseen. **Table 1** presents an overview of the most common practices for RDI in peach referred in literature. RDI has been mostly applied in the phase of late fruit development or after harvesting, and in general, the most reported effects refer to a decrease in vegetative vigor, production and fruit size, but an increase in fruit quality and water use efficiency.

Thus, for peach, considering the available information on the use of RDI, production is not significantly affected as long as applied in an adequate phase and bearing in mind, the variety relative precocity. Other advantages can be pointed out such as an easier management of the crop (if the vegetative vigor is restrained) and an increased efficiency in the use of water resources. Precaution is advised concerning long-term cumulative effects in production, as sometimes a negative influence has been observed.

PRD strategies for peach have showed contradictory results as sometimes a positive effect has been observed in yield, in comparison with other conventional DI practices [43], but other studies advocate no agronomic advantages in such technique, especially if the increased installation costs are considered [137].

4.2.3. Effect on fruits quality

Studies addressing the effect of deficit irrigation on peach fruit quality either refer to an improvement of it [71] or no effect [134, 136].

RDI	Phase															RDI effects					
Reference	Dormant bud	Bud swell	Pink stage	Early bloom	Full bloom	Late bloom	Petal fall	Split-jacket	Fruit set	Small fruitlets	Pit hardening	Final swell	Fruit veraison	Commercial ripening	Physiological ripening	Tree vigor	Production	Fruit size	Fruit quality	WUE	Irrigation water/ restrictions
Mitchell and Chalmers [32]						■	■	■	■							<	=	=			<30%
Johnson et al. [129]															■	<					Several
Girona et al. [130]									■	■	■	■	■	■	■						<40%
Bellvert et al. [89]											■	■	■	■	■	<			>		50% ETc
Lopez et al. [71]													■	■			</=	</=	>		15% ETc
De la Rosa et al. [131]															■	<					60% FI
Girona et al. [70]													■	■	■	<	=				35% ETc
Naor et al. [39]															■		<		<		SWP −2.0 MPa
Marsal et al. [133]													■	■			<	<			80% ETc
Marsal et al. [133]													■	■	■			<			SWP >−1.5 MPa
Marsal et al. [133]													■	■	■			<			SWP >−1.8, −2.02 MPa
Pascual et al. [134]											■	■				<		<	=		30% ETc
Pascual et al. [134]													■	■	■	<		<			70% ETc
Zhou et al. [135]												■	■	■		<	=	>	>	>	75% ETc SDI
Zhang et al. [136]															■		<	=/<	=		25% ETc
Abrisqueta et al. (2010)	■	■	■	■	■	■	■	■	■	■	■	■				<	<	<		>	25% ETc

SWP, midday stem water potential; ET_c, crop evapotranspiration (not stressed); FI, full irrigation.

Table 1. Deficit irrigation practices applied to peach—application phases and effects referred in literature.

Pérez-Sarmiento et al. [138] applying several RDI strategies to apricot have found improvements in some qualitative characteristics of the fruits, such as the level of soluble solids, sugar/acid ratio, and fruit color, without negative effects in yield. Along with these characteristics, fruit firmness was also improved in a study conducted by Zhou et al. [135] when applying an SDI strategy with a light water stress. Therefore, from these studies, it can be concluded that the use of deficit irrigation in peach doesnot seem to induce negative effects in the fruit quality parameters referred above. Nevertheless, several authors refer the occurrence of double fruits or fruit cracking, if severe water stress is imposed. For example, Naor et al. [39] refer this occurrence for values of stem water potential lower than −2.0 MPa. This suggests that, in what concerns fruit quality, there is an identifiable limit to the application of deficit irrigation, as discussed in Section 4.

Most of the studies addressing water use efficiency (WUE) in peach under deficit irrigation report an increase in comparison to full irrigation practices, although with lower yields for moderate or severe water stress [135].

4.3. Grapevines

4.3.1. Vegetative growth and production cycle

Grapevines (*Vitis vinifera* L.) develop over a number of periodic events, phenological stages, mentioned in the literature as budbreak, flowering and veraison [139]. Budbreak signals the beginning of the vine seasonal growth and physiological activity after a period of dormancy during the coldest months of the year but its starting date is neither influenced by winter temperature or precipitation [140, 141]. However, a recent report [142] mentions that water-stressed grapevines delay the onset of bud dormancy, reduce the cold exposure required for releasing buds from dormancy, and hasten budbreak. Flowering initiates the reproductive cycle and is followed by the fruit setting. At veraison, the ripening process is initiated when important must, and later wine, quality attributes develop. The time needed to reach berry maturity is related to temperature and precipitation and it is shortened as the temperature rises and precipitation decreases [141]. Grapevine phenology is strongly influenced by weather and climate [143] and the duration of each stage is largely determined by temperature [144]. Moreover, ambient temperature conditions the plant physiology, imparts the berry composition, and ultimately, the wine quality [145].

The climates with best potentials for quality wines are those with mild and wet winters, warm springs, and hot and dry summers. These climatic characteristics are common for the so-called Mediterranean climate well-known for its dry summer, and grapevines are well adapted to water scarcity because of its extensive, deep roots, and mechanisms of drought resistance such as tight control of stomatal aperture [146] and osmotic adjustment [147].

The cultivation of grapevines, fruit in Europe is mainly used for winemaking, is a climate-sensitive agricultural system and it expected a rise in average temperatures worldwide by 2050, some regions might be over the optimum range of temperature for the growing season [148]. Precipitation in many viticultural areas is expected to decrease substantially in the period between budbreaking and veraison [149] resulting in more intense water stress during a critical stage for grapevines. Given the actual trend in climatic change, the grapevines will advance their phenological stages, shorten the growing season with maturation occurring under hotter and drier conditions [150], a phenomenon already observed in the viticultural region of Alto Douro, Portugal [151].

4.3.2. Grapevines response to water stress

The wine grower has to manage irrigation for the benefit of yield and quality that maximizes the returns as the growers profits are a combination of both yield and quality, and a very low yield, no matter what quality might not be profitable [152].

It is well documented that irrigated grapevines increased significantly their yield per plant over rainfed plants. The increased yield is due to larger berries that diluted color, aroma, and soluble solids, and correspond to a lower quality of the must and hence the wine.

Imposing very high levels of water stress must be avoided because it results in declining vine capacity and productivity, eventually becoming economically unsustainable [153].

In viticultural regions where water stress can cause damages to the production objectives, DI strategy is a management tool that can ensure a balance between vegetative and reproductive development while maintaining yields and improving fruit composition [42] but the irrigation timing and amount must be adjusted to the local environment (*terroir*) and to wine typicity to avoid potential negative impacts [154]. Too small quantity of irrigation water can be an expensive procedure with no beneficial effect while too much water might induce an excessive vegetative growth, increase berry size, and reduce the concentration of important metabolites for quality wines [155].

Nevertheless, simultaneous events of high temperatures, drought and elevated evapotranspiration have detrimental effects on yield and berry composition as the plant carbon assimilation is much reduced due to lower photosynthetic activity compounded by loss of leaf area [156]. It is well documented that water stress decreases leaf stomatal conductance, leaf water potential, vegetative growth, leaf to fruit ratio, berry size and their fresh and dry weights, and yield [46, 141].

Water stress and temperature have a complex relationship. Higher temperatures can enhance both sugar accumulation and organic acid decay, but acidity is more affected than sugar levels, then, for the same sugar level, grapes grown under warmer conditions have lower acidity [157]. This decoupling has been reported for other metabolites, such as anthocyanins [141], proanthocyanidins [158], and aromas [159]. The decoupling of anthocyanins and sugars, in favor of anthocyanins, was observed in Cabernet Sauvignon under increasing water stress [160]. During the ripening period, if elevated temperature and drought occur simultaneously, the effects on the decoupling of anthocyanins and sugars can be felt only slightly due to the contrasting responses to these two factors, and in fact, restricted water supply during berry development can partially restore anthocyanin/sugar ratios disrupted by high temperature [161]. In “Red Tempranillo,” elevated temperature and drought reduced total polyphenol index, malic acid and increased color density, but did not modify anthocyanin concentration [119].

Grapevines exhibit a vigorous vegetative growth between budbreak and veraison [162] and as consequence, the plant has its highest demand for water during this period. If there is an ample availability of soil water that might be supplemented with occasional rains, the plant grows a dense, shaded canopy at expense of reproductive berries with negative impacts on fruit and wine quality potential, foster pests and diseases, and the grower has to resort to expensive canopy management such as shoot and leaf thinning, hedging, and shoot repositioning to correct the canopy architecture and manipulate the plant yield [163]. Attending the effects of these contrasting conditions, a degree of water stress is considered beneficial for the production of quality grapes [164, 165].

The use of irrigation in these increasingly stressful environments is a mitigating solution to maintain quality in wine production, minimize the most serious risks of drought damage, and in extreme cases, guarantee plant survival [151, 166].

Under RDI, plant water status is maintained within limits of deficit during certain phases of the seasonal development, normally when fruit growth is least sensitive to water reductions [167]; then, RDI at early stage of grapevine development looks more promising than in later stages. RDI has become widely adopted in the production of wine grapes in arid and semiarid areas [168] and several works have shown that it brings better results than simple DI or FI.

The demand for vineyard irrigation is on the rise as climate becomes more stressful but water is scarcer and the competition among stakeholders becomes acute, factors that require an improvement in the efficiency of water use.

In Alto Douro region, the highest water use efficiency (WUE) was reached in rainfed grapevines at expense of yields that were economically unsustainable because the benefits of irrigation were disproportional to the amount of water necessary to bring them about [152, 169]. To strike a balance between yields, berry quality and WUE, it is advisable to impose a moderate stress before veraison but after fruit setting. Pre-veraison RDI compared to SDI reduces vine water use and increases the canopy WUE, decreases the berry polyphenolic but might lower the financial return due to lower yields [170].

4.3.3. Effect on berries quality

There is no consensus among the various authors regarding the accumulation and concentration of important metabolites because it depends on skin to pulp ratio in berries [171] as smaller berries favor their concentration in the must. The soluble solids that determine the alcohol content in wine, was found to be more concentrated in grapevines subjected to SDI than in rainfed or abundantly irrigated plants [172], while others found a lower concentration under very restricted DI [153] or did not find any significant difference in their concentration [173]. These contradictory results might be related to the accuracy of vine water status monitoring necessary to regulate and manage the physiological changes imposed to the vines by DI [83]. In other words, DI might be beneficial if an accurate control of water deficits is exerted [94].

Studies have shown that changes in grapevine water status, at selected and critical phenological stages, are as important as the amount of water applied on influencing vegetative growth, yield, and fruit metabolism [40]. Experiments with DI of "Tinta Roriz" (Tempranillo) carried in Alto Douro (Portugal) [152, 166] showed that RDI was effective to increase the yields and also induced higher concentration of organic acids in the musts but insufficient to reach the desirable level of 6–7 mg L^{-1} equivalent of tartaric acid. Total soluble solids and the concentration of glucose and fructose decreased as the rate of irrigation increased, mainly if water was applied after veraison. Irrigation had no influence on pH, anthocyanidins and flavonols of the must when compared with rainfed grapevines, but the effect was negative upon the polyphenol index, the total anthocyanins, and the color intensity. The adverse effects of irrigation were mitigated when vines were deficit irrigated between flowering and veraison followed by no irrigation till harvest. Some of these results were corroborated by other authors [81, 174]. The experiment also showed that rainfed vines produced musts with attributes very desirable for high-end wines but the yield was too low (as little as 300 g per plant) to guarantee a satisfactory economic return. RDI can result in substantial improvements on fruit quality through decreasing yield and berry size [94] and has a positive effect over synthesis and concentration of phenolic compounds, soluble solids, and anthocyanins.

5. Conclusions

The recommended irrigation strategy should be the one that maintains better tree water status throughout the season, depending on the soil water content at the beginning and the availability of water. These factors change between years, so deficit irrigation studies should be carried out for longer time than 2 or 3 years to produce a better knowledge of water stress effects.

For the above reasons, and based on the successful use of RDI in fruit trees and grapevines reviewed herein, the adoption of RDI strategies in water-limited areas should be encouraged.

So, it is of great importance to bear in mind that results depend mainly on cultivar, orchard characteristics, environmental conditions, and agronomic practices and to the large variability in rainfall, climate, and soil types between the various growing regions; thus caution must be taken when applying the findings reported by different authors to a particular orchard.

Acknowledgements

This work is supported by: European Investment Funds by FEDER/COMPETE/POCI—Operational Competitiveness and Internationalization Programme, under Project POCI-01-0145-FEDER-006958 and National Funds by FCT—Portuguese Foundation for Science and Technology, under the project UID/AGR/04033/2013" and by fellowship (FCT/SFRH/BD/18441/2004) awarded to Fernandes-Silva, AA. This work was also developed under the activities of project: Water Saving in Agriculture: technological developments for the sustainable management of limited water resources in the Mediterranean area WASA, [ERANETMED/0006/2014] which aims at developing tools for deficit irrigation scheduling in woody crops.

Conflicts of interest

The author declares no conflict of interest.

Abbreviations

g_s	Stomatal conductance
ID	Irrigation depth
DTS	Daily trunk shrinkage
CWSI	Crop water stress index
Ks	Stress coefficient
IN	Irrigation needs
Kc	Crop coefficient
IA	Irrigation applied
Ψ_{leaf}	Leaf water potential, in general
OGR	Organ growth rate
Ψ_{pd}	Leaf water potential measured at predawn
PWP	Permanent wilting point
Ψ_{stem}	Stem water potential measured near solar noon
SDV	Stem diameter variations
θ_s	Volumetric soil water content
SWD	Soil water depletion
AW	Available water
TAW	Total available water
DI	Deficit irrigation
VPD	Vapor pressure deficit
WP	Water productivity

Author details

Anabela Fernandes-Silva[1*], Manuel Oliveira[1], Teresa A. Paço[2] and Isabel Ferreira[2]

*Address all correspondence to: anaaf@utad.pt

1 Centre for the Research and Technology of Agro-Environmental and Biological Sciences, CITAB, University of Trás-os-Montes and Alto Douro, UTAD, Quinta de Prados, Vila Real, Portugal

2 Linking Landscape, Environment, Agriculture and Food (LEAF), Instituto Superior de Agronomia (ISA), Universidade de Lisboa (ULisboa), Lisboa, Portugal

References

[1] Ondrasek G. Water scarcity & water stress in agriculture. In: Ahmad P, Wani MR, editors. Physiological Mechanism and Adaptation Strategies in Plants Under Changing Environments I. Springer New York Dordrecht Heidelberg London; 2014. pp. 75-96

[2] Valipour M. Pressure on renewable water resources by irrigation to 2060. Acta Advances in Agricultural Sciences. 2014;**2**:32-42. http://www.aaasjournal.org

[3] Godfray HCJ, Garnett T. Food security and sustainable intensification. Philosophical Transactions of the Royal Society B. 2014;**369**:20120273. DOI: 10.1098/rstb.2012.0273

[4] Fereres E, Evans RG. Irrigation of fruit trees and vines: An introduction. Irrigation Science. 2006;**24**:55-57. DOI: 10.1007/s00271-005-0019-3

[5] Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany. 2006;**58**:147-159. DOI: 10.1093/jxb/erl165

[6] Xiloyannis C, Montanaro G, Dichio B. Irrigation in mediterranean fruit tree orchards. In: Lee TS, editor. Irrigation Systems and Practices in Challenging Environments. Rijeka, Croatia: InTech; 2012. pp. 331-341. DOI: 10.5772/31350

[7] Katerji N, Itier B, Ferreira MI, Flura D, Durand B. Etude de quelques critères indicateurs de l'état hydrique d'une culture de tomate en région semi-arid. Agronomie. 1988;**8**: 425-433

[8] Naor A, Yoni Gal Y, Moti Peres M. The inherent variability of water stress indicators in apple, nectarine and pear orchards, and the validity of a leaf-selection procedure for water potential measurements. Irrigation Science. 2006;**24**:129-135. DOI: 10.1007/s00271-005-0016-6

[9] Ferreira MI, Conceição N, Malheiro AC, Silvestre JM, Silva RM. Water stress indicators and stress functions to calculate soil water depletion in deficit irrigated grapevine and kiwi. Acta Horticulturae. 2017;**1150**:119-126. DOI: 10.17660/ActaHortic.2017.1150.17

[10] Behboudian MH, Mills TM. Deficit Irrigation in deciduous orchard. In: Janick J, editor. Horticultural Reviews. 1997;**21**:105-131

[11] Iniesta F, Testi L, Orgaz F, Villalobos FJ. The effects of regulated and continuous deficit irrigation on the water use, growth and yield of olive trees. European Journal of Agronomy. 2009;**30**:258-265. DOI: 10.1016/j.eja.2008.12.004

[12] Fernandes-Silva AA, Ferreira TC, Correia CM, Malheiro AC, Villalobos FJ. Influence of different irrigation regimes on crop yield and water use efficiency of olive. Plant and Soil. 2010;**333**:35-47. DOI: 10.1007/s11104-010-0294-5

[13] Molden DA. Water-productivity framework for understanding and action. In: Kijne JW, Barker R, Molden D, editors. Water Productivity in Agriculture: Limits and Opportunities for Improvement. Colombo, Sri Lanka: International Water Management Institute; 2003. pp. 1-18. DOI: 10.1016/j.agwat.2011.08.022

[14] Pereira LS, Cordery I, Iacovides I. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agricultural Water Management. 2012;**108**:39-51

[15] Monteith JL. Evaporation and Environment. Symposia of the Society for Experimental Biology. 1965;**XIX**:205-234

[16] Fernandes-Silva AA, Gouveia JB, Vasconcelos P, Ferreira TC, Villalobos FJ. Effect of different irrigation regimes on the quality attributes of monovarietal virgin olive oil from cv. 'Cobrançosa'. Grasas y Aceites. 2013;**64**:41-49. DOI: 10.3989/gya.069712

[17] Machado M, Felizardo C, Fernandes-Silva AA, Nunes FM, Barros A. Polyphenolic compounds, antioxidant activity and L-phenylalanine ammonia-lyase activity during ripening of olive cv. 'Cobrançosa' under different irrigation regimes. Foodservice Research International. 2013;**51**:412-421. DOI: 10.1016/j.foodres.2012.12.056

[18] Ahumada-Orellana LE, Ortega-Farías S, Searles PS, Retamales JB. Yield and water productivity responses to irrigation cut-off strategies after fruit set using stem water potential thresholds in a super-high density olive orchard. Frontiers in Plant Science. 2017;**8**:1-11. DOI: 10.3389/fpls.2017.01280

[19] Fernández JE, Perez-Martin A, Torres-Ruiz JM, Cuevas MV, Rodriguez-Dominguez CM, et al. A regulated deficit irrigation strategy for hedgerow olive orchards with high plant density. Plant and Soil. 2013;**372**:279-295. DOI: 10.1002/jsfa.7828

[20] Fernández JE. Understanding olive adaptation to abiotic stresses as a tool to increase crop performance. Environmental and Experimental Botany. 2014;**103**:158-179. DOI: 10.1016/j.envexpbot.2013.12.003

[21] Connor DJ, Gómez-del-Campo M, Rousseaux MC, Searles PS. Structure, management and productivity of hedgerow olive orchards: A review. Scientia Horticulturae. 2014;**169**:71-93. DOI: 10.1016/j.scienta.2014.02.010

[22] Biasi R, Botti F, Barbera G, Cullotta S. The role of mediterranean fruit tree orchards and vineyards in maintaining the traditional agricultural landscape. Proc. XXVIIIth IHC—IS on the Challenge for a Sustainable Production. Acta Horticulturae. 2012;**940**:79-88. DOI: 10.17660/ActaHortic.2012.940.9

[23] Ruiz-Sanchez MC, Domingo R, Castel JR. Review. Deficit irrigation in fruit trees and vines in Spain. Spanish Journal of Agricultural Research. 2010;**8**(S2):S5-S20. http://www.inia.es/sjar

[24] Fereres E, Goldhamer D. Irrigation of deciduous fruit and nut trees. In: Lascano RJ, Sojya RE, editors. Irrigation of Agricultural Crops. ASA Monograph No. 30. American Society of Agronomy; 1990. pp. 987-1017

[25] Liu F, Shahanzari A, Andersen MA, Jacobsen SE, Jensen CR. Effects of deficit irrigation (DI) and partial root drying (PRD) on gas exchange biomasspartioning, and water use efficiency in potato. Scientia Horticulturae. 2006;**109**:113-117

[26] Katerji N, Mastrorilli M, Rana G. Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. European Journal of Agronomy. 2008;**28**:493-507. DOI: 10.1016/j.eja.2007.12.003

[27] Garcia-Orellana Y, Ruiz-Sanchez MC, Alarcon JJ, Conejero W, Ortuno MF, Nicolas E, et al. Preliminary assessment of the feasibility of using maximum daily trunk shrinkage for irrigation scheduling in lemon trees. Agricultural Water Management. 2007;**89**:167-171. DOI: 10.1016/j.agwat.2006.12.008

[28] Pérez-López D, Memmi H, Gijón-López MC, Moreno MM, Couceiro JF, Centeno A, et al. Irrigation of pistachios: Strategies to confront water scarcity. In: Tejero IFG, Zuazo VHD, editors. Water Scarcity and Sustainable Agriculture in Semiarid Environment: Tools, Strategies, and Challenges for Woody Crops. Academic Press: Elsevier; 2017. pp. 247-269

[29] Sofo A, Palese AM, Casacchia T, Dichio B, Xiloyannis C. Sustainable fruit production in mediterranean orchards subjected to drought stress. In: Ahmad P, Prasad MNV, editors. Abiotic Stress Responses in Plants Metabolism, Productivity and Sustainability. Springer; 2012. pp. 105-129. DOI: 10.1007/978-1-4614-0634-1-6

[30] Galindo AJ, Collado-Gonzalez J, Grinanc I, Corelld M, Centenof A, Martin-Palomod MJ, et al. Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems. Agricultural Water Management. 2018;**202**:311-324. DOI: 10.1016/j.gawt.2017.08.0.15

[31] Chalmers DJ, Mitchell PD, Vanheek L. Control of peach-tree growth and productivity by regulated water-supply, tree density, and summer pruning. Journal of the American Society for Horticultural Science. 1981;**106**:307-312

[32] Mitchell PD, Chalmers DJ. The effect of reduced water-supply on peach-tree growth and yields. Journal of the American Society for Horticultural Science. 1982;**107**:853-856

[33] McCarthy MG, Loveys BR, Dry PR. Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines. In: FAO, editor. Deficit Irrigation Practices. Water Reports Publication n. 22. Rome: FAO; 2002. pp. 79-87

[34] Domingo R, Ruiz-Sánchez MC, Sánchezblanco MJ, Torrecillas A. Water relations, growth and yield of Fino lemon trees under regulated deficit irrigation. Irrigation Science. 1996;**16**:115-123

[35] Geerts S, Raes D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agricultural Water Management. 2009;**96**:1275-1284

[36] Jones HG. Irrigation scheduling: Advantages and pitfalls of plant-based methods. Journal of Experimental Botany. 2004;**55**:2427-2436

[37] Shackel KA, Ahmadi H, Biasi W, Buchner R, Goldhamer D, Gurusinghe S, et al. Plant water status as an index of irrigation need in deciduous fruit trees. HortTechnology. 1997;**7**:23-29

[38] Marsal J, López G, Girona J. Recent advances in regulated deficit irrigation (RDI) in woody perennials and future perspectives. Acta Horticulturae. 2008;**792**:429-439. DOI: 10.17660/ActaHortic.2008.792.50

[39] Naor A, Stern R, Peres M, Greenblat Y, Gal Y, Flaishman MA. Timing and severity of postharvest water stress affect following-year productivity and fruit quality of field-grown 'Snow Queen' nectarine. Journal of the American Society for Horticultural Science. 2005;**130**:806-812

[40] Dry PR, Loveys BR. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Australian Journal of Grape and Wine Research. 1998;**4**:140-148. DOI: 10.1111/j.1755-0238.1998.tb00143

[41] Dry PR, Loveys BR, Botting D, During H. Effects of partial rootzone dryingon grapevine vigour, yield, composition of fruit and use of water. In: Stockley CS, Sas AN, Johnstone RS, Lee TH, editors. Proceedings of the 9th Australian Wine Industry Technical Conference. Adelaide, Australia: Winetitles; 1996. pp. 126-131

[42] Dry PR, Loveys BR, McCarthy MG, Stoll M. Strategic irrigation manage-ment in Australian vineyards. Journal International des Sciences de la Vigne et du Vin. 2001;**35**:129-139

[43] Dodd IC, Theobald JC, Bacon MA, Davies WJ. Alternation of wet and drysides during partial rootzone drying irrigation alters root-to-shoot signalling ofabscisic acid. Functional Plant Biology. 2006;**33**:1081-1089

[44] Wilkinson S, Hartung W. Food production: Reducing water consumption by manipulating long-distance chemical signalling in plants. Journal of Experimental Botany. 2009;**60**:1885-1891. DOI: 10.1093/jxb/erp121

[45] Adu MO, Yawson DO, Armah FA, Asare PA, Frimpong KA. Review: Meta-analysis of crop yields of full, deficit, and partial root-zone drying irrigation. Agricultural Water Management. 2018;**197**:79-90. DOI: 10.1016/j.agwat.2017.11.019

[46] Pellegrino A, Lebon E, Simonneau T, Wery J. Towards a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities of vegetative growth components. Australian Journal of Grape and Wine Research. 2005;**11**:306-315. DOI: 10.1111/j.1755-0238.2005.tb00030.x

[47] Ferreira MI, Katerji N. Is stomatal conductance in a tomato crop controlled by soil or atmosphere? Oecologia. 1992;**92**:104-107. DOI: 10.1007/BF00317269

[48] Ferreira MI. Stress coefficients for soil water balance combined with water stress indicators for irrigation scheduling of woody crops. Horticulturae. 2017;**3**:38. DOI: 10.3390/horticulturae3020038

[49] Vishwakarma K, Upadhyay N, Kumar N, Yadav G, Singh J, Mishra RK, et al. Abscisic acid signaling and abiotic stress tolerance in plants: A review on current knowledge and future prospects. Frontiers in Plant Science. 2017;**8**:161. DOI: 10.3389/fpls.2017.00161

[50] McCutchan H, Shackel K. Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). Journal of the American Society for Horticultural Science. 1992;**117**:607-611

[51] Schultz HR. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinífera* L. cultivars during drought. Plant, Cell & Environment. 2003;**26**:1393-1405. DOI: 10.1046/j.1365-3040.2003.01064

[52] Blanco-Cipollone F, Lourenço S, Silvestre J, Conceição N, Moñino MJ, Vivas A, et al. Plant water status indicators for irrigation scheduling associated with iso- and anisohydric behavior: Vine and plum trees. Horticulturae. 2017;**3**:47-64. DOI: 10.3390/horticulturae3030047

[53] Valancogne C, Ameglio T, Ferreira MI, Cohen M, Archer P, Dayau S, et al. Relations between relative transpiration and predawn leaf water potential in different fruit trees species. Acta Horticulturae. 1997;**449**:423-429

[54] Naor A. Irrigation scheduling and evaluation of tree water status in deciduous orchards. In: Horticultural Reviews. Oxford, UK: John Wiley & Sons, Inc.; 2010. pp. 111-165. DOI: 10.1002/9780470767986.ch3

[55] Kozlowski TT. Shrinking and swelling of plant tissues. In: Kozlowski TT, editor. Water Deficit and Plant Growth. New York, NY, USA: Academic Press; 1972. pp. 1-24

[56] Silvestre J, Ferreira MI, Conceição N, Malheiro AC. Can continuous records with plant-based methods be used to estimate water stress intensity in deficit irrigated vineyards? Ciência Técnica Vitivinicola. 2013;**28**:140-146

[57] Fernández JE. Plant-based methods for irrigation scheduling of woody crops. Horticulturae. 2017;**3**:35. DOI: 10.3390/horticulturae3020035

[58] Fernández JE, Cuevas MV. Irrigation scheduling from stem diameter variations: A review. Agricultural and Forest Meteorology. 2010;**150**:135-151. DOI: 10.1016/j.agrformet.2009.11.006

[59] Jackson RD, Idso SB, Reginato RJ, Pinter PJ. Canopy temperature as a drought stress indicator. Water Resources Research. 1981;**13**:651-656. DOI: 10.1029/WR017i004p01133

[60] Jones HG, Vaughan RA. Remote Sensing of Vegetation. Principles, Techniques, and Applications. London: Oxford Press; 2010. 384 p. ISBN: 9780199207794

[61] Alvino A, Marino S. Remote sensing for irrigation of horticultural crops. Horticulturae. 2017;**3**(2):40. DOI: 10.3390/horticulturae3020040

[62] Moriana A, Villalobos FJ, Fereres E. Stomatal and photosynthetic responsesof olive (*Olea europaea* L.) leaves to water deficits. Plant, Cell & Environment. 2002;**25**:395-405

[63] Moriana A, Orgaz F, Pastor M, Fereres E. Yield responses of a mature olive orchard to water deficits. Journal of the American Society for Horticultural Science. 2003;**128**(3):425-431

[64] Pérez-López D, Pérez-Rodríguez JM, Moreno MM, Prieto MH, Ramírez-Santa-Pau M, Gijón MC, et al. Influence of different cultivars-locations on maximum dailyshrinkage indicators: Limits to the reference baseline approach. Agricultural Water Management. 2013;**127**:31-39. DOI: 10.1016/j.agwat.2013.05.016

[65] Moriana A, Fereres E. Establishing reference values of trunk diameter fluctuations and stem water potential for irrigation scheduling of olive trees. Acta Horticulturae. 2004;**664**:407-412. DOI: 10.17660/ActaHortic.2004.664.51

[66] Fernández JE, Díaz-Espejo A, Infante JM, Durán P, Palomo MJ, Chamorro V, et al. Water relations and gas exchange in olive trees under regulated deficit irrigation and partial rootzone drying. Plant and Soil. 2006;**284**:273-291. DOI: 10.1007/s11104-006-0045-9

[67] Tognetti R, d'Andria R, Morelli G, Calandrelli D, Fragnito F. Irrigation effects on daily and seasonal variations of trunk sap flow and leaf water relations in olive trees. Plant and Soil. 2004;**263**:249-264

[68] Fernandes-Silva AA, López-Bernal A, Ferreira TC, Villalobos FJ. Leaf water relations and gas exchange response to water deficit of olive (cv. Cobrançosa) in field grown conditions in Portugal. Plant and Soil. 2016;**402**:191-209. DOI: 10.1007/s11104-015-2786-9

[69] Alcaras LMA, Rousseaux MC, Searles PS. Responses of several soil and plant indicators to post-harvest regulated deficit irrigation in olive trees and their potential for irrigation scheduling. Agricultural Water Management. 2016;**171**:10-20. DOI: 10.1016/j.agwat.2016.03.006

[70] Girona J, Gelly M, Mata M, Arbones A, Rufat J, Marsal J. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agricultural Water Management. 2005;**72**:97-108. DOI: 10.1016/j.agwat.2004.09.011

[71] Lopez G, Echeverria G, Bellvert J, Mata M, Behboudian MH, Girona J, et al. Water stress for a short period before harvest in nectarine: Yield, fruit composition, sensory quality, and consumer acceptance of fruit. Scientia Horticulturae. 2016;**211**:1-7. DOI: 10.1016/j.scienta.2016.07.035

[72] Li GY, Huang XF, Wang XW. Water use of drip irrigated peach trees under full irrigation and regulated deficit irrigation. In: Proceedings of the 6th International Micro-irrigation Congress; 22-27 October 2000; Cape Town, South Africa; 2000. pp. 1-6

[73] Paço T, Ferreira MI, Pacheco CA. Scheduling peach orchard irrigation in water stress conditions: Use of relative transpiration and predawn leaf water potential. Fruits. 2013;**68**:147-158. DOI: 10.1051/fruits/2013061

[74] Garcia A, André RG, Ferreira MI, Paço TA. Diurnal and seasonal variations of CWSI and non-water stressed baselines with nectarine trees. Acta Horticulturae. 2000;**537**:415-421. DOI: 10.17660/ActaHortic.2000.537.49

[75] Ferreira MI, Valancogne C, Michaelsen J, Pacheco CA, Ameglio T, Daudet F-A. Evapotranspiration, water stress indicators and soil water balance in a Prunus persica orchard, in central Portugal. Acta Horticulturae. 1997;**449**:379-384. DOI: 10.17660/ActaHortic.1997.449.53

[76] Martorell S, Diaz-Espejo A, Tomàs M, Pou A, El Aou-ouad H, Escalona JM, et al. Differences in water-use-efficiency between two *Vitis vinifera* cultivars (Grenache and Tempranillo) explained by the combined response of stomata to hydraulic and chemical signals during water stress. Agricultural Water Management. 2015;**156**:1-9. DOI: 10.1016/j.agwat.2015.03.011

[77] Bota J, Tomás M, Flexas J, Medrano H, Escalona JM. Differences among grapevine cultivars in their stomatal behavior and water use efficiency under progressive water stress. Agricultural Water Management. 2016;**164**:91-99. DOI: 10.1016/j.agwat.2015.07.016

[78] Girona J, Mata M, del Campo J, Arbonés A, Bartra E, Marsal J. The use of midday leaf water potential for scheduling deficit irrigation in vineyards. Irrigation Science. 2006;**24**:115-127. DOI: 10.1007/s00271-005-0015-7

[79] Malheiro AC, Gonçalves IN, Fernandes-Silva AA, Conceição N, Paço TA, Ferreira MI, et al. Relationships between relative transpiration of grapevines and plant and soil water status in Portugal's Douro Wine Region. Acta Horticulturae. 2011;**992**:261-268. DOI: 10.17660/ActaHortic.2011.922.34

[80] Brillante L, Mathieu O, Lévêque J, Bois B. Ecophysiological modeling of grapevine water stress in Burgundy Terroirs by a machine-learning approach. Frontiers in Plant Science. 2016;**7**:796-816. DOI: 10.3389/fpls.2016.00796

[81] Munitz S, Netzer Y, Schwartz A. Sustained and regulated deficit irrigation of field-grown Merlot grapevines. Australian Journal of Grape and Wine Research. 2017;**23**:87-94. DOI: 10.1111/ajgw.12241

[82] Sousa TA, Oliveira MT, Pereira JM. Physiological indicators of plant water status of irrigated and non-irrigated grapevines grown in a low rainfall area of Portugal. Plant and Soil. 2006;**282**:127-134. DOI: 10.1007/s11104-005-5374-6

[83] Acevedo-Opazo C, Ortega-Farias S, Fuentes S. Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. Agricultural Water Management. 2010;**97**:956-964. DOI: 10.1016/j.agwat.2010.01.025

[84] Lanari V, Palliotti A, Sabbatini P, Howell GS, Silvestroni O. Optimizing deficit irrigation strategies to manage vine performance and fruit composition of field-grown 'Sangiovese' (*Vitis vinifera* L.) grapevines. Scientia Horticulturae. 2014;**179**:239-247. DOI: 10.1016/j.scienta.2014.09.032

[85] Silvestre J, Ferreira MI, Valancogne C. Evapotranspiration and water relations from a vineyard in Central Portugal during spring-summer periods. Acta Horticulturae. 1999;**493**:213-218. DOI: 10.17660/ActaHortic.1999.493.21

[86] Martinez-De-Toda F, Balda P, Oliveira M. Estimation of vineyard water status (*Vitis vinifera* cv. Tempranillo) from the developmental stage of the shoot tips. Journal International des Sciences de la Vigne et du Vin. 2010;**44**:201-206. DOI: 10.20870/oeno-one.2010.44.4.1476

[87] Rodriguez Lovelle B, Trambouze W, Jacquet O. Evaluation of vegetative growth stage by the "shoot tip method". Le Progrès Agricole et Viticole. 2009;**126**:77-88

[88] Conceição N, Tezza L, Häusler M, Lourenço S, Pacheco AC, Ferreira MI. Three years of monitoring evapotranspiration components and crop and stress coefficients in a deficit irrigated intensive olive orchard. Agricultural Water Management. 2017;**91**:138-152. DOI: 10.1016/j.agwat.2017.05.011

[89] Bellvert J, Marsal J, Girona J, Zarco-Tejada PJ. Seasonal evolution of crop water stress index in grapevine varieties determined with high-resolution remote sensing thermal imagery. Irrigation Science. 2015;**33**:81-93. DOI: 10.1007/s00271-014-0456-y

[90] Grant OM, Ochagavía H, Baluja J, Diago MP, Tardáguila J. Thermal imaging to detect spatial and temporal variation in the water status of grapevine (*Vitis vinifera* L.). The Journal of Horticultural Science and Biotechnology. 2016;**91**:43-54. DOI: 10.1080/14620316.2015.1110991

[91] King BA, Shellie KC. Wine grape cultivar influence on the performance of models that predict the lower threshold canopy temperature of a water stress index. Computers and Electronics in Agriculture. 2018;**145**:122-129. DOI: 10.1016/j.compag.2017.12.025

[92] Selles G, Ferreyra R, Muñoz I, Silva H. Physiological indicators of plant water status as criteria for irrigation scheduling in table grapes cv. Crimson seedless, irrigated by drip. Acta Horticulturae. 2004;**664**:599-605. DOI: 10.17660/ActaHortic.2004.664.75

[93] Oliveira MT, Oliveira AC, Castro CB. Dependence of sap flow and stem diameter fluctuation of grapevines on reference evapotranspiration: An event coincidence analysis. Advances in Plants & Agriculture Research. 2017;**7**:279-287. DOI: 10.15406/apar.2017.07.00279

[94] Ojeda H, Andary C, Kraeva E, Carbonneau A, Deloire A. Influence of pre-and postveraison water deficits on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv Shiraz. American Journal of Enology and Viticulture. 2002;**53**:261-267. http://www.ajevonline.org/content/53/4/261.1

[95] Gaudin R, Kansou K, Christophe PJ, Pellegrino A, Gary C. A water stress index based on water balance modelling for discrimination of grapevine quality and yield. Journal International des Sciences de la Vigne et du Vin. 2014;**48**:1-10. DOI: 10.20870/oeno-one.2014.48.1.1655

[96] Rallo L, Cuevas J. In: Barranco D, Fernández-Escobar R, Rallo L, editors. Fruiting and Production, Olive Growing Madrid. Spain: Ediciones Mundi-Prensa; 2010. pp. 113-145

[97] Connor DJ, Fereres E. The physiology of adaptation and yield expression in olive. Horticultural Reviews. 2005;**31**:155-229

[98] Beltrán G, Uceda M, Hermoso M, Frias L. Maduracion. In: Barranco D, Fernández-Escobar R, Rallo L, editors. El cultivo de olivo. Madrid, Spain: Ediciones Mundi Prensa; 2008. pp. 163-187

[99] Costagli G, Gucci R, Rapoport H. Growth and development of fruits of olive "Frantoio" under irrigated and rainfed conditions. The Journal of Horticultural Science and Biotechnology. 2003;**78**:119-124

[100] Goldhamer DA. Regulated deficit irrigation for California canning olives. Acta Horticulturae. 1999;**474**:369-372. DOI: 10.17660/ActaHortic.1999.474.76

[101] Caruso G, Rapoport HF, Gucci R. Long-term evaluation of yield components of young olive trees during the onset of fruit production under different irrigation regimes. Irrigation Science. 2013;**31**:37-47. DOI: 10.1007/s00271-011-0286-0

[102] Hernandez-Santana V, Fernandes RDM, Perez-Arcoiza A, Fernández JE, Garcia JM, Diaz-Espejo A. Relationships between fruit growth and oil accumulation with simulated seasonal dynamics of leaf gas exchange in the olive tree. Agricultural and Forest Meteorology. 2018;**256**:458-469. DOI: 10.1016/j.agrformet.2018.03.019

[103] Correa-Tedesco G, Rousseaux MC, Searles PS. Plant growth and yield responses in olive (*Olea europaea*) to different irrigation levels in an arid region of Argentina. Agricultural Water Management. 2010;**97**:1829-1837. DOI: 10.1016/j.agwat.2010.06.020

[104] Conceição N, Tezza L, Lourenço S, Häusler M, Boteta L, Pacheco C, et al. Importance of very fine roots in deep soil layers for the survival of rainfed olive trees. Acta Horticulturae. 2018;**1199**:57-62. DOI: 10.17660/ActaHortic.2018.1199.9

[105] Martín-Vertedor AI, Pérez-Rodríguez JM, Prieto-Losada E, Fereres-Castiel E. Interactive responses to water deficits and crop load in olive (*Olea europaea* L., cv. Morisca). I: Growth and water relations. Agricultural Water Management. 2011;**98**:941-949. DOI: 10.1016/j.agwat.2011.01.002

[106] Martín-Vertedor AI, Pérez-Rodríguez JM, Prieto-Losada E, Fereres-Castiel E. Interactive responses to water deficits and crop load in olive (*Olea europaea* L., cv. Morisca). II: Water use, fruit and oil yield. Agricultural Water Management. 2011;**98**:950-958. DOI: 10.1016/j.agwat.2011.01.003

[107] Lavee S, Hanoch E, Wodner M, Abramowitch E. The effect of predetermined deficit irrigation on the performance of cv. Muhasan olives (*O. europaea* L.) in the eastern coastal plain of Israel. Scienctia Horticulturae. 2007;**112**:156-163. DOI: 10.1016/j.scienta.2006.12.017

[108] Wahbi S, Wakrim R, Aganchich B, Tahi H, Serraj R. Effects of partial rootzone drying (PRD) on adult olive tree (*Olea europaea*) in field conditions under arid climate: I. Physiological and agronomic responses. Agriculture, Ecosystems & Environment. 2005;**106**:289-301. DOI: 10.1016/j.agee.2004.10.015

[109] Richard C, Rosecrance RC, William H, Krueger WH, Milliron L, Bloese J, et al. Moderate regulated deficit irrigation can increase olive oil yields and decrease tree growth in super high density 'Arbequina' olive orchards. Scientia Horticulturae. 2015;**190**:75-82. DOI: 10.1016/J.scienta.2015.03.045

[110] Gómez del Campo M. Summer deficit–irrigation strategies in a hedgerow olive orchard cv. 'Arbequina': Effect on fruit characteristics and yield. Irrigation Science. 2013;**31**: 259-269. DOI: 10.1007/s00271-011-0299-8

[111] Padilla-Díaz CM, Rodriguez-Dominguez CM, Hernandez-Santana V, Perez-Martin A, Fernández JE. Scheduling regulated deficit irrigation in a hedgerow olive orchard from leaf turgor pressure related measurements. Agricultural Water Management. 2016;**164**: 28-37. DOI: 10.1016/j.agwat.2015.08.002

[112] Marra FP, Marino G, Marchese A, Caruso T. Effects of different irrigation regimes on a super-high-density olive grove cv. "Arbequina": Vegetative growth, productivity and polyphenol content of the oil. Irrigation Science. 2016;**4**:313-325. DOI: 10.1007/s00271-016-0505-9

[113] Aganchich B, Tahi H, Wahbi S, Elmodaffar C, Serraj R. Growth, water relations and antioxidant defence mechanisms of olive (*Olea europaea* L.) subjected to partial root drying (PRD) and regulated deficit irrigation (RDI). Plant Biosystems. 2007;**141**:252-264. DOI: 10.1080/11263500701401893

[114] Fernandes-Silva AA, Falco V, Correia CM, Villalobos FJ. Sensory analysisand volatile compounds of olive oil (cv. Cobrançosa) from different irrigationregimes. Grasas y Aceites. 2013;**61**:59-67. DOI: 10.3989/gya.069712

[115] Berenguer MJ, Vossen PM, Grattan SR, Connell JH, Polito VS. Tree irrigation levels for optimum chemical and sensory properties of olive oil. Hortscience. 2006;**41**:427-432

[116] Motilva MJ, Tovar MJ, Romero MP, Alegre S, Girona J. Influence of regulated deficit irrigation strategies applied to olive trees (*Arbequina cultivar*) on oil yield and oil composition during the fruit ripening period. Journal of the Science of Food and Agriculture. 2000;**80**:2037-2043. DOI: 10.1002/1097-0010

[117] García JM, Cuevas MV, Fernández JE. Production and oil quality in 'Arbequina' olive (*Olea eurpoaea*, L.) trees under two deficit irrigation strategies. Irrigation Science. 2013;**31**:359-370

[118] Dabbou S, Chehab H, Faten B, Dabbou S, Esposto S, Selvaggini R, et al. Effect of three irrigation regimes on Arbequina olive oil produced under Tunisian growing conditions. Agricultural Water Management. 2010;**97**:763-768. DOI: 10.1016/j.agwat.2010.01.011

[119] Magliulo V, d'Andria R, Lavini A, Morelli G, Patumi M. Yield and quality of two rainfed olive cultivars following shifting to irrigation. The Journal of Horticultural Science and Biotechnology. 2003;**78**:15-23. DOI: 10.1080/14620316.2003.11511578

[120] Rondanini DP, Castro DN, Searles PS, Rousseaux MC. Contrasting patterns of fatty acid composition and oil accumulation during fruit growth in several olive varieties and locations in a non-Mediterranean region. European Journal of Agronomy. 2014;**52**: 237-246. DOI: 10.1016/j.eja.2013.09.002

[121] Cano-Lamadrid M, Girón IF, Pleite R, Burló F, Corell M, et al. Quality attributes of table olives as affected by regulated deficit irrigation. Food Science and Technology. 2015;**62**:19-26. DOI: 10.1016/j.lwt.2014.12.063

[122] Cano-Lamadrid M, Hernández F, Corell M, Burló F, Legua P, et al. Antioxidant capacity, fatty acids profile, and descriptive sensory analysis of table olives as affected by deficit irrigation. Journal of the Science of Food and Agriculture. 2017;**97**:444-451. DOI: 10.1002/jsfa.7744

[123] Collado J, Moriana A, Giron I, Gil-Izquierdo A. The phytoprostane content in green table olives is influenced by Spanish-style processing and regulated deficit irrigation. Food Science and Technology. 2015;**64**:997-1003. DOI: 10.1016/j.lwt.2015.07.005

[124] Moriana A, Corell M, Giron IF, Conejero W, Morales D, et al. Regulated deficit irrigation based on threshold values of trunk diameter fluctuation indicators in table olive trees. Scientia Horticulturae. 2013;**164**:102-111. DOI: org/10.1016/j.scienta.2013.09.029

[125] Minghetti L, Salvi R, Maria LS, Ajmone-Cat MA, De Nuccio C, Visentin S, et al. Nonenzymatic oxygenated metabolites of α-linolenic acid B1- and L1-phytoprostanes protect immature neurons from oxidant injury and promote differentiation of oligodendrocyte progenitors through PPAR-γ activation. Free Radical Biology and Medicine. 2014;**73**:41-50. DOI: 10.1016/j.freeradbiomed.2014.04.025

[126] Mounzer OH, Conejero W, Nicolás E, Abrisqueta I, García-Orellana YV, Tapia LM, et al. Growth pattern and phenological stages of early-maturing peach trees under a Mediterranean climate. Hortscience. 2008;**43**:1813-1818

[127] Moing A, Rothan C, Svanella L, Just D, Diakou P, Raymond P, et al. Role of phosphoenolpyruvate carboxylase in organic acid accumulation during peach fruit development. Physiologia Plantarum. 2000;**108**:1-10. DOI: 10.1034/j.1399-3054.2000.108001001

[128] Chalmers DJ, Vandenende B. Productivity of peach trees—Factors affecting dry-weight distribution during tree growth. Annals of Botany. 1975;**39**:423-432

[129] Johnson RS, Handley DF, DeJong TM. Long-term response of early maturing peach trees to postharvest water deficits. Journal of American Society for Horticulture Science. 1992;**117**:881-886

[130] Girona J, Mata M, Goldhamer DA, Johnson RS, DeJong TM. Patterns of soil and tree water status and leaf functioning during regulated deficit irrigation scheduling in peach. Journal of American Society for Horticulture Science. 1993;**118**:580-586

[131] De la Rosa JM, Conesa MR, Domingo R, Aguayo E, Falagan N, Perez-Pastor A. Combined effects of deficit irrigation and crop level on early nectarine trees. Agricultural Water Management. 2016;**170**:120-132. DOI: 10.1016/j.agwat.2016.01.012

[132] Massai R, Remorini D, Ferreira M, Paço TA. Sap flow in peach trees during water stress and recovery in two environmental conditions. Acta Horticulturae. 2000;**537**:351-358. DOI: 10.17660/ActaHortic.2000.537.41

[133] Marsal J, Casadesus J, Lopez G, Mata M, Bellvert J, Girona J. Sustainability of regulated deficit irrigation in a mid-maturing peach cultivar. Irrigation Science. 2016;**34**:201-208. DOI: 10.1007/s00271-016-0498-4

[134] Pascual M, Villar JM, Rufat J. Water use efficiency in peach trees over a four-years experiment on the effects of irrigation and nitrogen application. Agricultural Water Management. 2016;**164**:253-266. DOI: 10.1016/j.agwat.2015.10.021

[135] Zhou HM, Zhang FC, Kjelgren R, Wu LF, Gong DZ, Zhao N, et al. Peach yield and fruit quality is maintained under mild deficit irrigation in semi-arid China. Journal of Integrative Agriculture. 2017;**16**:1173-1183. DOI: 10.1016/S2095-3119(16)61571

[136] Zhang HH, Wang D, Gartung JL. Influence of irrigation scheduling using thermometry on peach tree water status and yield under different irrigation systems. Agronomy. 2017;**7**:1-15. DOI: 10.3390/agronomy7010012

[137] Vera J, Abrisqueta I, Abrisqueta JM, Ruiz-Sanchez MC. Effect of deficit irrigation on early-maturing peach tree performance. Irrigation Science. 2013;**31**:747-757. DOI: 10.1007/s00271-012-0358-9

[138] Pérez-Sarmiento F, Miras-Avalos JM, Alcobendas R, Alarcon JJ, Mounzer O, Nicolas E. Effects of regulated deficit irrigation on physiology, yield and fruit quality in apricot trees under Mediterranean conditions. Spanish Journal of Agricultural Research. 2016;**14**. DOI: 10.5424/sjar/2016144-9943

[139] Lorenz DH, Eichhorn KW, Bleiholder H, Klose R, Meier U, Weber E. Growth stages of the grapevine: Phenological growth stages of the grapevine (*Vitis vinifera* L. ssp. vinifera)—Codes and descriptions according to the extended BBCH scale. Australian Journal of Grape and Wine Research. 1995;**1**:100-103. DOI: 10.1111/j.1755-0238.1995.tb00085.x

[140] Cortázar-Atauri GI, Brisson N, Gaudillere JP. Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). International Journal of Biometeorology. 2009;**53**:317-326. DOI: 10.1007/s00484-009-0217-4

[141] Martínez-Lüscher J, Kizildeniz T, Vučetić V, Dai Z, Luedeling E, van Leeuwen C, et al. Sensitivity of grapevine phenology to water availability, temperature and CO_2 concentration. Frontiers in Environmental Science. 2016;**4**:1-14. DOI: 10.3389/fenvs.2016.00048

[142] Shellie K, Kovaleski AP, Londo JP. Water deficit severity during berry development alters timing of dormancy transitions in wine grape cultivar Malbec. Scientia Horticulturae. 2018;**232**:226-230. DOI: 10.1016/j.scienta.2018.01.014

[143] Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR. Earlier winegrape ripening driven by climatic warming and drying and management practices. Nature Climate Change. 2012;**2**:259-264. DOI: 10.1038/nclimate1417

[144] Tomasi D, Jones GV, Giust M, Lovat L, Gaiotti F. Grapevine phenology and climate change: Relationships and trends in the Veneto region of Italy for 1964-2009. American Journal of Enology and Viticulture. 2011;**62**:329-339. DOI: 10.5344/ajev.2011.10108

[145] Bonada M, Sadras VO. Review: Critical appraisal of methods to investigate the effect of temperature on grapevine berry composition. Australian Journal of Grape and Wine Research. 2015;**21**:1-17. DOI: 10.1111/ajgw.12102

[146] Lovisolo C, Hartung W, Schubert A. Whole-plant hydraulic conductance and root-to-shoot flow of abscisic acid are independently affected by water stress in grapevines. Functional Plant Biology. 2002;**29**:1349-1356. DOI: 10.1071/FP02079

[147] Patakas A, Noitsakis B. Mechanisms involved in diurnal changes of osmotic potential in grapevines under drought conditions. Journal of Plant Physiology. 1999;**154**:767-774. DOI: 10.1016/S0176-1617(99)80256-9

[148] Jones GV, White MA, Cooper OR, Storchmann K. Climate change and global wine quality. Climatic Change. 2005;**73**:319-343. DOI: 10.1007/s10584-005-4704-2

[149] Jones GV, Alves F. Impacts of climate change on wine production: A global overview and regional assessment in the Douro Valley of Portugal. International Journal of Global Warming. 2012;**4**:383-406. DOI: 10.1504/IJGW.2012.049448

[150] Duchêne E, Huard F, Dumas V, Schneider C, Merdinoglu D. The challenge of adapting grapevine varieties to climate change. Climate Research. 2010;**41**:193-204. DOI: 10.3354/cr00850

[151] Oliveira M. Viticulture in warmer climates: Mitigating environmental stress in Douro Region, Portugal. In: Jordão AM, Cosme F, editors. Grapes and Wines—Advances in Production, Processing, Analysis and Valorization. Rijeka, Croatia: InTech; 2018. pp. 59-75. DOI: 10.5772/intechopen.71155

[152] Oliveira MT, de Freitas V, Sousa TA. Water use efficiency and must quality of irrigated grapevines of north-eastern Portugal. Archives of Agronomy and Soil Science. 2011;**58**:871-886. DOI: 10.1080/03650340.2011.551875

[153] Keller M, Romero P, Gohil H, Russell RP, Riley WR, Casassa F, et al. Deficit irrigation alters grapevine growth, physiology, and fruit microclimate. American Journal of Enolology and Viticulture. 2016;**67**:426-435. DOI: 10.5344/ajev.2016.16032

[154] Bonada M, Sadras V, Moran M, Fuentes S. Elevated temperature and water stress accelerate mesocarp cell death and shrivelling, and decouple sensory traits in Shiraz berries. Irrigation Science. 2013;**31**:1317-1321. DOI: 10.1007/s00271-013-0407-z

[155] Esteban MA, Villanueva MJ, Lissarrague JR. Effect of irrigation on changes in berry composition of Tempranillo during maturation. Sugars, organique acids and mineral elements. American Journal of Enology and Viticulture. 1999;**50**:418-433. http://www.ajevonline.org/content/50/4/418

[156] Chaves MM, Santos TP, Souza CR, Ortuño MF, Rodrigues ML, Lopes CM, et al. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. Annals of Applied Biology. 2007;**150**:237-252. DOI: 10.1111/j.1744-7348.2006.00123

[157] Etienne A, Genard M, Lobit P, Mbeguie-A-Mbeguie D, Bugaud C. What controls fleshy fruit acidity? A review of malate and citrate accumulation in fruit cells. Journal of Experimental Botany. 2013;**64**:1451-1469. DOI: 10.1093/jxb/ert035

[158] Cohen SD, Tarara JM, Gambetta GA, Matthews MA, Kennedy JA. Impact of diurnal temperature variation on grape berry development, proanthocyanidin accumulation, and the expression of flavonoid pathway genes. Journal of Experimental Botany. 2012;**63**:2655-2665. DOI: 10.1093/jxb/err449

[159] Bonada M, Jeffery DW, Petrie PR, Moran MA, Sadras VO. Impact of elevated temperature and water deficit on the chemical and sensory profiles of Barossa Shiraz grapes and wines. Australian Journal of Grape and Wine Research. 2015;**21**:240-253. DOI: 10.1111/ajgw.12142

[160] Sadras VO, Stevens R, Pech J, Taylor E, Nicholas P, McCarthy M. Quantifying phenotipic plasticity of berry traits using an allometrictype approach: A case study on anthocyanins and sugars in berries of Cabernet Sauvignon. Australian Journal of Grape and Wine Research. 2007;**13**:72-80. DOI: 10.1111/j.1755-0238.2007.tb00237

[161] Sadras VO, Moran MA. Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. Australian Journal of Grape and Wine Research. 2012;**18**:115-122. DOI: 10.1111/j.1755-0238.2012.00180

[162] Giese G, Velasco-Cruz C, Roberts L, Heitman J, Wolf TK. Complete vineyard floor cover crops favorably limit grapevine vegetative growth. Scientia Horticulturae. 2014;**170**: 256-266. DOI: 10.1016/j.scienta.2014.03.011

[163] Smart RE, Robinson M. Sunlight into Wine: A Handbook for Wine Grape Canopy Management. Adelaide, Australia: Winetitles, Pty. Ltd; 1991. 88 p

[164] Basile B, Marsal J, Mata M, Vallverdu X, Bellvert J, Girona J. Phenological sensitivity of Cabernet Sauvignon to water stress: Vine physiology and berry composition. American Journal of Enolology and Viticulture. 2011;**62**:452-461. DOI: 10.5344/ajev.2011.11003

[165] Intrigliolo DS, Perez D, Risco D, Yeves A, Castel JR. Yield components and grape composition responses to seasonal water deficits in Tempranillo grapevines. Irrigation Science. 2012;**30**:339-349. DOI: 10.1007/s002

[166] Resco P, Iglesias A, Bardají I, Sotés V. Exploring adaptation choices for grapevine regions in Spain. Regional Environmental Change. 2016;**16**:979-993. DOI: 10.1007/s10113-015-0811-4

[167] Kang S, Zhang J. Controlled alternate partial root-zone irrigation: Its physiological consequences and impact on water use efficiency. Journal of Experimental Botany. 2004;**55**:2437-2446. DOI: 10.1093/jxb/erh249

[168] Tarara JM, Peña JEP. Moderate water stress from regulated deficit irrigation decreases transpiration similarly to net carbon exchange in grapevine canopies. Journal of the American Society for Horticultural Science. 2015;**140**:413-426. http://journal.ashspublications.org/content/140/5/413.full.pdf+html

[169] Oliveira MT, Sousa TA. Organic acids and sugars in musts of irrigated grapevines in Northeast Portugal. Journal of Wine Research. 2010;**20**(1):1-13. DOI: 10.1080/09571260902978485

[170] Romero P, García JG, Fernández-Fernández JI, Muñoz RG, Saavedra FA, Martínez-Cutillas A. Improving berry and wine quality attributes and vineyard economic efficiency by long-term deficit irrigation practices under semiarid conditions. Scientia Horticulturae. 2016;**203**:69-85. DOI: 10.1016/j.scienta.2016.03.013

[171] Koundouras S, Marinos V, Gkoulioti A, Kotseridis Y, Van Leeuwen C. Influence of vineyard location and vine water status on fruit maturation of non-irrigated cv Agiorgitiko (*Vitis vinifera* L.). Effects on wine phenolic and aroma components. Journal of Agriculture and Food Chemistry. 2006;**54**:5077-5086. DOI: 10.1021/jf0605446

[172] Koundouras S, Van Leeuwen C, Seguin G, Glories Y. Influence of water status on vine vegetative growth, berry ripening and wine characteristics in Mediterranean zone (example of Nemea, Greece, variety Saint-George, 1997). International Journal of Wine Research. 1999;**33**:149-160. DOI: 10.20870/oeno-one.1999.33.4.1020

[173] Peterlunger E, Sivilotti P, Bonetto C, Paladin M. Water stress induces changes in polyphenol concentration in Merlot grape and wines. Rivista di Viticoltura e di Enologia. 2002;**1**:51-66

[174] Niculcea M, Martinez-Lapuente L, Guadalupe Z, Sánchez-Diaz M, Ayesteran B, Aantolín MC. Characterization of phenolic composition of Vitis vinifera L. 'Tempranillo' and 'Graciano' subjected to deficit irrigation during berry development. Vitis. 2015;**54**: 9-16

Chapter 6

Water Footprint Differences of Producing Cultivars of Selected Crops in New Zealand

Isaac R. Fandika, Peter D. Kemp,
James P. Millner and Davie Horne

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77509

Abstract

Water footprint (WF) is a measure of the amount of water used to produce goods and services. It is a very important concept on indicating how much water can be consumed to complete a process of growing or processing a product at a particular location. However, paucity of water footprint information in countries facing increased competition for water resources between industries limits market access and profit optimization. Water footprint differences of producing selected cultivars of potato, oca and pumpkin squash were determined under irrigation and rain-fed regimes. All crop husbandry practices were followed in potato, oca (3.3 plants m^{-2}) and pumpkin squash (2.2 plants m^{-2}). Water footprint was determined as the ratio of volume of evapotranspiration for irrigated and rain-fed crops plus grey water to total yield. The consumptive water use for the rain-fed crop was 75, 65 and 69% of the irrigated oca, potato and pumpkin squash, respectively, with high water consumption in heritage cultivars. The water footprint was low in pumpkin squash and highest in oca, while potato cultivars were intermediate. Irrigation reduced water footprint especially in crops more responsive to irrigation. Farmers should focus on improving the harvest index and irrigation to reduce water footprint.

Keywords: water footprint, irrigation, potato, oca, pumpkin squash

1. Introduction

The agricultural industry in New Zealand consumes 77% of the freshwater resources [1]. Climate change alongside population and urbanisation has broaden this demand by increasing water utilisation per capita [2]. Water consumption and pollution associated with agriculture has created a great competition for water [3]. As of now groundwater withdrawal and rainwater evaporation, in addition to environmental pollution are accelerating [4]. Until the recent past, there has been little attention to how water is consumed and polluted in agriculture in New Zealand. As a result, the profitability of traditionally irrigated crops reduced [5]. Improved understanding of water footprint (WF) differences in cultivars can reduce the pressure on freshwater, while still maintaining their profits and sustaining the environment. This can be achieved if farmers can start using water sparingly under both modern and heritage crop cultivars [6].

Information on water footprint differences in selected heritage cultivars used by Maori for over 200 years is of significant importance because of their social and cultural value to the economy [7]. McFarlane stated that these heritage cultivars attract a niche market and provide a cultural economy [8]. For instance, the Taewa Maori potato and Kamokamo are a treasured heritage used to enforce land rights, values and sustainable development in New Zealand [9]. Lately, modern crop cultivars have made a significant advancement in productivity, above heritage cultivars. The increased interest in heritage cultivars is restricted by a lack of information on their water use. There is need of information on new ways to grow heritage or modern crops while leaving more water available for people, plants and animals. Idea of considering water use along supply chain can be well explained by the concept of water footprint (WF).

1.1. Definition and significance of water footprint

Water footprint (m^3 ton^{-1}) is defined as the volume of water required to produce a given weight or volume of specific crop [10]. It is a multidimensional indicator showing water consumption volumes by source and polluted volumes by type of pollution where all components of total water footprint are specified geographically and temporally. This footprint is an important factor in future market access, water conservation and growing international trade in agriculture [11]. The study and literature on water footprint expose hidden uses of water resources in producing a crop product over a complete supply chain (producers to consumers). Discovery of such hidden links can form basis for the formulation of new strategies of water governance among growers and consumers. The knowledge of water footprint to final consumers, retailers, food industries and traders in water—intensive products can make them become agent of change in promoting sparing water use. Nevertheless, the water footprint of arable crops has not been sufficiently examined among standard and heritage crop cultivars in New Zealand. In this chapter, we discuss the water footprint differences of producing selected heritage and modern potato, oca and pumpkin squash cultivars grown under rain-fed and irrigated conditions, in New Zealand; and finally what the WF means in the context of the social-economic aspects of growers.

2. Method for assessing the process water footprint of growing selected crops

2.1. Site biophysical characteristics and crop management

Water footprint study of the process of growing crops was conducted at Massey University's Pasture and Crop Research Unit, Palmerston North, between November, 2009 and April, 2011. Massey University is located at a latitude of 40°22′ 54.02 S, longitude 175°36′ 22.80 E, and an altitude of 36 m a.s.l. The soil type is Manawatu sandy loam with Olsen P at 36 mg/L; K at 0.22

mg/100 g, available N at 106 kg ha^{-1} and anaerobically mineralised N kg^{-1} at 76.8 mg at the beginning of the experiment. Climatic data for the site is in **Figure 1**.

The study crops were managed at both supplementary irrigation and rain-fed conditions. There were four cultivars of potato (*Solanum tuberosum* L., *Solanum andigena* Juz & Buk.), two of oca (*Oxalis tuberosa* Mol.) and two of pumpkin squash (*Curcubita pepo* Linn and *Cucurbuta maxima* Duchesne) in each water regime. Rainfall treatment measured green water (rain water) while supplementary irrigation measured both green and blue water footprint (water from river, sea or ocean or ground) [12]. The four-selected potato cultivars included two modern cultivars (Agria and Moonlight (*S. tuberosum* L.)) and two heritage cultivars (Moe Moe (*S. tuberosum* L.) and Tutaekuri (*S. andigena* Juz & Buk.)). The two selected pumpkin squash cultivars included buttercup squash, Ebisu (*C. maxima* Duchesne, a modern cultivar) and Kamokamo (*C. pepo* Linn, a heritage cultivar), while two unnamed oca cultivars with dark orange and scarlet coloured tubers were used.

All crop husbandry practices were followed in potato, oca (3.3 plants m^{-2}) and pumpkin squash (2.2 plants m^{-2}). Potatoes and oca received 12 N:5.2 P:14 K:6 S + 2 Mg + 5 Ca, using 500 kg ha^{-1} Nitrophoska Blue TE at planting, followed by 100 kg N ha^{-1} of urea 21 days later. The pumpkin squash received 12 N:5.2 P:14 K:6 S + 2 Mg + 5 Ca, using 700 kg ha^{-1} Nitrophoska Blue TE at planting, followed by 66 kg N ha^{-1}, when the vines started running. Pests and diseases were also controlled accordingly [13].

2.2. Irrigation and crop water use measurement

In order to measure the actual water use, a soil water balance was used to determine the soil moisture deficit (SMD) on a daily basis during the growth of the crops [14]. The potential evapotranspiration (ETp) in the soil water balance was computed using the FAO 56 Penman-Monteith method [15, 16]. The crop coefficient factors used in the computation were for potato, because this was the most sensitive crop to water use [17]. NIWA/Ag Research in Palmerston North provided daily weather data for running the soil water balance model. The soil water balance model helped to scheduling irrigation centering on refilling 25 mm of the soil moisture deficit when it reaches 30 mm. It was made sure that approximately half the readily available water was supplied. An equation of actual crop evapotranspiration (ET_c) was used as in Eq. (1) [15]. Soil moisture was monitored using time-domain reflectometer (TDR) to determine soil moisture change (ΔS) [13] and surface runoff (R_o) was negligible.

$$ET_c = P + I - D_p - R_o + \Delta S \tag{1}$$

Consumptive water use (CWU) for the entire growing cycle, for irrigation and rain-fed treatments, were referred to as blue and green components, respectively. The CWU was determined according to Hoekstra [10], as in Eq. (2), where $\sum ETcblue$ and $\sum ETcgreen$ is the accumulation of actual water use (evapotranspiration) over the complete growing cycle for irrigated and rain-fed crops, respectively. Factor of 10 was required to convert water depths of mm into volume in m^3 ha^{-1} [10].

$$\begin{aligned} CWU_{blue+green} &= 10 \times \sum ETcblue + ETcgreen \\ CWUgreen &= 10 \times \sum ETgreen \end{aligned} \tag{2}$$

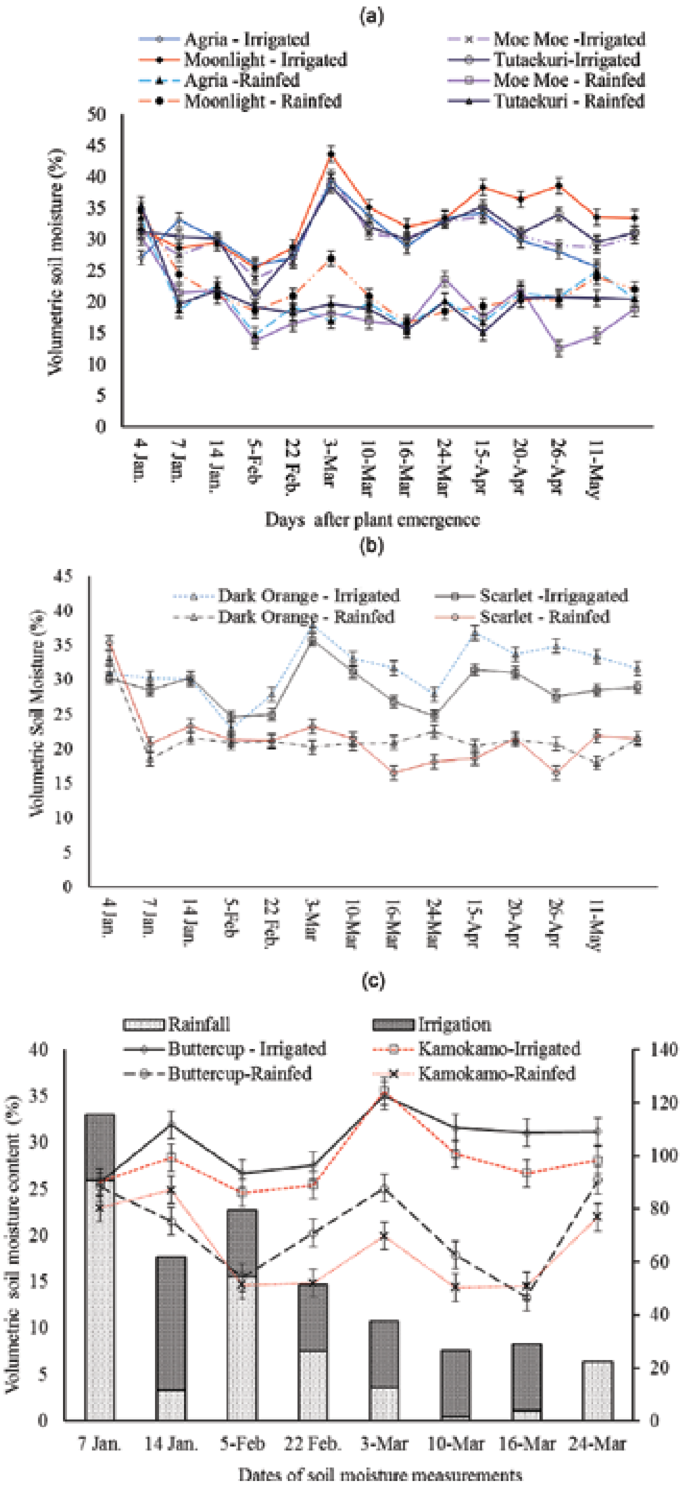

Figure 1. Soil moisture change in heritage and modern potato, oca and pumpkin squash cultivars under irrigation and rain-fed conditions.

2.3. Determination of water footprint differences of cultivars of selected crops

Water footprint (m^3 t ha^{-1}) was determined as the ratio of actual crop water use (m^3 ha^{-1}) to the total yield or total biomass yield (t ha^{-1}) [10]. Total water footprint was the sum of blue, green and grey water footprint. Blue and green water footprint (m^3 t ha^{-1}) was a ratio of blue and green crop water use (mm), to the total yield or total biomass yield (t ha^{-1}), respectively [18]. Grey water footprint (m^3 t ha^{-1}) was determined as a ratio of total volume of water (m^3) required diluting nitrogen that reached the ground water, per ton of produce [19]. Grey water footprint was estimated by multiplying the leaching fraction by the nitrogen application (kg ha^{-1}) and dividing the difference between the permissible limit and the natural concentration of nitrogen in the receiving water body. The study assumed a natural water nitrate concentration of 5.6 mg l^{-1} and the permissible limit of 11.3 mg l^{-1} [20]. Leaching fraction was assumed at 10% [18, 21]. This study compared the water footprint based on actual crop yield and crop water use, in order to remove the disparity of over-estimation, once hypothetical crop and crop water requirements are used [22, 23].

2.4. Social-economic analysis of the selected crop cultivar

An economic assessment of Taewa against modern potato varieties in relation to irrigation investments was done using the net present value (NPV) method. Net present value is an investment analysis also referred as a total of present value of a single project cashflow of the same unit [24]. In order to get NPV, fixed and annual operating costs and expected returns were estimated based on a 5-ha small scale irrigation using a Trail Travel Irrigator to obtain the economic implications of the system on crop production. The data in the study on marketable fresh tuber or marketable fruit yield were used to analyse the economics of Taewa and water footprint. Crop water use and total yield from the three crops were pooled, in order to determine their comparative water footprint differences.

3. Results

3.1. Crop water use and yield summary

Total consumptive water use (blue plus green water) for oca, potato and pumpkin squash in rain-fed and irrigation ranged from 5061 to 6824, 3470 to 5685 and 2551 to 4132 m^3 ha^{-1}, respectively. Consumptive water use (m^3 ha^{-1}) was greatest in oca and lowest in pumpkin squash, while potatoes were intermediate, despite variation within cultivars. The modern and heritage crops differed in their relationship between their maximum water requirement and actual evapotranspiration, thus crop coefficient (k_c) and maturity (**Figure 2**). Taewa and Kamokamo used more water compared to modern cultivars (**Table 1**). Green water was approximately 62, 65, 58 and 70% of consumptive water use, under irrigated modern potato, Taewa, pumpkin squash and oca, respectively. Blue water for oca and potato was 2000 m^3 ha^{-1}, while pumpkin squash received 1750 m^3 ha^{-1}, applied to meet at least 100% of the crop's water requirement.

Grey water also significantly differed between cultivars with the highest in potato and oca. An equivalency of diluting requirement to the grey water for the applied N in potato or oca and

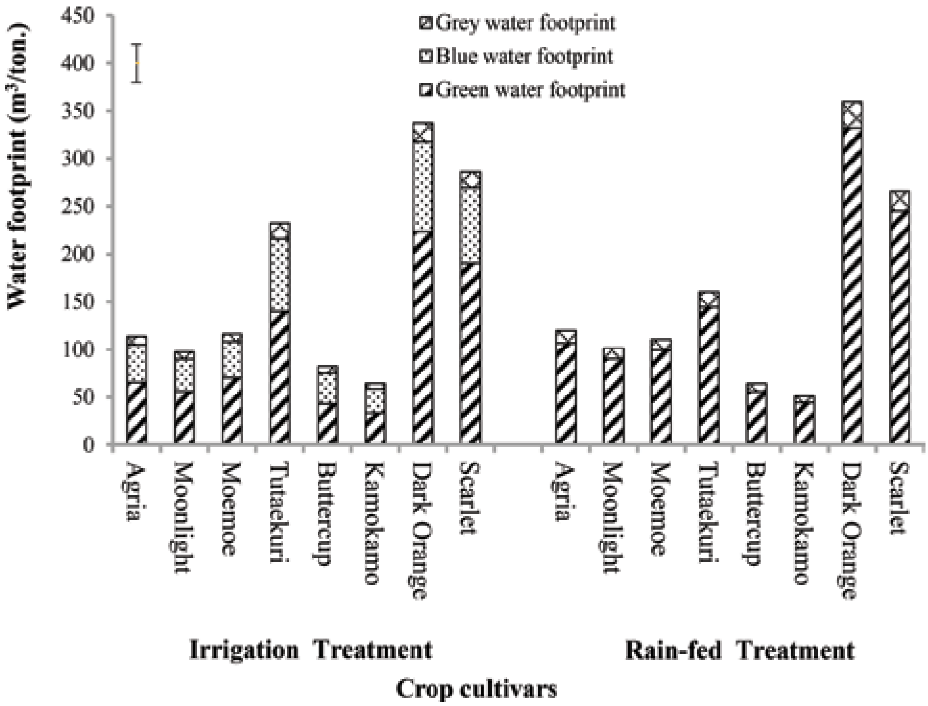

Figure 2. Blue, green and grey water footprint on total yield of potato, oca and pumpkin squash crop cultivars under irrigation and rain-fed condition in New Zealand, 2010. Error bar represents $LSD_{0.05}$.

pumpkin squash was 425 and 398 m^3 ha^{-1}, respectively (**Table 1**). An increase in N rate application raised the grey water in potato and oca compared to pumpkin squash. The actual crop water use for rain-fed crop in oca, potato and pumpkin squash was 74.9, 65.1 and 69% of the irrigated crop, respectively (**Table 1**). The total consumptive water use (m^3 ha^{-1}) was greatest in oca and lowest in pumpkin squash, while potato was intermediate, despite variation within cultivars. Heritage crops (Maori potato, Kamokamo) used more water because of its long growing season.

Differences in yields were observed to be influenced by water regime and crop cultivars among the eight selected crop cultivars. With exception of Tutaekuri, average yields continuously increased from rain-fed (16.7–67.7 t ha^{-1}) to irrigated conditions (23.2–78 t ha^{-1}). Kamokamo had the greatest yields while dark orange had the lowest yields under both water regimes. Average yields for other crops' varieties such as Agria, Moonlight and Moe Moe were similar but greatly lower than Kamokamo. Out of the crop cultivars, oca varieties and Tutaekuri proved to have lowest yield levels. Agria, Moonlight and Moe Moe also demonstrated an ability of partitioning more dry matter to economic yields basing on its harvest index (HI). In summary, the heritage crop cultivars extremely partition more to biomass unlike most of the modern cultivars which partition more to economic yields (**Table 1**).

3.2. Water footprint differences of cultivars of selected heritage and modern crops

3.2.1. Blue, green and grey water footprint on total yield

The green, blue and grey water footprint components varied with both crop cultivars and water regimes as presented in **Tables 2** and **3** and **Figure 2**. The total water footprint of consumptive

http://dx.doi.org/10.5772/intechopen.77509

Water regime/ cultivars	Planting date	Harvesting date	Total yield (t ha^{-1})	Total biomass (t ha^{-1})	Consumptive water use (m^3 ha^{-1})			Grey water (m^3 ha^{-1})
					Green water	Blue water	Total CWU	
Irrigation								
Agria	10-11-10	17-05-10	51.7	58.7	3326.6	2000	5326.6	424.8
Moonlight	10-11-10	17-05-10	59.4	76.6	3255.6	2000	5255.6	424.8
Moemoe	10-11-10	17-05-10	52.6	76.1	3685.2	2000	5685.2	424.8
Tutaekuri	10-11-10	17-05-10	27.6	54.7	3670.2	2000	5670.2	424.8
Buttercup	09-12-10	29-03-10	54.7	97.7	2325.8	1750	4075.8	398.2
Kamokamo	09-12-10	31-03-10	78.0	149.1	2382.0	1750	4132.0	398.2
Dark O	10-11-10	22-06-10	23.2	55.8	4742.2	2000	6742.2	424.8
Scarlet	10-11-10	22-06-10	25.5	69.5	4824.2	2002	6824.2	424.8
Rain-fed								
Agria	10-11-10	17-05-10	34.0	43.3	3470.6	—	3470.6	424.8
Moonlight	10-11-10	17-05-10	39.7	52.1	3513.0	—	3513.0	424.8
Moemoe	10-11-10	17-05-10	40.1	60.0	3950.0	—	3950.0	424.8
Tutaekuri	10-11-10	17-05-10	30.0	52.8	3933.0	—	3933.0	424.8
Buttercup	09-12-10	29-03-10	47.4	89.6	2551.0	—	2551.0	398.2
Kamokamo	09-12-10	31-0310	67.7	142.7	2603.8	—	2603.8	398.2
Dark O	10-11-10	22-06-10	16.7	42.0	5094.2	—	5094.2	424.8
Scarlet	10-11-10	22-06-10	21.2	50.7	5061.0	—	5061.0	424.8
Significance								
Cultivars			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	—
Water regime			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$LSD_{0.05}$								
Cultivar			10.7	6.23	—	—	—	—
Water regime			5.4	18.9	—	—	—	—

Table 1. Date of planting and harvesting, harvestable yield, total biomass yield and consumptive water use for heritage and modern potato, oca and pumpkin squash crop cultivars in New Zealand, 2010.

water use (blue plus green water footprint or pure green water footprint) of total yield ranges was high in irrigated field and low in rain-fed field (**Table 2**). **Figure 1** evidently show that the blue water footprint in rain-fed crop was zero while the green water footprint of total yield and total biomass yield related to rain-fed environment were high compared to the green water footprint of the irrigated field.

In the irrigated crops, the blue water footprint comprised 27–39% while the grey water footprint made up to 6–9% of the total water footprint of total yield (**Figure 2**). The total water footprint of consumptive water use increased with irrigation in Moe Moe, Tutaekuri, Ebisu, Kamokamo and scarlet oca whilst Agria, Moonlight and dark orange oca decreased total

Water regime/ cultivar	Green water footprint (m³ ton⁻¹)	Blue water footprint (m³ ton⁻¹)	Grey water footprint (m³ ton⁻¹)	Total water footprint (m³ ton⁻¹)
Irrigation				
Agria	65.5	39.4	8.4	113.3
Moonlight	55.8	34.3	7.3	97.4
Moemoe	70.1	38.0	8.1	116.2
Tutaekuri	139.8	76.2	16.2	232.2
Buttercup	42.8	32.2	7.3	82.3
Kamokamo	33.8	24.8	5.7	64.3
Dark orange	223.2	94.1	19.9	337.3
Scarlet	190.3	78.9	16.8	285.9
Rain-fed				
Agria	106.5	—	13.03	119.5
Moonlight	90.4	—	10.92	101.3
Moemoe	99.4	—	10.69	111.1
Tutaekuri	144.6	—	15.62	160.2
Buttercup	55.6	—	8.68	64.3
Kamokamo	44.3	—	6.78	51.1
Dark orange	331.8	—	27.67	359.5
Scarlet	244.8	—	20.55	265.4
Significance				
Cultivars	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Water regime	$p < 0.0001$	$p < 0.0001$	$p < 0.001$	Ns
$LSD_{0.05}$				
Cultivar	44.3	10.7	4.10	54.6
Water regime	15.5	3.7	2.02	27.3

Table 2. Total water footprint of heritage and modern potato, oca and pumpkin squash crop cultivars on total yield basis in New Zealand, 2010.

water footprint of consumptive water use with irrigation (**Table 2**). The dilution requirement for the applied nitrogen in potato, oca and pumpkin squash, had the equivalency of 424.8 and 398.2 $m^3\ ha^{-1}$, grey water footprint, respectively (**Table 1**). The green, blue and grey water footprint reflected the inverse trend observed in total yield and total biomass yield above. All water footprint components above were largest in dark orange oca and smallest in pumpkin squash, Kamokamo (**Figure 2**).

3.2.2. Total water footprint of total yield and total biomass yield

Total water footprint of potato, oca and pumpkin squash on total yield and total biomass yield basis varied with crop cultivars. The total water footprint on total yield basis ranged

Water regime/ cultivar	Green water footprint (m^3 ton^{-1})	Blue water footprint (m^3 ton^{-1})	Grey water footprint (m^3 ton^{-1})	Total water footprint (m^3 ton^{-1})
Irrigation				
Agria	57.5	34.6	7.3	99.4
Moonlight	43.7	26.8	5.7	76.3
Moemoe	48.8	26.5	5.6	80.9
Tutaekuri	68.2	37.2	7.9	113.2
Buttercup	23.8	17.9	4.1	45.9
Kamokamo	16.5	12.1	2.8	31.4
Dark orange	94.6	39.9	8.5	143.0
Scarlet	71.4	29.6	6.3	107.3
Rain-fed				
Agria	82.9	—	10.2	93.1
Moonlight	69.2	—	8.4	77.6
Moemoe	66.5	—	7.1	73.6
Tutaekuri	79.8	—	8.6	88.4
Buttercup	30.2	—	4.7	34.9
Kamokamo	19.7	—	3.0	22.7
Dark orange	141.8	—	11.8	153.6
Scarlet	105.2	—	8.8	114.0
Significance				
Cultivars	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Water regime	$p < 0.01$	$p < 0.0001$	$p < 0.01$	Ns
$LSD_{0.05}$				
Cultivar	25.57	5.08	2.32	30.48
Water regime	12.78	2.54	1.16	15.24

Table 3. Total water footprint of heritage and modern potato, oca and pumpkin squash crop cultivars on total biomass basis in New Zealand, 2010.

from 64.3 to 337.3 m^3 ton^{-1} under irrigation and from 47.3 to 343.6 m^3 ton^{-1} under rain-fed condition (**Table 2**). The total water footprint on total biomass yield basis was between 31.3 and 143 m^3 ton^{-1} under irrigation, and 22.7 to 153.6 m^3 ton^{-1} under rain-fed (**Table 3**). Regardless of a remarkable crop water use increase with irrigation, the total water footprint on total yield and total biomass yield basis under irrigation and rain-fed regimes were much different.

Figure 3 shows that dark orange oca had the largest average total water footprint of total yield and total biomass while pumpkin squash, Kamokamo had the least. The total water footprint on total yield exceeded total water footprint on total biomass basis in all crop

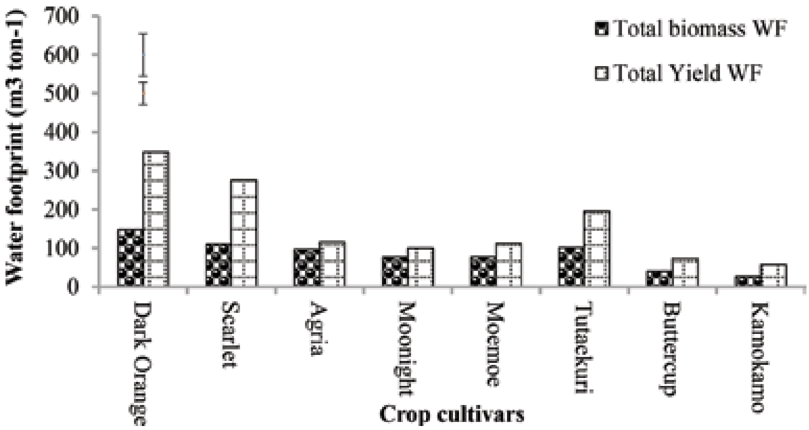

Figure 3. Average water footprint of total yield and total biomass in oca, potato and pumpkin squash cultivars. Error bar represents $LSD_{0.05}$.

cultivars (**Figure 3**, **Tables 2** and **3**). The pumpkin squash cultivars and Moonlight were not much different on total water footprint of total yield but were considerable different to Moe Moe, Agria, Tutaekuri and oca cultivars. Tutaekuri had the greatest total water footprint of total yield and total biomass among potato cultivars though extremely lower to oca cultivars. Nevertheless, the total biomass water footprint for Tutaekuri was not much different from Agria. Moonlight and Moe Moe were second from pumpkin squash in low water footprint of total biomass (**Table 3** and **Figure 3**).

3.3. Social-economic of the selected crop cultivars

Gross revenue on investment income; present value per ha from irrigation in 1st year; net present value was highest in Moe Moe among potato cultivars. Moe Moe also displayed shortest repayment period. The high market value and its intermediary yield response to full irrigation and low N-assisted Moe Moe to have high economic value among the selected potato cultivars. Agria, despite its highest yield response to full irrigation and nitrogen, ended up being the least economic crop enterprise. Agria gross revenue on investment income was NZ$8740; present value per ha from irrigation in the 1st year was NZ$7159; net present value was NZ41,764.5; and its repayment period was longer (0.92 years) than other enterprises. Low market value in Agria compared to Taewa contributed to its lowest economic status. An intermediary economic value was reported in Tutaekuri which had intermediary gross revenue on investment income; present value; net present value and intermediary repayment period. Tutaekuri outperformed modern potatoes in economic terms regardless of its low yield response to irrigation and N just because of its novelty value and reduced water and nitrogen fertiliser requirement.

4. Discussion

4.1. Consumptive water use and yield differences of cultivars of selected crops

Modern and heritage crops differ in their relationship between their maximum water requirement and actual evapotranspiration, thus crop coefficient (k_c), in addition to maturity. **Figure 1** shows how the crop coefficient (or growing stages) overlapped during the growing season between different crops leading to different water use. Application of one irrigation schedule in crops with different kc would result in over-irrigating pumpkin squash. Thus, irrigation scheduling (timing) based on soil water monitoring rather than some approximate modelling approach can significantly improve the water management [25], that is, the total water footprint. Differences in growth stages and date to maturity might contribute to great differences in crop water requirement and water footprint among the selected crops cultivars [15]. From the study, it is definite that Taewa and oca have the longest duration of growth to maturity compared to the other selected crop cultivars [13].

Most of heritage crop cultivars used more water than modern cultivars. Likely, the large biomass and longer growth cycle in heritage crop cultivars (Kamokamo, Tutaekuri, oca and Moe Moe) made them use more water than modern cultivars. This study considered actual evapotranspiration and other discharges in determining the water footprint, as suggested by Maes [23]. In this case, the water requirement was not equal to the actual total consumptive water use, thus remedying the over-estimation. This is in contrast to water footprint determination in other studies, where hypothetical crop yield and evapotranspiration were used [26]. Apart from, expected enormous variability in crop water use within the area in future, the current results provide a great benchmark of heritage and modern crop water requirement and water footprint for the studied area.

4.2. Water footprint differences of cultivars of selected heritage and modern potato, pumpkin squash and oca

Water footprint components differ with crop type or cultivars and water regimes as also reported in energy crops [27]. Pumpkin squash, Kamokamo, was the most efficient crop cultivar, while dark orange oca was the least efficient crop. Equivalency in water footprint could be noticed between pumpkin squash cultivar and Moonlight. Nevertheless, both were five times slighter than water footprint of oca. Likewise, Moonlight, Agria and Moe Moe equaled in water footprint. Tutaekuri has largest water footprint almost double that of other potato cultivars. There more benefits to grow Tutaekuri and pumpkin squash cultivars under rainfed than under irrigated conditions. If not, there is no gain in growing oca under irrigation, excluding in the case of a likely premium price, which would offset low water productivity, compared to potato and pumpkin squash.

The average water footprint of growing potato reported in this study (ranging from 46 m^3 ton^{-1} to 335 m^3 ton^{-1}) were greater than that for the Netherlands and almost equal to USA and Brazil, except for Tutaekuri, which was equal to the water footprint of growing potato in Zimbabwe [27]. The water footprint of 72 m^3 ton^{-1} was reported in Netherlands, 111 m^3 ton^{-1} in USA, 106 m^3 ton^{-1} in Brazil and 225 m^3 ton^{-1} in Zimbabwe [27] for producing potatoes. Besides, our study demonstrates that water footprint of growing potato and pumpkin squash in New Zealand is either average, or smaller than that of crops with smallest water footprint in referred regions. Oca was found to have largest total water footprint. However, oca average water footprint in this study is within the range of smallest water footprint reported in Netherlands, USA, Brazil and Zimbabwe among sugar beet, sugarcane and maize [27].

An average of 12, 10, 11, 20, 7, 5, 35 and 28 l of water (in virtual water content form) would be required to produce 100 g of Agria, Moonlight, Moe Moe, Tutaekuri, Buttercup squash, Kamokamo, dark orange and scarlet oca, respectively. Efficient crop water management and crop cultivar choice might contribute to lower virtual water content of producing potato and pumpkin squash than 25 l/100 g for potato tuber [28] and 23.8 l/100 g for pumpkin [22], which were reported as average global and Indian virtual water content, respectively. On the other hand, oca virtual water content is still falling outside the 25 l/100 g for potato tuber. These disparities in water footprint are within or above those reported in the 1995–2006 global water footprint of pumpkin squash (336 m^3 ton^{-1}) and potato (287 m^3 ton^{-1}) [12].

The results suggest that there are great disparities in virtual water content and water footprint within global averages, which may be due to climate, cultivars and methodological differences, when estimating crop water use [22, 28]. This study used actual water use and actual yield, as suggested by Maes [22], while the study referred to used hypothetical crop yields and water use [26]. On the other hand, the virtual water content and water footprint in this study, outweigh the global water footprint put forward by Mekonnen [12]. The reason for such disparities with this study is that most referred global water footprint studies theoretically estimated crop water use while this study practically recorded the actual water used. The theoretically estimated water use might have been over-estimated while our study might sparely use the water resulting into lower water footprint. It is globally agreed that smart and efficient practices in agriculture, selection of efficient crop cultivars in water use and good weather patterns do assist in reducing water footprint of producing various crops.

Irrigation increases total water use compared to rain-fed agriculture. In this study blue water raised total crop water use by 34, 48 and 59%, in oca, potato and pumpkin squash cultivars, respectively. Consequently, blue water clearly increased the total water footprint. Total water footprint increased by 5, 45, 28, 25 and 8% in irrigated Moe Moe, Tutaekuri, Buttercup squash, Kamokamo and Scarlet oca. However, irrigation reduced total water footprint in Agria, Moonlight and dark orange oca by 6, 4 and 7%. The earlier trends were reported in wheat whereas the later was reported in sugarcane and soybean, respectively [12]. For crop varieties which positively respond to irrigation, the intervention is indispensable to reduce the total water footprint, by improving the economic yields. Nevertheless, this is contrary to like Moe Moe, Tutaekuri, Buttercup squash, Kamokamo and scarlet because the intervention raised the actual evapotranspiration nearly to potential evapotranspiration resulting into reduced water footprint, even with improved yield. The findings emphasise that irrigation is very important for crop yield quality and yield enhancement as well as reduced water footprint where rainfall is limited. Apart from differences in water footprint influenced by crop varieties and differences and crops, water footprint also extensively differ in their water footprint at different irrigation management.

Irrigation scheduling method would influence the water footprint of producing various crops—however, this is dependent on crop cultivars. Partial irrigation reduced water footprint in Tutaekuri while full irrigation reduced water footprint in Moe Moe and Agria. The differences about crop varieties response to different irrigation schedules are very significant because they indicate disparity of water use among crop varieties. This result is very useful in selection for crop varieties that are sparing in water use or drought tolerant and breeding for water use efficiency.

Hedley proved that the water footprint of modern potato production is slighter small than that of maize and pasture [29]. Hedley report registered water footprint of 308 and 325 m^3 ton^{-1}

in potato 622 and 654 m^3 ton^{-1} in maize and 2651 and 2667 m^3 ton^{-1} in pasture at varied rate irrigation and uniform rate irrigation, respectively. It is noted that the total water footprint of growing potato by Hedley et al. [29, 30], was higher than those reported by Hoekstra [31] and the water footprint for this study, except for Tutaekuri. Similarly, the study under this report vividly shows that water footprint differed between full irrigation and rain-fed that ranged from 95 to 111 m^3 ton^{-1} (modern potato); 110–220 m^3 ton^{-1} (Taewa) in 2009/2010. In 2010/2011 the water footprint for water regimes ranged from 163 to 586 m^3 ton^{-1} (full irrigation), 173–406 m^3 ton^{-1} (partial irrigation) and 198–505 m^3 ton^{-1} (rain-fed). The lowest water footprint was found in Agria and the highest in Tutaekuri. From this discussion and **Figure 3**, it is well illustrated that water management within different crop cultivars influences levels of water footprint. Apart from differences in water footprint caused by varieties differences, water footprint may also extensively differ in their water footprint due to pests' infestation. Farmers need to keep fields weed free to reduce pests and diseases incidences.

Pests and diseases affect water footprint of producing selected crop cultivars because they reduce yields without affecting water input. In case of this study, water footprint of Taewa between seasons differed due to pests' infestation. As weather variations between seasons Water footprint was greatly higher in 2011 than in 2010 (**Figure 3**). Potato psyllid infestation influenced the increase in water footprint in 2011. However, the water footprint of producing potato without psyllid infestation, in 2009/2010, was smaller than the global water footprint (160 m^3 ton^{-1}) for producing potato. Potato infested with psyllid in 2010/2011 behaved differently, only a well-managed full irrigation regime of modern potato and Moe Moe, obtained a water footprint approaching the global water footprint of 160 m^3 ton^{-1}. A combination of proper management of irrigation under pests' infestation can help to reduce water footprint.

The water footprint indicator suggests there are numerous disparities, with global averages and within country or seasons, arising from irrigation management and methodological differences when estimating crop water use, climate variability, cultivars and pest and disease infestation [22, 28]. However, the water footprint for crops grown in New Zealand can be reduced through good management [12]. For instance, pumpkin squash (especially Kamokamo) had the lowest water footprint, compared to oca, potato, maize and pasture in New Zealand, and compared well with small water footprint crops such as sugar beet and sugarcane, at the global level [26]. This observation suggests that some heritage crop cultivars can compare with (or outperform) modern cultivars in relation to water footprint, when the crop husbandry is appropriate.

4.3. Social-economics of the selected crop cultivars

A premium that farmers get at market on crop cultivar has higher influence on smallholder farmer's social-economic status than sole yield and sole irrigation response factors. In our case, fully irrigated Moe Moe and partially irrigated Tutaekuri production systems, were economically viable due to their high value at market. The novel value of most heritage crops are value which have been based on social preferences based on their superiority flavour, texture and colour. Fully irrigated Moe Moe and partially irrigated Tutaekuri production systems, with low N, would be profitable investments for Taewa growers because they have high value and low N use. For growers to maintain these economic benefits they should be advised to produce Tutaekuri under partial irrigation and low high N, and Moe Moe under full irrigation with low N. It is not advisable for growers to produce Agria under partial irrigation and low N, because this production system has negative NPV. Economic water productivity is expected to be high in Taewa because of the premiums at market. Premiums, socially and economically forces production of Taewa among the highest producer but low valued. It is evidenced that issue of water footprint requires financial attachment to attract farmers.

5. Conclusion and recommendations

In the field, water regimes differently influence crop production and the value of water footprint for both heritage and modern crop cultivars, depending on the crop water use characteristics and field management. Pumpkin squash, Kamokamo, has a low water footprint, since it genetically uses water more sparingly, compared to all the other crop cultivars studied. In spite of this, the yield response to irrigation is highest in modern potato, while Kamokamo is comparable to Moe Moe and Buttercup squash and dark orange oca. It can be concluded that pumpkin squash requires only a small amount of water, in order to produce total fruit yield compared to potatoes and oca. Potatoes, except Tutaekuri, are more responsive to irrigation compared to pumpkin squash and oca. The yields and water footprint of heritage potato is greatly affected by cultivars used and water regimes, unlike the case of oca. It can be concluded that there are water footprint differences between cultivars of different crops and within crops in New Zealand. Knowledge of these water footprint differences can assist growers to manage their crops and water resources sparingly. It is therefore recommended that growers should be properly selecting crops and crop varieties according to their water availability, market price, properly schedule irrigation and nitrogen application as well as pests and disease control in order to reduce water footprint of growing their crops at field level.

It is recommended that farmers should strive to reduce water footprint either by avoidance of using two much of other inputs or by replacement of inefficient technologies by very efficient technologies as detailed below:

1. Farmers should be advised to strive to reduce grey water footprint in their fields. Grey water footprint would be decreased if application of chemical fertilisers, pesticides and herbicides to the field is avoided or reduced or by following efficient ways of using fertilisers as well as applying better application techniques or use of organic fertilisers and proper timing of fertiliser and irrigation application.

2. Farmers should also be advised to decrease green water footprint and blue water footprint. The green and blue water footprints would be greatly lessened by enhancing green and blue water productivity. Our study indicates that application of less water through smart irrigation scheduling (replacing full irrigation by partial irrigation) and selection of water efficient crop cultivars (replacing heavy water users by efficient water users) would help to maximise water productivity (striving for higher yield per cubic of water used for production) thereby reducing both green and blue water footprint.

http://dx.doi.org/10.5772/intechopen.77509

3. Agricultural Extension Officers need to be guided to assist farmers in defining their target of best agricultural technology practices for reducing water footprint and formulating targets to be achieved in order to contribute to reduction of water footprint. Where possible farmers should be assisted to monitor and measure their water footprint in their environment. This can be achieved by setting environmental and social safeguards plan that would help to reduce risk of water footprint by investing in reasonable water use, better-quality catchment water management and sustainable water use.

4. Governments should formulate policies that include goal of sustainable usage of water resources. The policies should promote smart agriculture: that is, efficient irrigation (drip irrigation), conservation agriculture, system of rice intensification (SRI), crops that are efficient in water use and organic fertilisers.

Author details

Isaac R. Fandika[1,2]*, Peter D. Kemp[1], James P. Millner[1] and Davie Horne[1]

*Address all correspondence to: fandikai@yahoo.co.uk; fandika68@gmail.com

1 Institute of Natural Resources, Massey University, Palmerston North, New Zealand

2 Kasinthula Agricultural Research Station, Department of Agricultural Research Services, Chikwawa, Malawi

References

[1] Hooijdonk B, Behboudian H. Strategies to save water and manage export apple production during seasons of high crop demand and low water availabilty. The Orchards. 2004:64-67

[2] Fowler A. Potential climate change impacts on water resources in the Auckland Region—New Zealand. Climate Research. 1999;**11**:221-245

[3] Halloy SRP, Mark AF, Dickson KJM. Management of New Zealand's terrestrial bidiversity as a complex adaptive system. Complext International; **200**:8

[4] Francis GS, Trimmer LA, Tregurtha CS, Williams PH, Butler RC. Winter nitrate leaching losses from three land uses in the Pukekohe area of New Zealand. New Zealand Journal of Agricultural Research. 2003;**46**:215-224

[5] MAF. Ministry of Agriculture and Forestry Technical Paper N0:04/01. 2000

[6] Howell T. Enhancing water use efficiency in irrigated agriculture. Agronmy Journal. 2001; **93**:281-289

[7] Roskruge N. Taewa Maori; their Management, Social Importance and Commercial Viability. A Research Report Presented in Partial Fulfillment of the Requirements of

the Diploma in Maori Resource Development, Institute of Natural Resources, Massey University. New Zealand: Palmerston North; 1999

[8] McFarlane TR. The Contribution of Taewa (Maori Potato) Production to Maori Sustainable Development. Master of Applied Science Dissertation, Lincoln 7647. New Zealand: Lincoln University; 2007

[9] Harris GF, Niha PP. Maori potato. Working Paper. The Open Polytechnic of New Zealand. 1999

[10] Hoekstra AY, Chapagain AK, Aldaya MM, Melkonnen MM. Water footprint manual—State of art 2009. In: W. f. Network (Ed.). Enschede, Netherlands: 2009

[11] MAF: The economic value of irrigation in New Zealand. MAF technical Paper No: 04/01. 2004

[12] Mekonnen MM, Hoekstra AY. The Green, Blue and Grey Water Footprint of Crops and Derived Products. Delft, the Netherlands: UNESCO-IHE; 2010

[13] Fandika IR, Kemp PD, Milner JP, Horne D, Roskruge N. Irrigation and nitrogen effects on tuber yield and water use efficiency of heritage and modern potato cultivars. Agricultural Water Management. 2016;**170**:148-157

[14] Premrov A, Schulte RPO, Coxon CE, Hackett R, Richards KG. Predicting soil moisture conditions for arable free draining soils in Ireland under spring cereal crop production. Irish Journal of Agricultural and Food Research. 2010;**49**:99-113

[15] Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration. Guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper. Vol. 56. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO), Rome; 1998

[16] Kassam A, Smith M. FAO Methodologies on Crop Water Use and Crop Water Productivity. Rome, Italy: Food and Agriculture Oorganisation of the United Nations (FAO); 2001

[17] Shock C, Pereira A, Eldredge E. Irrigation best management practices for potato. American Journal of Potato Research. 2007;**84**(1):29-37

[18] Mekonnen MM, Hoekstra AY. A global and high-resolution assessment of the green, blue and grey water footprint of wheat. Hydrology and Earth System Sciences. 2010;**14**: 1259-1276

[19] Chapagain AK, Hoekstra AY, Savenije HHG, Gautam R. Water footprint of cotton consumption. Value of Water: Research Report Series No. 18. Deft, The Netherlands: UNESCO-IHE; 2005

[20] Ministry for the Environment: The State of New Zealand's Environment. Wellington: New Zealand Government; 2005

[21] Chapagain AK, Hoekstra AY, Savenije HHG, Gautam R. The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecological Economics. 2006;**60**(1):186-203

[22] Kumar V, Sharad K. Status of virtual water trade from India. Current Science. 2007;**93**:8

[23] Maes WH. Plant–water relationships and growth strategies of Jatrophacurcas L. saplings under different levels of drought stress. Journal of Arid Environments. 2009;**73**:877-884

[24] FAO. Investment Decisions—Capital Budgeting Marketing and Agribusiness Texts. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); 1997

[25] Ondrasek G. Water scarcity & water stress in agriculture. In: Ahmad P, Wani MR, editors. Physiological Mechanism and Adaptation Strategies in Plants Under Changing Environments I. New York Dordrecht Heidelberg London: Springer; 2014. pp. 75-96

[26] Gerbens-Leenes PW, Hoekstra AY, van der Meer T. The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bioenergy in energy supply. Ecological Economics. 2009;**68**(4):1052-1060

[27] Gerbens-Leenesa W, Hoekstraa AY, Meerb TH. The water footprint of bioenergy. Proceedings of the National Academy of Sciences of the United States of America. 2009;**106**:10219-10223

[28] Hoekstra A, Chapagain A. Water footprints of nations: Water use by people as a function of their consumption pattern. Water Resources Management. 2007;**21**(1):35-48

[29] Hedley CB, Yule IJ, Bradbury S, Scotter D, Vogeler I, Sinton S. Water use efficiency indicators for variable rate irrigation in variable soils. In: Proceedings of the 13th Annual Symposium on Precision Agriculture in Australasia; 10-11th September 2009; University of New England, Armidale, NSW Australia. 2009

[30] Hedley CB, Yule IJ, Tuohy M, Vogeler I. Key performance indicators for variable rate irrigation implementation on variable soils. In: Proceedings of ASABE Annual International Meeting; June 21–June 24; Grand Sierra Resort and Casino, Reno, Nevada. 2009

[31] Hoekstra AY. Virtual water: An introduction. In: Proceedings of the International Expert Meeting on Virtual Water Trade. The Netherlands: IHE Delft; 2003

Chapter 7

Water Quality in Irrigated Paddy Systems

Jian Liu, Hongbin Liu, Ruliang Liu,
MG Mostofa Amin, Limei Zhai, Haiming Lu,
Hongyuan Wang, Xubo Zhang, Yitao Zhang,
Ying Zhao and Xiaodong Ding

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77339

Abstract

Irrigated paddy rice (*Oryza sativa* L.) is a staple food for roughly half of the world's population. Concerns over water quality have arisen in recent decades, particularly in China, which is the largest rice-producing country in the world and has the most intensive use of nutrients and water in rice production. On the one hand, the poor water quality has constrained the use of water for irrigation to paddy systems in many areas of the world. On the other hand, nutrient losses from paddy production systems contribute to contamination and eutrophication of freshwater bodies. Here, we review rice production, water requirement, water quality issues, and management options to minimize nutrient losses from paddy systems. We conclude that management of nutrient source, rate, timing, and placement should be combined with the management of irrigation and drainage water to reduce nitrogen and phosphorus losses from paddies. More research is needed to identify cost-effective monitoring approaches and mitigation options, and relevant extension and policy should be enforced to achieve water quality goals. The review is preliminarily based on China's scenario, but it would also provide valuable information for other rice-producing countries.

Keywords: water quality, paddy, irrigation, water management, nutrient management

1. Introduction

Rice (*Oryza sativa* L.) is a staple food for roughly 50% of the world's population. Globally, rice is planted on a total of 155 million hectares of land, and annual rice production amounts to up to 480 million metric tons [1]. Nearly 90% of the rice is produced in Asian countries. The top seven rice-producing countries, i.e., China (30%), India (22%), Indonesia (8%), Bangladesh (7%),

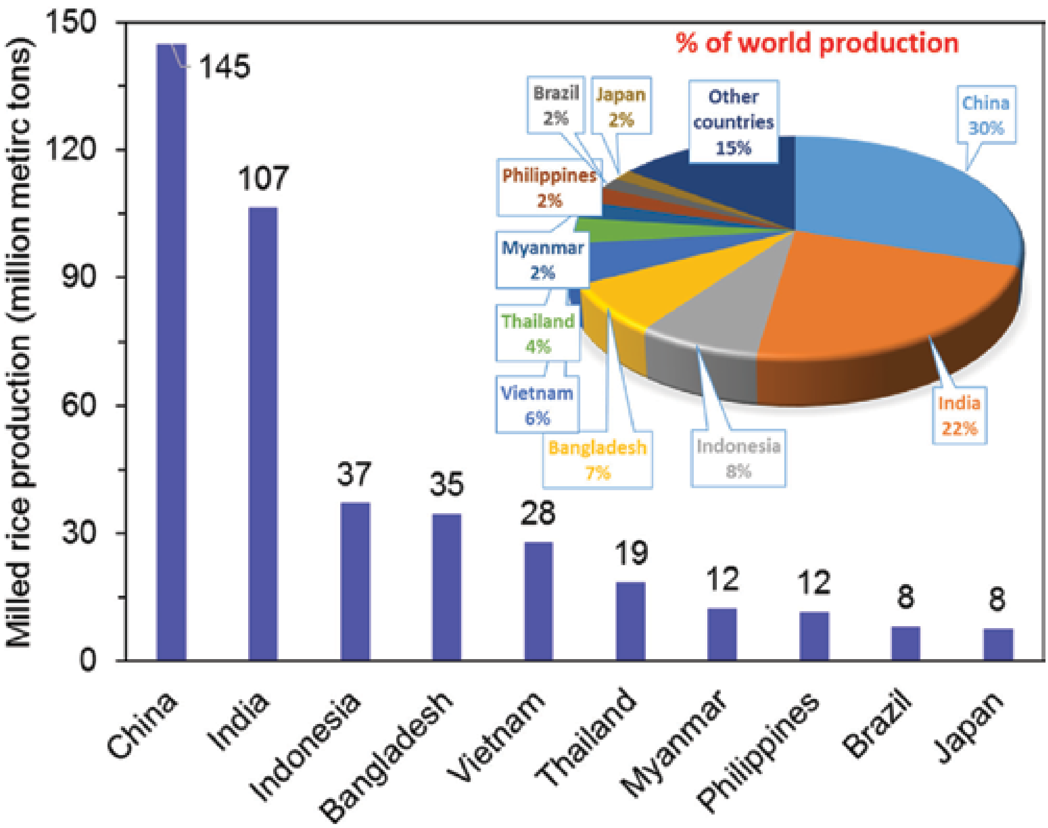

Figure 1. Rice production of world top 10 countries in 2016 (based on data from www.statista.com; [2]).

Vietnam (6%), Thailand (4%), and Myanmar (3%), collectively account for 80% of the world's total rice production (**Figure 1**).

Worldwide, agriculture accounts for 70% of all water consumption, far more than the 20% for industry and the 10% for domestic use (http://www.worldometers.info/water/). As water is needed throughout the rice-growing season, paddy fields altogether consume up to 90% of the total water used for irrigation in Asia [3]. Therefore, paddy water management is crucial to save water resources in the context of water quantity. Meanwhile, there have been frequent reports on environmental and ecological concerns related to paddy production. In particular, water quality issues have received increasing attention. Rice is commonly grown in regions close to inland streams and lakes, which is a double-bladed sword. On the one hand, such a landscape arrangement resulting from long-term human adaptation to the environment allows the most convenient and economic use of water resources in agricultural production. On the other hand, it generates risks of eutrophication in the streams and lakes where the ecological systems are sensitive to nutrients. Indeed, several previous studies identified phosphorus losses from paddy production systems as an important cause of eutrophication in the local, enclosed lakes in China (e.g., [4, 5]). This is because such regions are commonly characterized by enhanced, extensive hydrological networks between paddy fields and between the fields and their adjacent water bodies, which elevate the risk of nutrient runoff from paddy fields to the waters. In the context of water quality, both nutrient and water management are of great importance.

In this chapter, we reviewed water quality issues related to paddy rice production and discussed the potential strategies to reduce nutrient losses to the water environment. As China is the largest rice-producing country in the world, we focused the review and discussion on China's scenario. Even so, we included information from other countries whenever it was relevant.

2. Rice production in China

In China, rice is the first major food crop, owning a total planting area of 30 million hectares. The rice production of 207 million metric tons is equivalent to 34% of the total grain crop production [6]. Rice production is mainly concentrated in three geophysical regions: Yangtze River Basin (covering provinces of Hunan, Jiangxi, Jiangsu, Hubei, Sichuan, Anhui, Yunnan, Zhejiang, Chongqing, Guizhou, and Shanghai), Southeast Coastal Plains (Guangxi, Guangdong, Fujian, Hainan, Hong Kong, Macao, and Taiwan), and Northeast Plains (Heilongjiang, Jilin, and Liaoning; **Figure 2**). Specifically, the Yangtze River Basin accounts for 65% of China's total rice planting

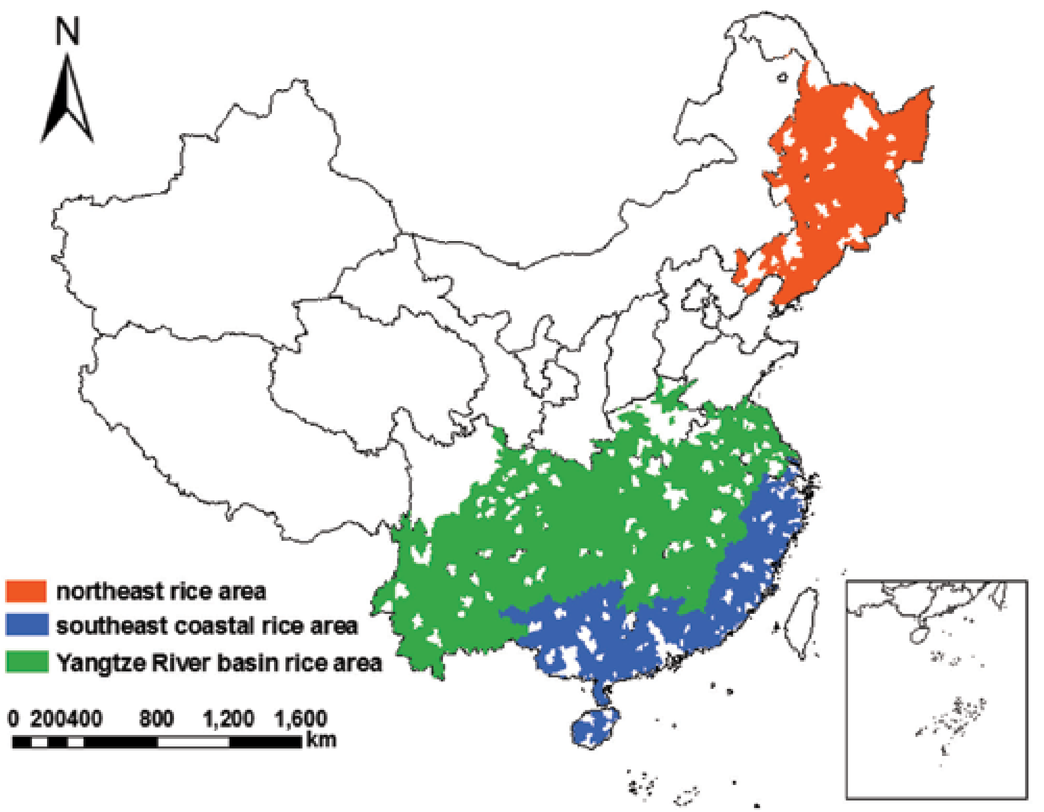

Figure 2. Major rice-producing regions in China [7].

area, followed by the Southeast Coastal Plains (16%), the Northeast Plains (15%), and other regions (4%; **Figure 3**). Due to its nature of requiring large amounts of water throughout the growing season, over 80% of the rice planting areas are located in Southern China where annual precipitation ranges from 1000 to >2000 mm. Notably, the rice planting areas make up over 10% of the total provincial areas in Hunan, Jiangxi, Jiangsu, Hubei, Anhui, Shanghai, and Guangdong. In line with the patterns of planting areas, the Yangtze River Basin dominates the national rice production (65%), which is followed by the Northeast Plains (16%), the Southeast Coastal Plains (14%), and other regions (5%; **Figure 3**). In 2016, the top five rice-producing provinces, i.e., Hunan,

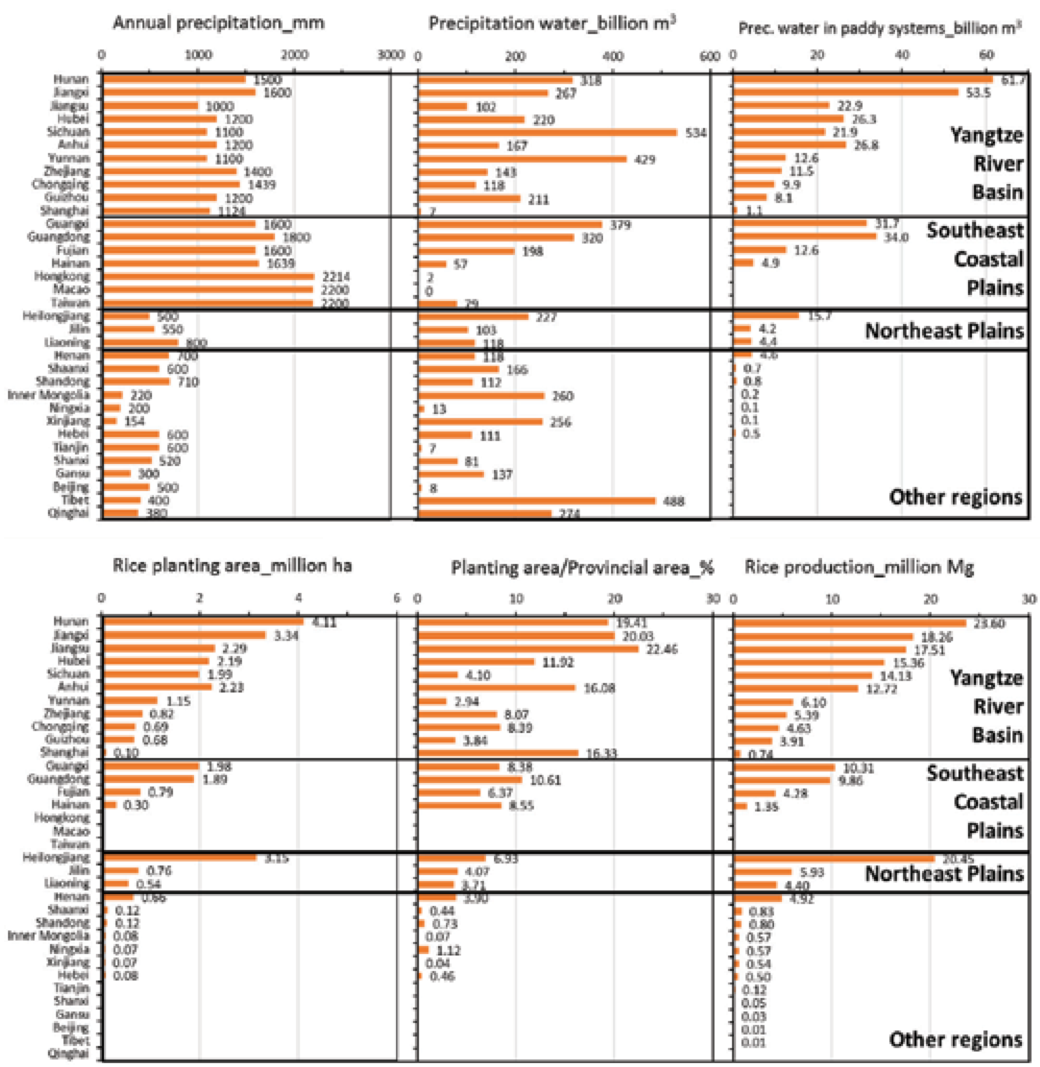

Figure 3. Annual precipitation, precipitation water volume, rice planting area, and rice production by provinces of China in 2016 [8, 9].

Heilongjiang, Jiangxi, Jiangsu, and Hubei, produced 51% of China's total rice. In combination, these five provinces receive a total of 180 billion m^3 of precipitated water in paddy fields, which is 49% of the precipitated water received by all paddy fields.

Across the world, rice cropping systems vary from monoculture (e.g., northern China) to double (e.g., southern China) and triple cropping (e.g., India and Bangladesh) depending on climatic conditions. In most areas of China, the rice-growing season starts in spring with steeping paddy fields and the transplantation of rice seedlings and ends in the fall with the draining of the fields and harvesting rice grains. Despite large variabilities in paddy management by regional and local conventions as well as available technologies, rice cultivation is commonly characterized by the flooding of the paddy fields during most of the growing season along with intensive irrigation and fertilization. Flooding the rice fields is essential for most rice varieties to maintain good growth and achieve high yields. **Figure 4** presents typical management schedules for paddy rice in Hubei Province, Yangtze River Basin, China. Due to favorable climatic conditions, the vast area of this province allows a double-cropping system represented as the rotation of rice with winter wheat (*Triticum aestivum* L.) or oilseed rape (*Brassica napus* L.). The rice-growing season starts in late May with irrigation to steep field for a few days, followed by plowing and basal fertilization prior to transplanting rice seedlings. During the process of transplanting rice in early June and harvesting of rice in late September, there are often a couple of fertilizer top dressings to meet rice's need of nitrogen. There are also a number of irrigation and drainage operations to maintain appropriate depths of ponding water.

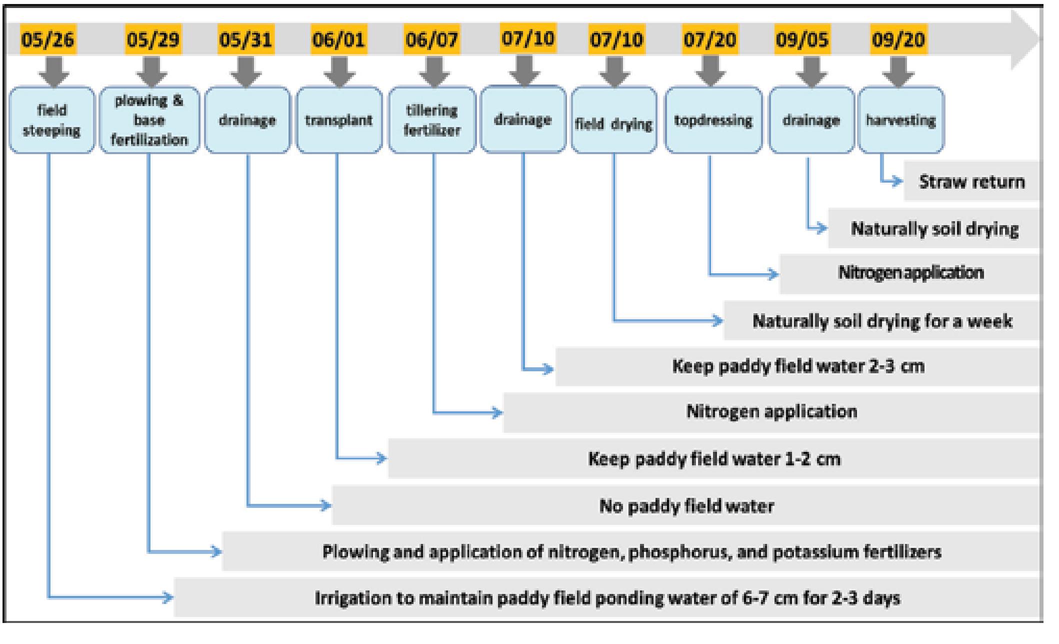

Figure 4. Typical management schedules for paddy rice in Hubei Province, Yangtze River basin, China.

3. Water requirement of rice

Water requirement of rice crop is influenced significantly by environmental conditions such as climate. For example, in Bangladesh, with a tropical climate all over the country, more than 2000 liters of water is required to produce every kilogram of rice dry substance. In China, where rice production areas span from the cold Northeast to the subtropic and tropic South, such water requirement ranges from 400 to 1500 liters. Based on a 30-year meteorological data, statistics of crop growth stages, crop water requirement, and net irrigation requirement, Liu et al. [10] estimated the requirement of water and irrigation for the rice across China, using the FAO Penman-Monteith equation and crop coefficient method. Across the three major rice-producing regions, the rice crop requires 250–950 mm of water, which is greater than the 200–620 mm required for corn (*Zea mays* L.), wheat, or cotton (*Gossypium* spp.) crops. Likewise, rice requirement for irrigation (usually 70–500 mm) is also greater than the other crops (0–350 mm).

Region	Province	Crop	Water requirement (mm)	Net irrigation requirement (mm)
Yangtze River Basin (middle and lower portion)	Hunan, Jiangxi, Jiangsu, Hubei, Anhui, Zhejiang, Shanghai	Early rice	400–580	80–300
		Middle rice	500–800	150–420
		Late rice	500–650	150–400
		Spring corn	250–550	0–200
		Summer corn	330–450	100–200
		Cotton	450–620	50–300
Yangtze River Basin (upper portion)	Yunnan, Guizhou, Sichuan, Chongqing	Early rice	350–700	100–500
		Middle rice	550–950	100–500
		Late rice	400–700	100–350
		Spring corn	300–500	10–250
		Summer corn	300–450	20–100
		Winter wheat	200–600	100–350
Southern Coastal Plains	Guangxi, Guangdong, Fujian, Hainan	Early rice	400–580	70–300
		Middle rice	450–570	90–250
		Late rice	600–700	100–450
		Spring corn	200–400	0–120
		Summer corn	250–420	50–150
		Cotton	450–520	30–180
Northeast Plains	Heilongjiang, Jilin, Liaoning	Middle rice	250–750	80–450
		Spring corn	200–500	10–220
		Spring wheat	250–450	100–300

Table 1. Water requirement and irrigation requirement of the rice crop in comparison to other crops in China (adapted from [10]).

It should be noted that rice water requirement and net irrigation requirement vary widely both between regions and within regions (**Table 1**), reflecting the spatial and temporal variability of water needs by the crop. Furthermore, water requirement and irrigation requirement also differ with rice varieties and growing seasons. Typically, middle rice and late rice need more irrigation water than early rice, due to their prolonged growing seasons.

4. Water quality issues in paddy systems

Water quality problems evolve at both sides of the paddy systems, i.e., inputs of contaminants with irrigation water and exports of nutrients to the surrounding water environment. In the case of contaminant inputs with irrigation water, wastewater or reclaimed wastewater irrigation has generated particular concerns [11–14]. In a recent review on the impacts of wastewater irrigation, Amin et al. [11] concluded that even though wastewater is a valuable source of nutrients, it may contribute many emerging contaminants to the water environment. Indeed, wastewater may contain an array of contaminants such as heavy metals, pathogens, and organic contaminants, along with nutrients (e.g., those listed in **Table 2**). As a result, there is a potential risk of contamination of both shallow groundwater and surface water associated with wastewater irrigation [14]. In a field study, Cao and Hu [12] found that irrigation with copper-rich wastewater increased soil copper concentration in the surface soil layer (0–10 cm) by sixfold and reduced rice yield by 18–25% as compared with the control with normal irrigation water. Accumulation of copper in the surface soil greatly elevated the potential risks of copper pollution through surface runoff. Elsewhere, however, Kang et al. [13] found no adverse effects of reclaimed wastewater on both rice grains and the paddy fields after appropriate treatments of the wastewater. These results point to the importance of monitoring and treatment of wastewater before use for irrigation.

In the case of nutrient exports to the surrounding water environment, the issue of water quality is closely related to water and nutrient turnover and management in the paddy systems. Budget of water in paddy systems involves water inputs in the forms of rainfall and irrigation and water outputs through evapotranspiration, runoff, and deep percolation (**Figure 5**). Rainfall is a

Nutrients	Unit	Range	Contaminants	Unit	Range
Total nitrogen	mg/L	20–70	Total solid	mg/L	390–1230
Total phosphorus	mg/L	4–12	Total dissolved solid	mg/L	270–860
Total organic carbon	mg/L	80–260	Total suspended solid	mg/L	120–400
			Biochemical oxygen demand	mg/L	110–350
			Chemical oxygen demand	mg/L	250–800
			Total coliform	Counts/100 mL	10^6–10^9
			Fecal coliform	Counts/100mL	10^3–10^7

Table 2. Typical nutrients and contaminants in untreated domestic wastewater (based on [15]).

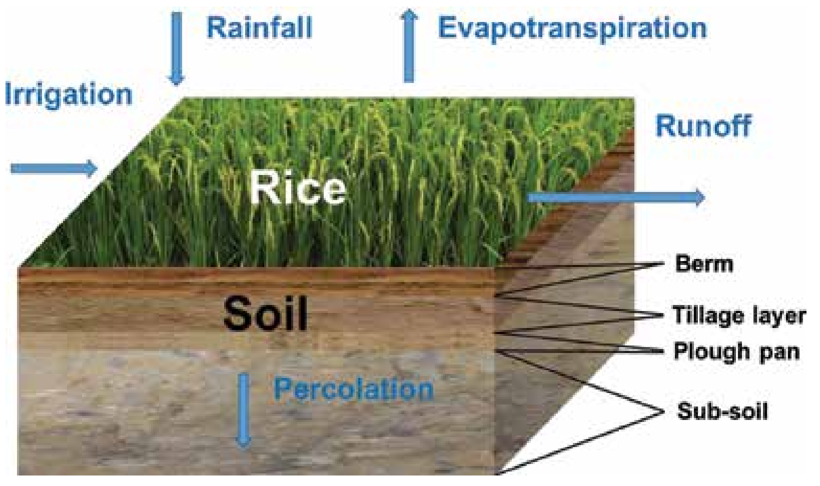

Figure 5. Water budget in rice production.

common, major water input to paddy fields. However, irrigation is usually needed to maintain an appropriate depth of ponding water enclosed by a constructed field berm (**Figure 5**). In addition to evapotranspiration, surface runoff is a major water output from paddy fields. Along with runoff water, phosphorus and nitrogen applied to rice or those in the soil materials are exported from paddy fields. Runoff occurs when the depth of the field ponding water is greater than the height of field berm. Runoff can be generated following small rainfall events when ponding water has been already substantial but more frequently during rainfall storms [16, 17]. Paddy soils are often heavily textured and have a plow pan beneath the surface soil (particularly for long-term cultivated paddy fields). Therefore, the amount of water percolating to the subsoil and out of the root zone is relatively small as compared to surface runoff. Nonetheless, Qiu et al. [18] reported that nitrate-nitrogen concentrations could reach 30–50 mg/L in the leachate from some paddy soils within 1–2 days after fertilizer applications. Due to the flooding nature of paddy fields, the surface soil is often water saturated with a predictably small change in soil water content throughout the paddy growing periods. The anaerobic condition may lead to an elevation of dissolved phosphorus concentrations in runoff water because when iron cation is transformed from iron^{3+} to iron^{2+} under anaerobic conditions, the phosphorous ions bound by iron^{3+} is dissolved. Moreover, artificial drainage that is made to prepare the field (**Figure 4**) forms a direct pathway for nutrient transport to surrounding water environments. Finally, paddy irrigation with nutrient-rich water (such as domestic wastewater; **Table 2**) can also greatly elevate risks of nutrient losses to the water environments.

Phosphorus and nitrogen applied to paddies with fertilizers and manures contribute to both short-term and long-term nutrient losses to the water environments. In a 3-year field study on the hydromorphic paddy soil, for example, Liu et al. [19] found that annual total phosphorus loss in surface runoff ranged from 0.63 kg/ha in the unfertilized rice-wheat rotation to 0.96–2.86 kg/ha when rice and wheat were fertilized with 50–230 kg phosphorus per hectare. In the same study, they found relatively smaller total phosphorus losses from the

http://dx.doi.org/10.5772/intechopen.77339

Soil	Rice growing season					Wheat growing season			
	Rainfall depth (mm)	Irrigation depth (mm)	Phosphorus rate (kg/ha)	Days between fertilizer application and the first runoff	Total phosphorus loss (kg/ha)	Rainfall depth (mm)	Phosphorus rate (kg/ha)	Days between fertilizer application and the first runoff	Total phosphorus loss (kg/ha)
Hydromorphic paddy	604	833	0	5	0.13±0.01	449	0	10	0.23±0.01
	604	833	30	5	0.19±0.02	449	20	10	0.41±0.03
	604	833	75	5	0.48±0.08	449	40	10	0.64±0.02
	604	833	150	5	0.92±0.06	449	80	10	0.97±0.05
	761	868	0	2	0.76±0.05	688	0	31	0.13±0.01
	761	868	30	2	1.06±0.12	688	20	31	0.21±0.01
	761	868	75	2	2.27±0.31	688	40	31	0.24±0.02
	761	868	150	2	4.18±0.33	688	80	31	0.49±0.03
	531	1290	0	1	0.36±0.06	547	0	14	0.27±0.03
	531	1290	30	1	0.59±0.05	547	20	14	0.43±0.04
	531	1290	75	1	0.93±0.09	547	40	14	0.65±0.07
	531	1290	150	1	1.56±0.19	547	80	14	1.11±0.08
Degleyed paddy soil	548	833	0	58	0.14±0.02	439	0	11	0.26±0.01
	548	833	30	58	0.16±0.01	439	20	11	0.41±0.02
	548	833	75	58	0.23±0.03	439	40	11	1.03±0.04
	548	833	150	58	0.29±0.03	439	80	11	1.31±0.09
	723	868	0	45	0.20±0.04	667	0	32	0.22±0.02
	723	868	30	45	0.32±0.02	667	20	32	0.37±0.02
	723	868	75	45	0.27±0.04	667	40	32	0.51±0.02
	723	868	150	45	0.55±0.09	667	80	32	0.78±0.03
	555	1290	0	49	0.17±0.01	468	0	13	0.18±0.02
	555	1290	30	49	0.23±0.01	468	20	13	0.76±0.19
	555	1290	75	49	0.28±0.01	468	40	13	1.18±0.17
	555	1290	150	49	0.38±0.02	468	80	13	1.39±0.12

Table 3. Phosphorus losses in runoff from a rice-wheat rotation cropping system under different natural and management conditions (mean ± standard error, n = 4 for the hydromorphic paddy soil or 6 for the degleyed paddy soil; adapted from [19]).

degleyed paddy soil that ranged from 0.41 kg/ha in the control group to 0.70–1.49 kg/ha in the treatments with 50–230 kg phosphorus per hectare. Although the differences in magnitude of phosphorus losses in the two soils could result from different soil characteristics and rainfall patterns, both revealed increased phosphorus losses with greater phosphorus fertilizer application rates (**Table 3**). Furthermore, Liu et al. [19] found that the time interval between fertilizer application and the subsequent first large runoff event played a critical role in determining the annual phosphorus losses. Phosphorus losses greatly increased with decreasing time interval. The finding was supported by Guo et al. [20] who claimed that about 40% of total phosphorus loss from a rice-wheat rotation occurred within 10 days after fertilizer application to paddies.

In addition to "incidental" nutrient losses, overuse of fertilizers or manure also constitutes long-term risks of nutrient losses. A number of studies have demonstrated evidential buildup of soil phosphorus status and elevated degree of phosphorus saturation due to long-term phosphorus applications at rates exceeding crop needs [21–23]. In turn, phosphorus losses in surface runoff and leaching have been found to increase with elevated soil phosphorus status or degree of phosphorus saturation [22, 24]. This has been widely referred as legacy phosphorus issues [25]. Even though most of the research on this topic has been conducted on dryland soils, a few studies have reported that long-term excessive application of nutrients could enhance environmental pollution risk in paddy fields [4, 26]. In double cropping systems where flooded rice is planted in rotation with drained dryland crop, we can expect nutrient surplus from both rice and dryland crop-growing seasons [27]. It should be noted that China has the most intensive nutrient use in paddy systems among the world's top 10 rice-producing countries (**Table 4**). Therefore, there is a special need of better water and nutrient management to minimize nutrient losses from paddy systems.

Country	Average yield (Mg/ha)	Nitrogen (kg/ha)	Phosphorus (kg/ha)	Potassium (kg/ha)
China	6.2[#]	145	26.2	33.2
India	2.7	68	10.5	7.5
Indonesia	4.1	105	9.6	11.6
Bangladesh	3.2	72	6.5	8.3
Vietnam	4.1	115	19.6	34.9
Thailand	2.4	62	14.4	14.1
Myanmar	3.2	35	5.2	3.3
Philippines	3.0	51	6.5	9.1
Brazil	3.0	40	21.8	24.9
Japan	5.8	78	40.2	59.7

#: Estimation of rice yield in China is made by the authors of this chapter.

Table 4. Rice yield and nutrient applications to rice in world's major rice-producing countries (data adapted from [28]).

5. Monitoring of water quality in paddy systems

In China, the approach for monitoring water quality in paddy systems has become standardized over the past 2 decades [12, 19, 29]. In the field, research plots are separated with plastic films down to 0.9 m in the soil profile and with soil berms up to 0.2 m on the soil surface to prevent flow of surface and shallow subsurface water between the plots (**Figure 6**). Soil berm is a common practice to maintain field ponding water for rice production. During the rice-growing season, irrigation water is applied to individual plots through polyvinyl chloride pipe inlets when needed. During the non-rice crop-growing season in a double-cropping system, irrigation is usually not applied. Excessive ponding water is drained through shallow open ditches. Outside each plot on the opposite side of the irrigation water inlet, a cement pond is constructed to collect runoff water from every plot. Two water outlets of polyvinyl chloride pipe are installed on the wall of the cement pond, at depths of approximately 10 cm above and 10 cm below the soil surface, for collecting runoff water during the rice-and wheat-growing seasons, respectively. The runoff water collected in the pond is measured for volume and sampled for analyses of nutrients and sediments. Usually, one sample is taken after every regular runoff event and multiple samples during a large runoff event (i.e., rain storms).

Even though the approach described earlier is widely used such as in a national program to estimate nutrient losses from paddy systems across China, there has been an increasing interest in seeking alternative, simplified monitoring approaches. One potential approach is to monitor nutrient concentrations in the field ponding water. Liu et al. [19] found that concentrations of both total phosphorus and dissolved reactive phosphorus in surface runoff were significantly correlated with their concentrations in the field ponding water (r^2 = 0.83–0.88, $p < 0.0001$). In a follow-up study, Hua et al. [27] monitored different forms of phosphorus concentrations in field ponding water of five paddy soils over 2 years. They found that 2 weeks after fertilizer application is a critical period for phosphorus loss from paddies, which supported findings of others [19, 20]. Despite the large potential of monitoring field ponding water to save a lot of work associated with constructing runoff collection facilities, it should be

Figure 6. Monitoring of water quality in paddy systems: Research plots and field ponding water on the left and runoff collection facility on the right.

noted that this approach would not give information on runoff volume, and it is not practical for dryland crops. Further research is needed with respect to achieving cost-effective monitoring methodologies.

6. Mitigation options to improve water quality in paddy systems

In China, paddy systems are attributed to an important cause for local and regional water eutrophication (e.g., [4, 5]). Both its wide distribution and intensive nutrient and water inputs point to the need for improved management to minimize its impacts on water quality. A number of studies have emphasized the importance of adopting “4R” nutrient stewardship, i.e., Right source, Right rate, Right timing, and Right placement in paddy systems (e.g., those summarized in **Table 5**). For example, Fujisawa et al. [30] proposed the use of thermoplastic resin-coated fertilizers that allow the application of the fertilizers at full rates to rice seedlings and thereafter the release of nutrients in line with crop needs. Liu [31] found that adopting this technology could substantially increase nitrogen use efficiency by the rice crop as compared to the urea fertilizer and conventional management practices. The technology decreased peak nitrogen concentrations in field ponding water by 85–91%, postponed the appearance of peak concentrations by a week, and reduced total nitrogen (nitrate nitrogen plus ammonium nitrogen) losses in leachate by 36–55%. As discussed earlier, overuse of fertilizers should be avoided because the nutrient surplus contributes to both short-term and long-term nutrient losses. Liu et al. [19] and Hua et al. [27] pointed out that phosphorus fertilizer applications to paddy systems should be at rates balancing crop phosphorus removal, and that phosphorus needs to be managed for both rice and the non-rice crop in a rotation to minimize phosphorus losses in the rice-growing season. Fertilizer rate management should go hand in hand with management of fertilizer application timing. Planning fertilizer timing based on local/regional weather patterns and real-time weather forecast to avoid coincidence with rainfall storms is an important timing management approach [19, 20]. In the regions where the coincidence of fertilizer application and rainfall storm is difficult to avoid, one of the optional management practices

Category	Mitigation options	References
Nutrient management	Use slow-release fertilizer and apply all fertilizers at the seedling stage	Fujisawa et al. [30]; Liu et al. [31]
	Reduce fertilizer application rate	Liu et al. [19]; Hua et al. [27]
	Avoid fertilizer application during rainstorm period; split and reduce basal fertilizer dose	Guo et al. [20]; Liu et al. [31]; Liu et al. [19]
	Apply fertilizer as side bars	Yang and Yang [32]
Water management	Alternate drying and wetting	Peng et al. [33]
	Control irrigation and drainage water volume	Zhang et al. [5]; Gao et al. (2017)
	Control irrigation water quality	

Table 5. Mitigation options to improve water quality in paddy systems.

might be to split fertilizer to multiple doses and reduce the dose of basal fertilizers [31]. Furthermore, Yang and Yang [32] suggested applying fertilizers as side bars close to paddy roots, which could significantly increase nutrient use efficiency and reduce losses as compared with broadcasting the fertilizers.

Water management is also of great importance to reduce nutrient losses from paddy fields to surrounding water bodies. In a field study in China's Taihu Lake Region, Peng et al. [33] found that adopting an alternate drying and wetting technology reduced total phosphorus losses by up to 52% in surface runoff and 55% in subsurface drainage across an array of nutrient management practices, as compared to the conventional irrigation and drainage management. Zhang et al. [5] proposed a "zero-drainage water management" approach, which used natural field drying to replace conventional surface drainage based on the physiological water need for rice growth. They found that a combination of improved irrigation and field drying based on rainfall forecasting eliminated all drainage and phosphorus export from paddy fields (0.65 kg/ha under conventional management), while successfully meeting the physiological water requirement of plant growth. Elsewhere, Gao et al. [34] also found that appropriate control of irrigation and drainage could significantly reduce nitrogen and phosphorus concentrations in the field ponding water. Furthermore, when irrigation water is rich in nutrients such as in the scenario of wastewater irrigation [15], control of irrigation water quality is necessary to reduce paddy nutrient release to the water environments. Potentially, nutrient management practices and water management practices should be combined to achieve most desirable water quality outcomes and a sustainable agroecosystem.

7. Conclusions

Grand challenges exist in improving water quality in paddy systems. China is the largest rice-producing country in the world and also has the most intensive use of nutrients and water in rice production. Challenges to minimize the impacts of paddy nutrient losses on the water environment in China are even greater than anywhere else. Past research related to paddy systems has proved the importance of nutrient and water management on improving water quality. A combination of management in nutrient source, rate, timing and placement, and management in irrigation and drainage of water shows a great potential to reduce nitrogen and phosphorus losses from paddy fields. Even so, more research is needed to identify cost-effective monitoring approaches and mitigation options. Furthermore, extension and policy enforcement is needed beyond research to achieve water quality goals. Nonetheless, it should be noted that management of paddy water quality needs to be placed in a larger context of environmental protection. Our ongoing work has estimated that nutrient loss from paddy fields is smaller than that from intensively managed non-paddies such as vegetable fields. In some regions with high nutrient concentrations in surface water, paddy fields have even smaller nutrient losses in surface runoff than the nutrient inputs to the fields through irrigated and precipitated water.

Acknowledgements

This study was funded by the National Key Research and Development Program of China (2016YSD0800500).

Author details

Jian Liu[1], Hongbin Liu[2], Ruliang Liu[3], MG Mostofa Amin[4], Limei Zhai[2]*, Haiming Lu[5], Hongyuan Wang[2], Xubo Zhang[6], Yitao Zhang[2], Ying Zhao[7] and Xiaodong Ding[8]

*Address all correspondence to: zhailimei@caas.cn

1 School of Environment and Sustainability, Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

2 Key Laboratory of Nonpoint Source Pollution Control, Ministry of Agriculture, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China

3 Institute of Agricultural Resources and Environment, Ningxia Academy of Agriculture and Forestry Sciences, Yinchuan, Ningxia, China

4 Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh, Bangladesh

5 Nanjing Hydraulic Research Institute, State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing, China

6 Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

7 College of Resources and Environmental Engineering, Ludong University, Yantai, Shandong, China

8 College of Resources and Environment, Qingdao Agricultural University, Qingdao, Shandong, China

References

[1] Muthayya S, Sugimoto JD, Montgomery S, Maberly GF. An overview of global rice production, supply, trade, and consumption. Annals of the New York Academy of Sciences. 2014; **1324**:7-14

[2] FAO. FAOSTAT Database. Rome, Italy: Food and Agricultural Organization; 2017

[3] Khepar S, Yadav A, Sondhi S, Siag M. Water balance model for paddy fields under intermittent irrigation practices. Irrigation Science. 2000;**19**:199-208

[4] Zhang N, Li C, Li Y. Accumulation and releasing risk of phosphorus in soils in Dianchi watershed. The Soil. 2007:665-667

[5] Zhang ZJ, Zhang JY, He R, Wang ZD, Zhu YM. Phosphorus interception in floodwater of paddy field during the rice-growing season in TaiHu Lake Basin. Environmental Pollution. 2007;**145**:425-433

[6] National Bureau of Statistics of China. National Data on Crop Production in China. http://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0D0G&sj=2016. 2016; Data accessed: 4–1-2018

[7] China Ministry of Agriculture. Rice Regional Layout Planning 2008–2015. Beijing, China; 2008

[8] China Ministry of Agriculture. http://www.moa.gov.cn/; 2017

[9] China Meteorological Administration. http://www.cma.gov.cn/; 2017

[10] Liu Y, Wang L, Ni G, Cong Z. Spatial distribution characteristics of irrigation water requirement for main crops in China. Transactions from the Chinese Society of Agricultural Engineering. 2009;**25**(12):6-12 (In Chinese)

[11] Amin MGM, Rahman MM, Hasan MM. Irrigation with wastewater: Impacts, scope and challenges. In: Irrigation Management, Technologies and Environmental Impact. Hauppauge, NY, USA: NOVA Science Publishers, Inc.; 2013. pp. 285-300

[12] Cao ZH, Hu ZY. Copper contamination in paddy soils irrigated with wastewater. Chemosphere. 2000;**41**(1–2):3-6

[13] Kang MS, Kim SM, Park SW, Lee JJ, Yoo KH. Assessment of reclaimed wastewater irrigation impacts on water quality, soil, and rice cultivation in paddy fields. Journal of Environmental Science and Health, Part A. 2007;**42**(4):439-445

[14] Pham DD, Watanabe T. Municipal Wastewater Irrigation for Rice Cultivation. Intech Open: Current Perspective on Irrigation and Drainage; 2017

[15] Asano T, Burton FL, Leverenz HL, Tsuchihashi R, Tchobanoglous G. Water Reuse: Issue, Technology, and Application. New York, USA: McGraw Hill; 2007. p. 1570

[16] Si Y, Wang S, Chen H. The loss of farmland nitrogen and phosphorus and water eutrophication. The Soil. 2000:188-193 (In Chinese)

[17] Xu AL, Wang P. Phosphorus losses with surface runoff from farm lands in polder area around Taihu basin. Journal of Agro-Environment Science. 2008;**27**:1106-1111 (In Chinese)

[18] Qiu W, Tang H, Wang C. Characteristics of nitrogen loss in the leakage water of rice fields and the control measures. Journal of Agro-Environment Science. 2005;**24**:99-103 (In Chinese)

[19] Liu J, Zuo Q, Zhai LM, Luo CY, Liu HB, Wang HY, Liu S, Zou GY, Ren TZ. Phosphorus losses via surface runoff in rice−wheat cropping systems as impacted by rainfall regimes and fertilizer applications. Journal of Integrative Agriculture. 2016;**15**(3):667-677

[20] Guo H, Zhu J, Wang X, Wu Z, Zhang Z. Case study on nitrogen and phosphorus emissions from paddy field in Taihu region. Environmental Geochemistry and Health. 2004;**26**:209-219

[21] Li HG, Liu J, Li GH, Shen JB, Bergström L, Zhang FS. Past, present, and future use of phosphorus in Chinese agriculture and its influence on phosphorus losses. Ambio–A Journal of the Human Environment. 2015;**44**(2):274-285

[22] Liu J, Aronsson H, Ulén B, Bergström L. Potential phosphorus leaching from sandy top soils with different fertilizer histories before and after application of pig slurry. Soil Use and Management. 2012;**28**:457-467

[23] Xi B, Zhai LM, Liu J, Liu S, Wang HY, Luo CY, Ren TZ, Liu HB. Long-term phosphorus accumulation and agronomic and environmental critical phosphorus levels in Haplic Luvisol soil, northern China. Journal of Integrative Agriculture. 2016;**15**(1): 200-208

[24] Kleinman P, Sharpley A, Buda AR, McDowell RW, Allen AL. Soil controls of phosphorus in runoff: Management barriers and opportunities. Canadian Journal of Soil Science. 2011; **91**:329-338

[25] Sharpley AN, Bergstrom L, Aronsson H, Bechmann M, Bolster CH, Borling K, et al. Future agriculture with minimized phosphorus losses to waters: Research needs and direction. Ambio. 2015;**44**:163-179

[26] Susumu SA, Seiko H, Takayuki U, Takeshi Y, Sadahiro Y, Satoshi Y. Excessive application of farmyard manure reduces rice yield and enhances environmental pollution risk in paddy fields. Archives of Agronomy and Soil Science. 2016;**62**:1208-1221

[27] Hua L, Liu J, Zhai LM, Xi B, Zhang F, Wang HY, Liu HB, Chen AQ, Fu B. Risks of phosphorus runoff losses from five Chinese paddy soils under conventional management practices. Agriculture, Ecosystems and Environment. 2017;**245**:112-123

[28] Chapagain AK, Hoekstra AY. The Green, Blue and Grey Water Footprint of Rice from both a Production and Consumption Perspective. Value of Water Research Report Series No. 40. Delft, the Netherlands: UNESCO-IHE Institute for Water Education; 2010

[29] Zuo Q, Lu C, Zhang W. Preliminary study of phosphorus runoff and drainage from a paddy field in the Taihu Basin. Chemosphere. 2003;**50**:689-694

[30] Fujisawa E, Kobayashi A, Hanyu T. A mechanism of nutrient release from resin-coated fertilizers and its estimation by kinetic methods, 5: Effect of soil moisture level on release rates from resin-coated mixed fertilizer. Japanese Society of Soil Science and Plant Nutrition. 1998;**69**:582-589

[31] Liu R. Study on the characteristics of n leaching losses and process control in paddy field in the yellow river irrigation region of Ningxia. PhD Thesis. Beijing, China: Chinese Academy of Agricultural Sciences; 2013

[32] Yang S, Yang Z. Development and Application of Agronomic Technologies to Control Non-point Source Pollution in Irrigated Agriculture of Ningxia. Beijing, China: Chinese Agricultural Science and Technology Press; 2014

[33] Peng S, Yang S, Xu J, Gao H. Field experiments on greenhouse gas emissions and nitrogen and phosphorus losses from rice paddy with efficient irrigation and drainage management. Science China Technological Sciences. 2011;**54**:1581-1587

[34] Gao S, Yu S, Shao G, She D, Wang M, Guo R, Cao R, Yan S, Ding J. Effects of controlled irrigation and drainage on nitrogen and phosphorus concentrations in paddy water. Journal of Chemistry. 2016; Article ID 2576015:9

[35] Cao Z, Zhang H. Phosphorus losses to water from lowland rice fields under rice-wheat double cropping system in the tai Lake region. Environmental Geochemistry and Health. 2004;**26**:229-236

Chapter 8

Management of Plant Disease Epidemics with Irrigation Practices

Adalberto C. Café-Filho, Carlos Alberto Lopes and Maurício Rossato

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.78253

Abstract

Adequate water provision to roots is essential to warrant sustainable harvests of agricultural crops globally. However, water applied in excess or in deficit may result in the development of many fungal and bacterial plant diseases, which compromise produce yield and quality. Leaf wetness duration, soil water tension and related water variables impact several aspects of different plant disease cycles, such as the sporulation, survival of pathogen propagules, their dispersal to new hosts, germination and infection. Irrigation is thus arguably the most important cultural practice in the management of plant diseases, especially in the context of the quest of a more sustainable, less chemically dependent agriculture. The technology of water application and method of irrigation have been profusely studied as to their direct relation to plant diseases. Irrigation management has a strong impact on the disease severity and epidemic progress rates of many plant pathosystems, ranging from leaf blights to vascular wilts. In addition, plant virus vector population levels and vector dispersal are also affected by the method of irrigation. This chapter reviews experimental data on the effect of different irrigation configurations and management systems on some representative plant diseases.

Keywords: bacteria, nematode, oomycetes, fungi, virus, leaf wetness, pathogen propagule, dispersion, water

1. Introduction

Plant diseases are one of the main constraints for agricultural production, leading to great loses annually all around the globe [1]. Plant pathology evolved along with agriculture, starting with the earliest farmers competing against plant pathogens with religious, supernatural or other practices [2] to come to the modern era, where science is used to track the conditions which favors pathogens and consequently allows growers to how to avoid them on a rational basis.

The irrigation efficiency not only ensures the most efficient crop growth, but it is also essential for high-quality production of seeds, food, textiles and other produce with increasing perception of the economical and environmental impacts. It is estimated that 30–40% of the world food production is from irrigated agriculture [3, 4]. Its importance can be exemplified by reports on potato production which indicate that variations as low as 10% of the potato water need result in significant yield losses, either from water deficiency, leading to deformation and reduced tuber size, or excess, which increases the intensity of many diseases [5].

Choice of the irrigation system in itself, regardless of the volume of the water supply, affects plant development as well as disease onset, pathogen dispersal and rates of disease progress. For example, furrow irrigation which requires large amounts of water, usually demands higher rates of nitrogen fertilization which can predispose the plant to many diseases; in addition, soil borne pathogens easily spread in the irrigation furrows following water flow [6]. In areas infested with *Ralstonia solanacearum*, the furrow and some drip irrigation systems increased tomato wilt incidence and reduced yield, while conventional overhead sprinkler irrigation had much lower disease levels and higher yields [7, 8].

Drip irrigation, in addition to a more efficient water use, is usually recommended to avoid wetting of aerial plant parts and generally results in less foliar diseases [9]. On the other hand, the direct (mechanical) and indirect (environmental) effects of delivering irrigation water droplets onto the leaf surfaces have been demonstrated to significantly reduce powdery mildews on Cucurbitaceae [10], Fabaceae [11] and Solanaceae [12] while also depressing virus vector movement [13]. These two situations indicate that diseases vary as to their response to irrigation. Therefore, a precise determination of the disease frequency and intensity in a given area must be done before choosing the most adequate irrigation method.

The sprinkle irrigation systems usually allow for better water distribution to the crop, at reasonable economic costs. It is generally more efficient than furrow irrigation, but it promotes foliar wetting, required for many pathosystems, and is favorable to propagule dispersion, especially of bacterial and most fungal spores.

In addition to the choice of the irrigation method, other factors must be taken into consideration, such as irrigation timing. Most fungal plant pathogens produce spores during nighttime, being dispersed after dawn. Consequently, morning irrigations are prone to dislodge and disperse spores, also offering humidity and free water for germination at the leaf surface. Some fungal pathogens may form spores or propagules later in the day and are thus favored by afternoon irrigations, while night irrigation will reduce spore dispersion, as reported for *Phytophthora infestans* [14].

With exception of the members of the Erysiphales (Ascomycota), fungi and bacteria need free water on the leaf surface to initiate infectious processes. In fact, the leaf wetness duration has been considered the most determinant microclimatic variable for disease establishment and progress, and it is one of the main variables monitored in disease prediction systems [15].

The pathogen success in establishing itself in the aerial plant parts is highly dependent on the duration of foliar wetting, which is directly affected by irrigation timing and other factors [16]. If the moisture provided by irrigation is enough to retain free water in the plant surface for the minimum time required for infection, it will lead to more intense disease epidemics. For many years, we have observed that processing tomato in Central Brazil display significantly lower incidence of diseases caused by *Phytophthora infestans, Septoria solani, Xanthomonas* spp. and *Alternaria* spp. under drip when compared to sprinkle irrigation.

In addition to water availability, the evaporation process must be considered. Evaporation is affected directly by relative humidity, air temperature, wind speed, air vapor pressure [4] and plant tissue position. For example, within Israeli climatic conditions, sprinkler-irrigated tomato leaves take from 5 min (external leaves, strong wind, 36°C, 16% RH) to 4 h (internal leaves, no wind, no direct sun, 17°C, 16% RH) to dry. In the latter climatic conditions, the leaves may remain wet until dew formation at nighttime, completing a total 20 h of total humidity [17]. A similar phenomenon occurs in the dry season (April–September) in Central Brazil, when almost all processing tomato and potato crops are grown. Both crops are hosts of late blight (caused by the oomycete *Phytophthora infestans*) and early blight (caused by the true fungus, *Alternaria solani*). These pathogens have different resistance levels to dryness and widely different temperature requirements, serving as illustrative models for the discussion on infection and the influence of the leaf microenvironment on disease severity.

The way plant pathogens relate to irrigation and water availability depends on a diverse number of characteristics intrinsic of each group of microorganisms. In the present review, diseases and their respective causal agents were grouped according to their primary niche in the plant, either diseases of aerial plant parts or as crown and root diseases. Other divisions were made below for clarifying the effect of the water on each plant part or phase of the disease cycle. Oomycetes, for example, are very well adapted to the availability of free water, while other fungi, as the *Erysiphaceae,* (the powdery mildews) have a negative interaction resulting in damage of conidia when overhead irrigation is used. Bacteria are also highly dependent on water to prevent desiccation (which usually causes sharp decrease on their populations) and then to allow multiplication until they reach the threshold numbers necessary for invasion and infection. Fungi with a gelatinous matrix also respond differently when compared to other fungal groups: For instance, aerial transport by wind does not play an essential role for these organisms, whereas sprinkler irrigation typically provides the main dispersal method.

2. Diseases of the aerial plant parts

Fungi, oomycetes, virus and bacteria infect aerial parts of susceptible host plant (leaves, stem, flowers and fruits) resulting in diseases responsible for losses due to direct damage to the commercial produce or to yield reduction as a consequence of impaired photosynthesis and loss of photoassimilates.

These pathogens, different from the soil-habitant ones, must be resilient to adverse environmental conditions such as dehydration, large temperature fluctuations, nutrient scarcity in an epiphytic phase, incidence of UV light, among other physical, chemical or biological harmful factors [18].

While wind plays a critical role on the dispersion of plant pathogens, irrigation water and rain, provide conditions for spore germination, avoiding desiccation of fungal and bacterial cells or, in some instances, damaging propagules sensible to water.

Many reports have indicated that more frequent sprinkle irrigations increase disease incidence of several foliar diseases [6, 14]. The understanding of the dynamics of each pathosystem is therefore mandatory for choosing the method of irrigation to be implemented in a given situation.

While oomycetes, fungi, bacteria and viruses all infect aerial parts of plants and are affected by irrigation, the latter is indirectly influenced because water affects insects and other vectors which transmit them.

2.1. Oomycetes

The oomycetes, long treated as fungi and studied by mycologists due to their morphological, functional and ecological similarities with the Fungi Kingdom actually belong to the Chromista Kingdom and are more closely related to algae than to fungi [19]. They include Phytophthora wilts and blights, the downy mildews caused by the Peronosporales, the white rusts (genus *Albugo*) and root, crown and fruit rots by the genus *Pythium* and *Phytophthora*.

In general, oomycetes are greatly dependent on high humidity levels for all stages of the life cycle, including sporangia formation [20], and especially so for the indirect germination of sporangia in the form of zoospores, a process of great epidemiological consequence which requires not only high humidity levels, but actual free water [21]. High relative humidity (RH) can be achieved in several ways, including the method of application of irrigation water, high plant density and reduced plant spacing [22]. Shtienberg [23] also warned about the use of polyethylene mulch as a means to increase irrigation efficiency by reducing water evaporation.

Irrigation may also be responsible for the short or long-distance introduction of oomycete inoculum into new growing areas, which was reported for the first time in 1921 [24]. Ranging from 6 to 45 days, the survival of plant pathogen propagules on irrigation water varies accordingly to the pathogen species, other abiotic conditions (temperature, pH, etc.) and especially with the propagule type [25, 26].

Free water on leaves, generally reported as leaf wetness duration, is a combined consequence of rains, irrigation events and microclimatic conditions prevailing in the plant canopy. Due to the strong dependence of oomycetes to leaf wetness, the ones infecting aerial plant parts can be controlled by the choice of irrigation method in favor of the systems that reduce leaf wetness. This has been shown for *Peronospora sparsa,* the causal agent of the blackberry downy mildew [22]. Mildew severities of 97% were recorded in the sprinkler overhead irrigation, compared to less than 10% in the drip system. Greater severity was associated with larger periods of time of leaf wetness durations, in the sprinkler irrigated treatment.

Other oomycetes can be controlled by drip irrigation, as for *Phytophthora infestans* infecting greenhouse-grown tomatoes [27], or even in tomato field crops, planted in the dry season in the Brazilian Midwest (unpublished). *P. infestans* requires 2 to 6 h of leaf wetness (depending on temperature); nevertheless, high humidity levels inside the greenhouse (due evaporation) may favor disease development, stimulating spore germination [23, 28].

2.2. Gelatinous matrix fungi

Fungus is one of the most diverse Kingdoms, with many species pathogenic to plants. Most fungi do not require water for spore dispersion, being easily dispersed in the dry air. However, numerous fungi, including important plant pathogens, are dependent on water splash for the dissemination. Commonly, this kind of fungi produces conidia associated to a gelatinous matrix in asexual sporulation structures such as picnidium (*Ascochyta*, *Phoma, Septoria*) or acervulus (*Colletotrichum*).

If one fungus species requires water splash for dispersion, again the type of irrigation has a strong effect on such group of pathogens. The size and amount of the water drops may alter its capacity of spore dispersion, since smaller drops are unlikely to dislocate and disseminate spore from one spot to another [29].

An example of the effect of irrigation method on fungi dissemination are the high severities of gummy stem blight (*Didymella bryoniae*) and anthracnose (*Colletotrichum gloeosporioides* f. sp. *cucurbitae*) of watermelon irrigated by overhead sprinkler, which presented reduced productivity and fruit quality. When shifting overhead to furrow irrigation, both diseases were drastically reduced [6]. These changes were associated with strong reductions of the foliar and fruit wetness periods, resulting in less dispersion and germination of spores. The same pattern was seen for anthracnose (*Colletotrichum acutatum*) in strawberry, when drip irrigation leads to very low disease incidence, postponing disease onset, and, therefore, reducing loses [30]. The same pattern has been observed for sweet pepper anthracnose, caused by *Colletotrichum* spp. (unpublished) and *Septoria lycopersici* on tomato [31]. For the septoria leaf spot, disease progress rates varied widely in the sprinkler, microsprinkler, drip and furrow irrigated plots, and severity increased most in treatments that kept leaves wet the longest.

The concept of leaf wetness is also an issue for *Glomerella cingulata* in apple. This pathogen requires high RH (>99%) and foliar wetness duration of 2.76 h, for significant germination of conidia. Additionally, the spore release from the acervuli and subsequent dispersal need rain or irrigation water for the splash-dispersal effect. Therefore, in the absence of these conditions, lesions are sparse and do not spread, even within a single host plant [15].

2.3. Dry propagule fungi

Several species in the Fungi Kingdom reproduce asexually by producing dry conidia, with no gelatinous matrix, and may or may not be affected by irrigation management.

Powdery mildew, for example, caused by a number of species on the *Erysiphaceae* (Ascomycota), can infect several hosts, and is characterized by the presence of a whitish growth (mycelium, conidiophores and conidia), mainly in the adaxial leaf surface. Still fairly dependent on humidity as several other pathogens, its development may increase until a maximum of 80% RH as reported for *Uncinula necator* in grapevine [32]. Nonetheless, different from other fungal diseases, sprinkler irrigation is harmful for powdery mildews disease progress. The mechanical impact of water droplets harms the fungal structures, hindering disease progress. This phenomenon was previously found by Ruppel et al. [33] who observed lower disease incidence on sprinkler-irrigated sugar beet fields when compared to furrow irrigated ones. The effect of free water in powdery mildew conidia was analyzed by Shomari and Kennedy [34] in conidia of *Oidium anacardii*, a pathogen of cashew, by immersion of infected leaves in water, exhibiting a significant reduction on spore germination after an immersion period of 4 h. This interaction with conidia is only seen before germination: after that phase, leaf wetness does not influence any further on the host tissue colonization.

Other examples of the irrigation effects over powdery mildew may be seen with *Leveillula taurica* in tomato, which displays a critical increase of incidence when the crop is drip-irrigated, due to the absence of free water on leaves [27]. On pumpkin, powdery mildew is progressively reduced with increasing water volumes applied by the conventional overhead sprinkler irrigation system [10].

Conversely, *Alternaria solani,* the causal agent of tomato and potato early blight, does not suffer any negative effects of sprinkler irrigation. In fact, *A. solani*, as the great majority of plant pathogens that form dry propagules, benefits from the increased leaf wetness duration delivered by irrigation systems that wet aerial plant parts. Processes such as spore production and germination rates are favored. Reduced amounts of water may not markedly affect the development of *Alternaria* diseases, since its dark, thick-walled, multicellular spores are resilient to desiccation. In addition, germination of *A. solani* can take place with the only source of moisture deriving from nighttime dew, without need for irrigations [6].

Fusarium head blights (*Fusarium graminearum, F. culmorum, F. avenaceum*) of maize, wheat and other Poaceae, are economically devastating diseases not only for the direct losses of reduced grain yield but also for the accumulation of mycotoxins in the produce. Timing of irrigation is determinant for avoiding the occurrence of these diseases, and water should be avoided before anthesis and early grain fill periods [35]. Irrigation or rain water stimulates spore production, dispersion and germination of the *Fusarium* and of its sexual form (*Gibberella zeae*). High humidity levels (>94%) are also a requirement for most of the disease cycle phases [36, 37].

2.4. Bacteria

Bacteria, single-celled prokaryotes (1–2 μm in size) which reproduce by binary fission, are natural inhabitants on the rhizosphere or plant surfaces where they are mostly harmless as residents or epiphytes. The plant pathogenic ones will cause problems to a susceptible host only when conditions are favorable for their establishment, infection and multiplication. These conditions include high humidity and poor air circulation around plants. A film of free water on the leaf surface is the right condition for bacterial multiplication. Since they are microscopic, their presence is noticed only in large quantities, such as colonies in laboratory culture media or as viscous substances oozing from plant vessels and biofilms, or upon manifestation of symptoms of the diseases they induce.

As for the diseases caused by oomycetes and true fungi, bacterial diseases in plants may occur in the aerial plant parts, including leaves and fruits, causing several symptoms such as cankers, pustules, blights, spots and specks. The symptomatology may vary with plant variety, host age and climatic conditions [38].

Bacterial diseases are strongly affected by irrigation. Water, because it is necessary for the epidemiological processes of dispersal, infection and colonization, is considered one of the most, if not the most, important inputs that move bacterial disease expression on most crops.

Leaf wetness is essential for bacterial infection and colonization of aerial parts of the plants. Bacteria penetrate through wounds or natural openings such as stomata and hydathodes. From diseased plants, bacterial cells are dispersed within and among fields through aerosols, insects, windblown soil and sand particles, movement of plant propagules and water flow.

For instance, bacterial spot (*Xanthomonas euvesicatoria*) is a recurrent disease that can devastate pepper fields whenever warm, wet weather is present. The pathogen is seed borne and is responsible for the formation of leaf spots that harbors large number of bacterial cells. Upon impacting on lesions, droplets from rain or overhead irrigation disperse bacterial cells through many micro-droplets from infected plants to neighboring healthy plants, especially under windy conditions. In addition, when foliage is wet, farm operations allow bacterial cells from infected plants to be carried to healthy plants within or between field areas [39].

In this example, which applies to many other bacterial spot diseases, switching from overhead to drip irrigation will warrant necessary moisture accessible to the roots while keeping the foliage dry. It is necessary to keep in mind that, as discussed elsewhere in this chapter, other diseases and pests might be favored by one particular kind of irrigation. An overall analysis of the crop management is necessary for the decision-making process, in a way to cope with different diseases and obtain desirable yields.

2.5. Viruses

Viruses are intracellular pathogens not capable of reproducing outside a living cell but possessing the genetic means for the manipulation of the host replication machinery for such action.

Vectors of plant viruses have a major role on the epidemics of plant virus because they are needed for the transportation and introduction of the virus particles into the host plant cell [40]. Most plant viruses can be transmitted by one of several groups of insects. A minority may also be vectored by other organisms such as mites, nematodes and pseudofungi (as those from kingdom Protozoa) [41, 42]. Nematodes that disseminate plant viruses will be addressed below. In some cases, diseases of complex etiology combine damages from the nematode with the virus, compounding losses.

Irrigation water does not affect the several viral pre-infection stages that are found within the fungi and bacteria life cycles. When lacking or in excess, water and irrigation may cause physiological host changes, which may accentuate or attenuate symptoms or alter the relationship of the vector with the virus and the host plant [43]. In some cases, the virus may protect its host from severe drought by avoiding irreversible wilt, as reported by Xu et al. [44]. Another similar example is during the infection of wheat by the *Barley yellow dwarf virus*; when the host is stressed from severe drought, the survival of the infected plant is increased, and it offers a more favorable growth for the aphid vector, *Rhopalosiphum padi* [45]. Turnip plants suffering from water deficiency stress can increase the transmission of *Cauliflower mosaic virus* (CaMV) by 34%, while the transmission of the *Turnip mosaic virus* may be increased by 100%. The increase in transmission was not related to higher virus tittering but for a rapid response by CaMV in producing transmissible morphs [43].

The main effect of irrigation on plant virus diseases concerns its effects on the vectors. Irrigation may affect the vectors, by altering its feeding habits, the efficiency of virus acquisition from an infected host, and, especially, by physically removing or disturbing the feeding of the insect. This latter effect is most noticeable by the application of water by sprinkler irrigation, which can reduce the population when compared to other irrigation methods in experimental plots [46]. These findings were confirmed not only for whiteflies (*Bemisia tabaci*) [27, 47] but also for *Myzus persicae* [48], each of which are important vectors of numerous plant viruses worldwide.

3. Crown and root diseases

Crown and root diseases are caused by soilborne pathogens and usually result in great losses since control measures are more difficult because the "enemy" is protected by the soil layers. Frequently, soilborne pathogens lead to the abandonment of an infested field or make the whole farm improper for the cultivation of particular crops. These soil pathogens belong to different taxa in the fungi, oomycetes, bacteria and nematodes, and infect roots and crowns. They spend most of their life cycle in soil, with high resilience to changes in the physical environment and enhanced competitive skills. They are generally facultative pathogens, with good saprophytic activity. The dispersal of these pathogens is mostly associated to soil movement, adhered to implements and machines, even though spores of some may be dispersed by wind and water [49]. In tropical and subtropical conditions, these pathogens are favored, given the lesser oscillations in the soil physical parameters [50]. Soil is considered an environment that favors organisms which use water for movement, as the flagellate zoospores from oomycetes, flagellate bacterial cells, and nematodes that move in water films. Evidently, all these organisms may be passively transported even faster, and further, in flows of water.

The way irrigation methods affect crown and root diseases, and their causal agents vary accordingly to the group of microorganisms and other characteristics, such as the capacity for facultative anaerobiosis (in flooded or water-logged soil), which is conducive to soft rots caused by pectolytic bacteria.

Nematodes, mostly soilborne pathogens, are highly affected by water availability, typically by the aid of water for active movement in the root zone. Also, water allows for the passive movement following the water flow on soil, as when furrow irrigation is used.

In the following sections, the same group of pathogens addressed previously is discussed for the development root and crown diseases.

3.1. Oomycetes in soil

Many of the previously addressed factors in topic 2.1 can be applied for oomycetes causing disease in lower plant parts. The dependence on water still exists, although, different from the aerial organs, soil tends to be more stable for physical factors in general, and for temperature and humidity in particular, while it is a generally more competitive environment.

As for various pathogens, the epidemiology of a given oomycete is bound to irrigation or rainfall intensity and frequency. *Phytophthora capsici,* for example, during seasons of intense rainfall, causes much faster epidemics than when in conditions of moderate rainfall or irrigation [51].

Soil oomycetes are in general highly adapted to survive in soil, with varying times of survival accordingly to temperature and a few other abiotic factors. Irrigation water plays an especially important role on the dispersal of oomycetes, due to their flagellate zoospores. "True fungi" (those in the Kingdom Fungi) do not have flagellate spores, and so are less efficiently dispersed by soil water.

As discussed earlier, irrigation water and free soil water aid pathogens that are immovable, as non-flagellate bacteria which go with the water flux, but also for zoospores of oomycetes, flagellate spores that may dislocate in water [50]. Zoospores are also capable of host plant detection, allowing chemotaxis to the host and a quick attachment to the host tissue and the initiation of the infection process. *Phytophthora parasitica,* a pathogen of citrus, is one of those organisms that uses water for dispersal: irrigation spreads this pathogen not only within one field, but to an entire region, affecting growers that use the same water source [52]. The same pattern is found for *Phytophthora capsici,* in bell pepper, tomato and squash fields: for this pathogen, furrow irrigation has been shown to carry sporangia and zoospores to long distances. The number of infected plants along an irrigation line is attributed to the collection of secondary inoculum produced by the first infected plants [53]. *Phytophthora capsici* and *P. parasitica* were readily dispersed in furrow irrigation water up to 70 m from the point sources of inoculum in Solanaceae and Cucurbitaceae [54], and the mere reduction of furrow irrigation frequencies drastically reduced Phytophthora wilt on squash [53] and sweet pepper [55].

Frequent irrigations saturate soils and keep humidity for long periods of time, favoring propagule dispersal. Bowers et al. [56] and Ansani and Matsuoka [57] showed that in warm conditions (15–25°C), *P. capsici* resists for several days, even buried at several depths in the soil. In addition, soil moisture may render some hosts more predisposed to oomycete infection [58]. However, this has not been confirmed for all oomycete pathosystems, as for *P. capsici* in bell pepper [59]. Constant soil moisture at saturation or low saturation levels is not as positive for disease development as fluctuations of soil moisture [60]. Therefore, a lesser number of irrigation events are usually a form of disease control. For *Pythium aphanidermatum* in petunia, low and constant irrigation reduced plant infection, in contrast with constantly saturated soils or soils submitted to a cycling of wetting and drying [61].

Different irrigation methods may increase or reduce diseases caused by oomycetes in soil. Gencoglan et al. [62] showed that drip irrigation was the most efficient system to avoid *P. capsici*, with only 1.7% of incidence, versus 3.1% and 3.2% for furrow and sprinkler irrigations, respectively, and lastly and most prejudicial, basin irrigation, which caused 93.9% dead plants. Several authors have confirmed that drip irrigation is the most efficient irrigation method for oomycete control [63, 64].

3.2. Fungi in soil

True fungi in soil must not only survive humidity and temperature fluctuations but also the competitive environment that prevails in the rhizosphere. The effect of irrigation is different from what is commonly seen on above soil plant organs, and here, diseases may be favored by drip irrigation due to the large availability of water next to the host roots and crowns.

Some plant pathogenic soil fungi have a complex relationship with the host, and infection may be hampered at low soil moisture, while high soil moisture may reduce symptom expression and improve yields. For example, the most effective management strategy to reduce Verticillium wilt, without decrease of dry matter production, is to irrigate at water deficit levels to the host during the vegetative stage and at 90% of soil capacity during the production phase (unpublished).

Accumulation of water in soil due to irrigation is increased when field soil is compacted (e.g., as a consequence of intensive agrotechnical operations) and/or native pedosphere properties (e.g., texture heavier soils). Several pathogenic soil fungi are favored by this condition of reduced aeration, such as *Fusarium oxysporum* pv. *solani, F. oxysporum* pv. *phaseoli, Rhizoctonia* spp. and *S. sclerotiorum* [65]. For *Rhizoctonia* infections causing root dieback in *Pinus* nurseries, excessive water interacts negatively with the host due to lack of root aeration, reducing growth and favoring the fungal infection. The ensuing root decay and water accumulation further stimulates the development of other secondary plant pathogens [66].

Irrigation may also aid on the propagule dispersion and disease development. For example, Fusarium root rot (*Fusarium solani* f. sp. *phaseoli*) in beans is greatly reduced when sprinkler irrigation is used, contrarily to the negative effects of furrow or drip irrigations on the disease [67]. For *Sclerotinia minor,* the causal agent of lettuce drop, drip irrigation has a suppressive effect on the pathogen, while furrow increases substantially the sclerotial population. Irrigation not only provided humidity but also lowered the soil temperature, with furrow irrigation allowing the establishment of a more suitable temperature (18°C) for the fungus [68].

As several other group of pathogens, fungi can also enter a new area by means of irrigation water. Previous studies on *V. dahliae* in irrigated olives showed a great dispersion of propagules [69] while its survival is also remarkable, with reports of up to 15,000 propagules of per liter of water in ponds used for irrigation [70].

3.3. Bacteria in soil

Soil-associated bacteria are highly influenced by soil moisture. For most plant pathogenic bacteria, high humidity favors disease onset and development. Incidentally, bacterial wilt

(*Ralstonia solanacearum*) was first known as the "moisture disease" of potatoes, before the causal agent was identified [71]. In fact, the disease is prevalent during the wet summers, when high temperatures and high humidity are combined in a perfect condition for bacterial multiplication.

When comparing irrigation methods on bacterial wilt, Marouelli et al. [7] found that disease was significantly higher when processing tomato in Central Brazil was drip-irrigated, with an average of 42.5% wilted plants, 65 days after seedling transplant, in comparison with 5.0% incidence with sprinkle irrigation. Frequency of drip irrigation did not affect bacterial wilt incidence. It is believed that drip irrigation maintains the plant rhizosphere close to field capacity, thus favoring the disease, contrasting with the sprinkle irrigation, which provides periods of dry and wet conditions. Furrow irrigation was not studied, but it would most probably have an effect similar to the drip irrigation, or even more pronounced, if dispersion of the pathogen in the furrow is taken into account.

Contrasting with bacterial wilt, potatoes are affected by common scab, induced by *Streptomyces* spp. In this case, however, low soil humidity during tuber growth phase favors scab formation, what makes irrigation management recognized as one of the most efficient scab control measures. According to Wharton et al. [72], keeping soil moisture near field capacity for a few weeks at the beginning of tuberization substantially inhibits pathogen infection and disease development. The most likely explanation for this phenomenon is that the maintenance of high soil moisture is a condition that favors a more varied and competitive microbiota in the host rhizosphere, to the detriment of *Streptomyces* species.

Overall, because plant pathogenic bacteria may be viable in water for long periods of time, irrigation deserves special attention for two important epidemiological processes: survival and dispersal [73].

3.4. Nematodes

Nematodes infect root systems of a great number of plants species and are one of the most difficult plant pathogens to control. Some parasitize upper plant organs, causing galls or lesions on leaves and seeds. However, most nematodes are root pathogens that not only act as plant parasites, but also facilitate infections by other soil pathogens, that penetrate through lesions caused by the nematodes on the root systems.

Nematode populations usually keep a steady growth if a susceptible host is available, soil texture is ideal and irrigation is not excessive (reducing oxygen availability), or restricted (preventing movement), as reported for *Meloidogyne enterolobii* in guava [74].

The influence of water in this group of plant pathogens is mostly related to dissemination and movement in soil. Soil moisture, depending on the nematode species is essential to allow movement of juveniles and adults from colloid to colloid on water films around soil particles.

In addition to active movement, eggs, juveniles and adult nematodes can be carried passively by irrigation water to short or long distances. Nematode spreads through large field areas, if water is collected from the same infested source [75]. Also, intensive irrigation is conducive to high nematode population levels, due to its effect on soil texture remodeling, altering abiotic conditions as aeration and particle arrangement creating new niches for protection [76]. Nematode locomotion depends on water, as studied for the J2 of *Meloidogyne incognita,* which could not travel against the water flow, limiting itself to resist the flow, trying to remain static. In sand substrate tests, when water percolated, the nematode moved with the water flow, resulting in the distribution of the nematode along irrigated areas [77].

Nematodes are already plant parasites *per se* but can also act as vectors for viruses as *Xiphinema index* (and other species) capable of transmitting *Grapevine fanleaf virus* into grapes [78]. Two nematode orders are known as vectors of plant viruses, Dorylaimida and Triplonchida [79]. For these nematode vectors, and several other species, soil is not required to be saturated, if humidity is kept at "normal levels" the parasite can survive and still act as a vector even 4 years in the absence of its hosts [80]. Also, *X. index* can be disseminated by contaminated irrigation water [81]. In some cases, these parasites are highly resistant to dehydration, in a survival strategy termed anhydrobiosis. Anhydrobiosis has been observed in many nematodes, such as among *Pratylenchus* (the lesion nematodes), one of the most important plant pathogenic nematode genera [82].

Differences among irrigation methods have not been very well explored for this group of plant pathogens. However, taking into consideration the effect of water flow and irrigation on the nematode's movement and displacement, drip irrigation could result in lesser dispersal and consequently, less infected plants in the fields.

4. Conclusion

The response of plant pathogens (fungi, oomycetes, bacteria, nematodes, viruses) to the range of irrigations methods and management configurations varies widely and must be addressed for each particular plant-pathogen system (**Figure 1**). Among furrow, overhead sprinkler, microsprinkler, and drip irrigation, there are a variety of management choices that may strongly affect propagule dispersion, induction of germination, biofilm formation, penetration and survival of each specific group of pathogens. For the oomycetes and bacteria associated to aerial plant organs, due to their strong dependency on free water and high humidity, drip irrigation might be the appropriate choice. Among the true fungi, the effects of the irrigation system and management differ, and species of dry and wet spores respond distinctly to each individual method. In some groups, such as the Erysiphales, free water may hamper disease progress. Nematodes and oomycetes need free water in the soil to be actively distributed in the crop. Viruses, accompanying their vectors, can be controlled by sprinkle irrigation water, which disrupts the contact of the insect with the plant. The knowledge of the causal agent and of the disease epidemiological components is essential when deciding the type of irrigation, frequency and water volume to be applied to manage one particular plant disease and is key to achieve good yields and high product quality.

http://dx.doi.org/10.5772/intechopen.78253

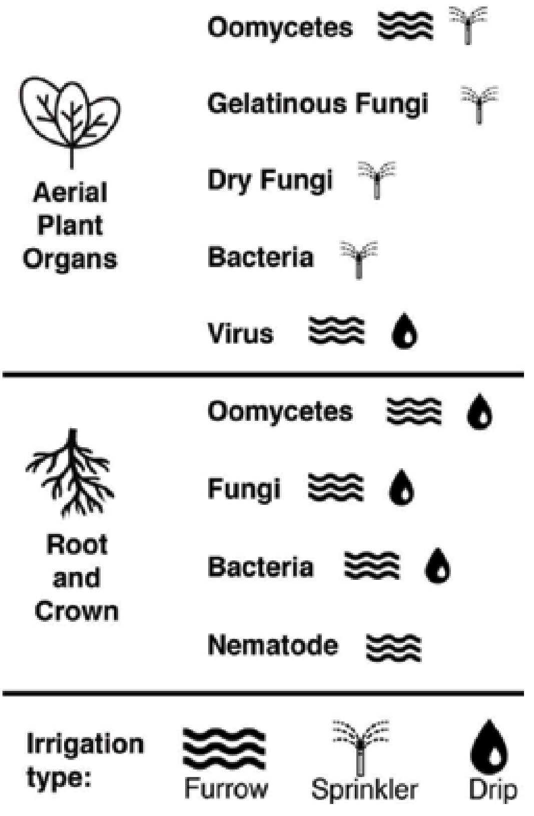

Figure 1. Schematic representation of irrigation methods which benefit disease development according to the plant pathogen group and affected plant organ. Furrow irrigation is conducive for oomycetes when aerial plant parts are in contact to the ground, as in processing tomato fields. Exceptions may exist for all groups.

Conflict of interest

The authors state no conflict of interest.

Author details

Adalberto C. Café-Filho[1*], Carlos Alberto Lopes[2] and Maurício Rossato[1]

*Address all correspondence to: cafefilh@unb.br

1 University of Brasília, Brasília, Brazil

2 Embrapa Vegetable Crops, Brasília, Brazil

References

[1] Oerke E-C. Crop losses to pests. The Journal of Agricultural Science. 2006;**144**(1):31-43

[2] Martinelli F, Scalenghe R, Davino S, Panno S, Scuderi G, Ruisi P, et al. Advanced methods of plant disease detection. A review. Agronomy for Sustainable Development. 2015; **35**(1):1-25

[3] Martinelli. Feeding the World: An Economic History of Agriculture 1800-2000. Princeton, NJ, USA: Princeton University Press; 2005

[4] Ondrasek G. Water scarcity & water stress in agriculture. In: Ahmad P, Wani M, editors. Physiological Mechanism and Adaptation Strategies in Plants under Changing Environments. New York, NY: Springer; 2014. pp. 77-96

[5] King B, Stark J. Potato Irrigation Management for On-Farm Potato Research. Potato Research and Extension Proposals for Cooperative Action. Moscow, ID, USA: University of Idaho, College of Agriculture; 1997. pp. 88-95

[6] Lopes C, Marouelli W, Café Filho A. Associação da irrigação com doenças de hortaliças. Revisão Anual de Patologia de Plantas. 2006;**14**:151-179

[7] Marouelli WA, Lopes CA, Silva WL. Incidência de murcha-bacteriana em tomate para processamento industrial sob irrigação por gotejamento e aspersão. Horticultura Brasileira. 2005;**23**(2):320-323

[8] Cabral RN, Marouelli WA, Da Costa Lage DA, Lapidus GÁ, Café Filho AC. Incidência da Murcha Bacteriana em Tomateiro Orgânico sob Diferentes Sistemas de Irrigação, Níveis de Água e Coberturas de Solo. Cadernos de Agroecologia. 2011;**6**:1-2

[9] Bhat RG, Subbarao V. Cultural control. In: Maloy OC, Murray TD, editors. Encyclopedia of Plant Pathology 1. New York, NY, USA: John Wiley & Sons; 2001. pp. 274-279

[10] Coelho M, Cafe Filho A, Lopes C, Marouelli W. Severidade de oidio em abobora hibrida sob diferentes laminas de irrigacao e niveis de nitrogenio. Fitopatologia Brasileira. 2000; **25**:157-160

[11] Oliveira CaDS, Marouelli WA, Santos J, Giordano L. Produção de escleródios de *Sclerotinia sclerotiorum* e severidade de oídio em cultivares de ervilha sob diferentes lâminas de água. Horticultura Brasileira. 2000;**18**(1):16-20

[12] Lage D, Marouelli W, Cafe-Filho A. Tomato powdery mildew may be significantly reduced by choice and management of irrigation system in the Brazilian middle west. Phytopathology. 2011;**101**(6):S97

[13] Michereff Filho M, Marouelli W, Gravina C, Resende F, Da Silva P, Nagata A. Influência de práticas culturais na infestação de pragas em tomateiro orgânico. Brasília, DF, Brazil: Embrapa Hortaliças; 2014. p. 32

[14] Rotem J, Palti J. Irrigation and plant diseases. Annual Review of Phytopathology. 1969; **7**(1):267-288

[15] Lee KJ, Kang JY, Lee DY, Jang SW, Lee S, Lee B-W, et al. Use of an empirical model to estimate leaf wetness duration for operation of a disease warning system under a shade in a ginseng field. Plant Disease. 2016;**100**(1):25-31

[16] Wang B, Li B-H, Dong X-L, Wang C-X, Zhang Z-F. Effects of temperature, wetness duration, and moisture on the conidial germination, infection, and disease incubation period of *Glomerella cingulata*. Plant Disease. 2015;**99**(2):249-256

[17] Rotem J, Cohen Y. The effect of temperature on the pathogen and on the development of blue mold disease in tobacco inoculated with Peronospora tabacina. Phytopathology. 1970;**60**(1):54-57

[18] Vorholt JA. Microbial life in the phyllosphere. Nature Reviews Microbiology. 2012; **10**(12):828

[19] Wang Q, Sun H, Huang J. Re-analyses of "algal" genes suggest a complex evolutionary history of oomycetes. Frontiers in Plant Science. 2017;**8**:1540

[20] Sanogo S, Ji P. Water management in relation to control of *Phytophthora capsici* in vegetable crops. Agricultural Water Management. 2013;**129**:113-119

[21] Ploetz R, Heine G, Haynes J, Watson M. An investigation of biological attributes that may contribute to the importance of *Phytophthora capsici* as a vegetable pathogen in Florida. Annals of Applied Biology. 2002;**140**(1):61-67

[22] O'neill T, Pye D, Locke T. The effect of fungicides, irrigation and plant density on the development of *Peronospora sparsa*, the cause of downy mildew in rose and blackberry. Annals of Applied Biology. 2002;**140**(2):207-214

[23] Shtienberg D, Elad Y, Bornstein M, Ziv G, Grava A, Cohen S. Polyethylene mulch modifies greenhouse microclimate and reduces infection of *Phytophthora infestans* in tomato and *Pseudoperonospora cubensis* in cucumber. Phytopathology. 2010;**100**(1):97-104

[24] Bewley W, Buddin W. On the fungus flora of glasshouse water supplies in relation to plant disease. Annals of Applied Biology. 1921;**8**(1):10-19

[25] Shokes F, Mccarter S. Occurrence, dissemination, and survival of plant pathogens in surface irrigation ponds in southern Georgia. Phytopathology. 1979;**69**(5):510-516

[26] Roberts P, Urs R, French-Monar R, Hoffine M, Seijo T, Mcgovern R. Survival and recovery of *Phytophthora capsici* and oomycetes in tailwater and soil from vegetable fields in Florida. Annals of Applied Biology. 2005;**146**(3):351-359

[27] Marouelli WA, Lage DaDC, Gravina CS, Michereff Filho M, Souza RBD. Sprinkler and drip irrigation in the organic tomato for single crops and when intercropped with coriander. Revista Ciência Agronômica. 2013;**44**(4):825-833

[28] Becktell M, Daughtrey M, Fry W. Temperature and leaf wetness requirements for patho-gen establishment, incubation period, and sporulation of *Phytophthora infestans* on *Petu-nia* × *hybrida*. Plant Disease. 2005;**89**(9):975-979

[29] Gregory P, Guthrie E, Bunce ME. Experiments on splash dispersal of fungus spores. Microbiology. 1959;**20**(2):328-354

[30] Coelho MV, Palma FR, Cafe-Filho AC. Management of strawberry anthracnose by choice of irrigation system, mulching material and host resistance. International Journal of Pest Management. 2008;**54**(4):347-354

[31] Cabral RN, Marouelli WA, Lage DA, Café-Filho AC. Septoria leaf spot in organic tomatoes under diverse irrigation systems and water management strategies. Horticultura Brasileira. 2013;**31**(3):392-400

[32] Carroll J, Wilcox W. Effects of humidity on the development of grapevine powdery mildew. Phytopathology. 2003;**93**(9):1137-1144

[33] Ruppel E, Harrison M, Nielson AK. Occurrence and cause of bacterial vascular necrosis and soft rot of sugarbeet in Washington. Plant Disease Reporter. 1975;**59**(10):837-840

[34] Shomari S, Kennedy R. Survival of *Oidium anacardii* on cashew (*Anacardium occidentale*) in southern Tanzania. Plant Pathology. 1999;**48**(4):505-513

[35] Wegulo SN, Baenziger PS, Nopsa JH, Bockus WW, Hallen-Adams H. Management of fusarium head blight of wheat and barley. Crop Protection. 2015;**73**:100-107

[36] Fernando WG, Miller J, Seaman W, Seifert K, Paulitz T. Daily and seasonal dynamics of airborne spores of *Fusarium graminearum* and other *Fusarium* species sampled over wheat plots. Canadian Journal of Botany. 2000;**78**(4):497-505

[37] Rossi V, Scandolara A, Battilani P. Effect of environmental conditions on spore production by *Fusarium verticillioides*, the causal agent of maize ear rot. European Journal of Plant Pathology. 2009;**123**(2):159-169

[38] Pusey P. The role of water in epiphytic colonization and infection of pomaceous flowers by *Erwinia amylovora*. Phytopathology. 2000;**90**(12):1352-1357

[39] Pernezny KL, Roberts PD, Murphy JF, Goldberg NP. Compendium of Pepper Diseases. St. Paul, MN, USA: The American Phytopathlogical Society; 2003. p. 64

[40] Irwin ME, Kampmeier GE, Weisser WW. Aphid movement: Process and consequences. In: Emden HF, Harrington R, editors. Aphids as Crops Pests. Wallingford,UK: CAB International; 2007. p. 714

[41] Bragard C, Caciagli P, Lemaire O, Lopez-Moya J, Macfarlane S, Peters D, et al. Status and prospects of plant virus control through interference with vector transmission. Annual Review of Phytopathology. 2013;**51**:177-201

[42] Katis NI, Tsitsipis JA, Stevens M, Powell G. Transmission of plant viruses. In: Emden HF, Harrington R, editors. Aphids as Crops Pests. Wallingford,UK: CAB International; 2007. p. 714

[43] Van Munster M, Yvon M, Vile D, Dader B, Fereres A, Blanc S. Water deficit enhances the transmission of plant viruses by insect vectors. PLoS One. 2017;**12**(5):e0174398

[44] Xu P, Chen F, Mannas JP, Feldman T, Sumner LW, Roossinck MJ. Virus infection improves drought tolerance. New Phytologist. 2008;**180**(4):911-921

[45] Davis TS, Bosque-Pérez NA, Foote NE, Magney T, Eigenbrode SD. Environmentally dependent host–pathogen and vector–pathogen interactions in the barley yellow dwarf virus pathosystem. Journal of Applied Ecology. 2015;**52**(5):1392-1401

[46] Gencsoylu I, Sezgin F. Sprinkler irrigation as a management practice for *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton fields. The Great Lakes Entomologist. 2003;**36**(3 and 4):2

[47] Castle S, Henneberry T, Toscano N. Suppression of *Bemisia tabaci* (Homoptera: Aleyrodidae) infestations in cantaloupe and cotton with sprinkler irrigation. Crop Protection. 1996;**15**(7):657-663

[48] Parihar SBS, Name S. Influence of irrigation methods on the aphid, Myzus persicae (Sulzer). Insect Environment. 1999;**5**(1):25-26

[49] Hillocks RJ, Waller JM. Soilborne diseases and their importance in tropical agriculture. In: Soilborne Diseases of Tropical Crops. Wallingford, UK: CAB International; 1997. pp. 3-16

[50] Correia KC, Michereff SJ. Fundamentos e desafios do manejo de doenças radiculares causadas por fungos. In: Lopes UP, Michereff SJ, editors. Desafios do manejo de doenças radiculares causadas por fungos. Recife, Brazil: Universidade Federal Rural de Pernambuco; 2018. pp. 1-16

[51] Ristaino J, Hord M, Gumpertz M. Population densities of *Phytophthora capsici* in field soils in relation to drip irrigation, rainfall, and disease incidence. Plant Disease. 1992; **76**:1017-1024

[52] Thomson S, Allen R. Mechanisms of survival of zoospores of *Phytophthora parasitica* in irrigation water. Phytopathology. 1976;**66**(10):1198-1202

[53] Café-Filho A, Duniway J, Davis R. Effects of the frequency of furrow irrigation on root and fruit rots of squash caused by *Phytophthora capsici*. Plant Disease. 1995;**79**(1):44-48

[54] Duniway J. Dispersal of *Phytophthora capsici* and *P. parasitica* in furrow-irrigated rows of bell pepper, tomato and squash. Plant Pathology. 1995;**44**(6):1025-1032

[55] Café-Filho A, Duniway J. Effects of furrow irrigation schedules and host genotype on Phytophthora root rot of pepper. Plant Disease (USA). 1995;**79**(1):39-43

[56] Bowers J, Papavizas G, Johnston S. Effect of soil temperature and soil-water matric potential on the survival of *Phytophthora capsici* in natural soil. Plant Disease. 1990;**74**(10): 771-777

[57] Ansani CV, Matsuoka K. Survival of *Phytophthora capsici* Leonian in soil. Fitopatologia Brasileira. 1983;**8**:269-276

[58] Kuan T, Erwin D. Predisposition effect of water saturation of soil on Phytophthora root rot of alfalfa. Phytopathology. 1980;**70**(10):981-986

[59] Sanogo S. Predispositional effect of soil water saturation on infection of Chile pepper by *Phytophthora capsici*. Hortscience. 2006;**41**(1):172-175

[60] Hord M, Ristaino J. Effect of the matric component of soil water potential on infection of pepper seedlings in soil infested with oospores of *Phytophthora capsici*. Phytopathology. 1992;**82**(7):792-798

[61] Wheeler WD, Williams-Woodward J, Thomas PA, Van Iersel M, Chappell MR. Impact of substrate volumetric water on *Pythium aphanidermatum* infection in *Petunia* × *hybrida*: A case study on the use of automated irrigation in phytopathology studies. Plant Health Progress. 2017;**18**(2):120-125

[62] Gencoglan C, Akinci IE, Akinci S, Gencoglan S, Ucan K. Effect of different irrigation methods on yield of red hot pepper and plant mortality caused by *Phytophthora capsici* Leon. Journal of Environmental Biology. 2005;**26**(4):741-746

[63] Rista L, Sillon M, Fornasero L. Effect of different irrigation strategies on the mortality of pepper by *Phytophthora capsici* Leonian in greenhouses. Horticultura Argentina. 1995;**14**(37):44-51

[64] Sanogo S, Carpenter J. Incidence of *Phytophthora* blight and *Verticillium* wilt within Chile pepper fields in New Mexico. Plant Disease. 2006;**90**(3):291-296

[65] Tu J, Tan C. Effect of soil compaction on growth, yield and root rots of white beans in clay loam and sandy loam soil. Soil Biology and Biochemistry. 1991;**23**(3):233-238

[66] Lilja A, Heiskanen J, Heinonen R. Effects of irrigation on uninucleate *Rhizoctonia* on nursery seedlings of *Pinus syivestris* and *Picea abies* grown in peat growth medium. Scandinavian Journal of Forest Research. 1998;**13**(1-4):184-188

[67] Naseri B, Shobeiri SS, Tabande L. The intensity of a bean *Fusarium* root rot epidemic is dependent on planting strategies. Journal of Phytopathology. 2016;**164**(3):147-154

[68] Bell A, Liu L, Reidy B, Davis R, Subbarao K. Mechanisms of subsurface drip irrigation-mediated suppression of lettuce drop caused by *Sclerotinia minor*. Phytopathology. 1998;**88**(3):252-259

[69] García-Cabello S, Pérez-Rodríguez M, Blanco-López M, López-Escudero F. Distribution of *Verticillium dahliae* through watering systems in widely irrigated olive growing areas in Andalucia (southern Spain). European Journal of Plant Pathology. 2012;**133**(4):877-885

[70] Rodriguez-Jurado D, Bejarano-Alcazar J. Dispersión de Verticillium dahliae en el agua utilizada para riego de olivares en Andalucía. Boletín de Sanidad Vegetal Plagas. 2007;**33**: 547-562

[71] Kelman A. The bacterial wilt caused by pseudomonas solanacearum–A literature review and bibliography. North Carolina Agricultural Experiment Station Technical Bulletin. 1953;**99**:194

[72] Wharton PS, Driscoll J, Douches D, Hammerschmidt R, Kirk W. Common scab of potato. Michigan State University Extension Bull. 2007. e2990

[73] Lamichhane J, Bartoli C. Plant pathogenic bacteria in open irrigation systems: What risk for crop health? Plant Pathology. 2015;**64**(4):757-766

[74] Almeida EJ, Santos JM, Martins AB. Flutuação populacional de *Meloidogyne enterolobii* em pomar de goiabeira (*Psidium guajava*). Nematologia Brasileira. 2010:164-168

[75] Hong C, Moorman G. Plant pathogens in irrigation water: Challenges and opportunities. Critical Reviews in Plant Sciences. 2005;**24**(3):189-208

[76] Prot J-C, Van Gundy S. Effect of soil texture and the clay component on migration of *Meloidogyne* incognita second-stage juveniles. Journal of Nematology. 1981;**13**(2):213

[77] Fujimoto T, Hasegawa S, Otobe K, Mizukubo T. The effect of soil water flow and soil properties on the motility of second-stage juveniles of the root-knot nematode (*Meloidogyne incognita*). Soil Biology and Biochemistry. 2010;**42**(7):1065-1072

[78] Alfaro A, Goheen A. Transmission of strains of grapevine fanleaf virus by *Xiphinema index*. Plant Disease Reporter. 1974;**58**(6):549-552

[79] Brown D, Robertson W, Trudgill D. Transmission of viruses by plant nematodes. Annual Review of Phytopathology. 1995;**33**(1):223-249

[80] Demangeat G, Voisin R, Minot J-C, Bosselut N, Fuchs M, Esmenjaud D. Survival of *Xiphinema index* in vineyard soil and retention of grapevine fanleaf virus over extended time in the absence of host plants. Phytopathology. 2005;**95**(10):1151-1156

[81] Hugo H, Malan AM. Occurrence and control of plant-parasitic nematodes in irrigation water–A review. South African Journal of Enology and Viticulture. 2016;**31**(2):169-180

[82] Mcsorley R. Adaptations of nematodes to environmental extremes. Florida Entomologist. 2003;**86**(2):138-142

Chapter 9

Paddy Fields as Artificial and Temporal Wetland

Tsugihiro Watanabe

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80581

Abstract

Paddy cultivation plays a significant and vital role on rice production. Most of the global population depends on the 480 million tons of rice produced each year as the basis for their lives. While about 90% of the world's 160 million hectares of paddy fields are in Asian countries, mainly in monsoon regions, paddies are also seen in North America and Africa, even in dry regions. Most of the paddy fields are flooded naturally or artificially during rice production period. In the case that paddy fields are kept submerged artificially, hydraulic structures are required. Irrigated paddy fields produce traditionally much rice, taking befits of stable water supply and continuous ponding. Paddy fields are simultaneously performing other functions for local environment, including climate mitigation, flood control, groundwater recharge, biodiversity, and ecosystem development. On the other hand, since paddy fields require much water and modify the original and natural hydrological regime, they might cause adverse effect on local environment. Much water supply by irrigation sometimes requires drainage system, which also might alter local water balance. In this chapter, implication of paddy fields as artificial and temporal wetland is reviewed comprehensively with various aspects, focusing mainly on their role for local hydrological environment.

Keywords: paddy field, flooding, multi-function of flooding, irrigation and drainage, hydrological environment

1. Introduction

Paddy cultivation plays a significant and vital role on rice production. Most of the global population depends on the 480 million tons of rice produced each year as the basis for their lives. While about 90% of the world's 160 million hectares of paddy fields are in Asian countries, mainly in monsoon regions, paddies are also seen in North America and Africa, even in dry regions where irrigation has reclaimed dry land for paddy fields.

Rice, as one of the main staple for human being, is cultivated in various regions of the world from the wettest areas in the world to the driest deserts, with various conditions of natural environment including climate, topography, and soil conditions. For example, rice is grown in the area with more than 5000 mm of rain for one growing season, and with less, almost zero, of rainfall. The growing season average temperature of rice producing areas varies from more than 30°C to less than 15°C. Rice cultivation is observed in a higher mountain region with more than 2500 m above the sea level, as well as in ocean coast even in sea level region [1].

Most of the fields, where rice is produced, are flooded, or submerged by water, naturally or artificially during rice production period. To keep paddy fields submerged artificially, some infrastructures like reservoirs or ponds, intake and diversion works and canals are constructed. The infrastructures, after construction, are operated and maintained generally by local society, usually with some supports of the government. Rice is produced mostly in the fields with artificial water management with irrigation and drainage system, than in naturally flooded fields.

The stable water supply and continuous ponding in the fields are the base for much rice production. On the other hand, as mentioned above, they need hydraulic structures and the appropriate operation and management of the structures. The artificial ponding with stable and much water supply mostly results in better rice growth, while it might change the local environment both positively and negatively. In the case that the impacts of ponding and irrigation on the environment are positive, they are to be recognized as their "multi-functions." Recently, much water use for rice cultivation and necessity of water saving in paddy irrigation have been discussed often, and simultaneously the role of flooding in paddy fields has been highlighted in terms of environmental conservation (for example, see [2–4]).

On the other hand, since rice production area has been reducing in some developed countries and regions with long history of rice cultivation, like Japan, Taiwan, and Korea, the role of rice fields and their flooding is to be reevaluated. In this chapter, the irrigated fields for rice are recognized as artificial and temporal wetland and reviewed comprehensively, focusing mainly on their role for local hydrological environment.

2. Definition and outline of paddy field in the world

2.1. "Paddy field" as a farmland with rice and flooded water

The words of "paddy field" are usually and widely used for the farmland, where rice is cultivated, and they generally imply the area flooded, like the definitions of Cambridge Dictionary as "a field planted with rice growing in water" [5], Collins English Dictionary as "a flooded piece of land used for growing rice" [6], and The Free Dictionary as "a field, often flooded with water, in which rice is grown" [7]. The definition of "paddy field," however, is intricate slightly. Fundamentally "paddy" means "rice" especially in the husk. Consequently, a "paddy field" means a field planted with rice. Some dictionaries describe that only "paddy" could mean "paddy field," without any word for indicates the space, like the definition of the

Oxford Living Dictionary as "A field where rice is grown" [8], and of Merriam-Webster as "wet land in which rice is grown" [9], while it also show the meaning as "Rice before threshing or in the husk."

Since rice is usually grown in level basin flooded with water throughout most of the growing season, "paddy field" generally means "a field flooded with water for growing rice," and the definitions of "paddy field" in most of the current dictionaries include words of "rice" and "water" or "flood," as introduced above.

In Japan, the English words "paddy field" is translated to the Japanese word "*suiden*," while there this word "*suiden*" is used for flooded farm land, which distinguishes "flooded field" from "upland field" or "*hatake*" in Japanese. The upland field is not flooded and cultivated for normal crops like vegetables and flowers. Accordingly, in Japan, it is expressed that some aquatic crops like lotus and tatami are cultivated in "paddy fields." This Japanese case is recognized as an exceptional case. In this chapter, "paddy field" is to be used basically as "a field planted with rice."

As mentioned below, actually, in considerable area in the world, rice is produced in fields without flooding. Then, some parts of paddy fields of the world are not identified as the "wetland" with water submergence.

2.2. Outline of paddy field in the world

Generally, rice is a major food crop for the people in the world. Especially in the Asia region, rice is a staple food for about 2.4 billion people, and there the 90% of the world's rice is produced and consumed [10].

As summarized above, rice production and paddy fields are developed in a wide range of environments even in the arid region of the world and during the dry season. The paddy fields in dry areas sometime show very high and stable yields with much solar radiation.

The paddy fields or the environments of the rice production are classified usually based on the hydrological characteristics, since they are most essential condition to the production scheme. The most popular classification includes: (1) irrigated lowland, (2) rain-fed lowland, (3) flood prone, and (4) upland [1].

The first category "irrigated" paddy fields distributed in lowland are the area, where rice is grown in fields surrounded by ridges. Its water condition is managed by farmers, generally maintaining water depth as 5–10 cm. It covers about 90 million ha, as almost half of the world paddy area. The major portion of this irrigated area is in the Asian region.

The second category "rain-fed lowland" or "lowland rain-fed" is a field, where rice is also grown in fields with bunds, while they are flooded with rainwater for some period of a growing season. It covers about 50 million ha. There, water is flooded naturally by rain water, not fully controlled by the man-made irrigation system. These two types of paddy fields are usually predominantly puddled, and after it, rice seedlings are transplanted. These two types of paddy fields produce 75 and 19% of the world's rice production, as almost 95% of rice is produced in the area, of which water condition is fully or partly controlled by humans like farmers.

In the third category "flood-prone field," deep-water rice and floating rice are grown in the uncontrolled flood environments, suffering periodically from excess water and deep flooding, sometime with deeper flood of 100 cm for some certain part of the growing season. This covers about 15 million ha.

The last, forth category "upland," is a field where rice is grown under dryer conditions, without ponded water, and then it is not surrounded by ridges to keep water and not equipped with irrigation system. The area of "flood-prone" and "upland" is about 11 and 15 million ha, respectively [1].

2.3. Paddy fields in the dry region

Paddy fields are found even in dry region, where rainfall effective to rice growth is not expected. They fundamentally cannot be cultivated without irrigation, where consequently rice is grown in fields with surrounding ridges to keep water. They are generally to maintain 5–10 cm of water, and usually puddled and rice are transplanted. The paddy fields reclaimed in the arid zones are recognized as the typical artificially created wetland.

Paddy fields in the dry region are irrigated and require much water to maintain flooding, since ponding water evaporates much into the atmosphere and seeps much into the soil profile that is generally much sandier compared with the paddy field in the wet regions. Basically in the dry region or dry condition, water availability is limited, and consequently the development of paddy production or paddy fields that requires much water is not preferred. Even with this constraint, actually there are many paddy fields in those conditions. There must be some reasons for the expansion of them with definite advantages.

First, the people in the dry region like the taste of rice. Second, rice contains much nutrients compared with wheat and maize as main cereal crop. Calorie per grain weight of rice is larger than wheat and maize. Protein of rice is less than them, while its quality of rice is better than others for human health. Maize contains much lipid, while its contents of rice and wheat are almost the same.

In addition to the advantage of rice in terms of the nutrients of the grain, land productivities of these crops are quite different. The weight of grains harvested per area of rice is almost 1.5 times of wheat. Furthermore, rice can be cultivated every year continuously in the same field, and the land used as paddy field can produce stable harvest.

Rice has another advantage of grain including its easiness for cooking and longer preservation. Although paddy cultivation, however, needs much labor in terms of time and efforts to maintain the field and its surrounding ridges and to perform water management, its advantages promote expansion of paddy fields even in dry region or condition.

These challenges have created the artificial wetlands in dry region.

3. Significance of water ponding in paddy fields

3.1. Water management in paddy plot

Rice cultivation has some superiority on food production mentioned above. On the other hand, paddy fields, where rice is grown, need much water due to its flooding. The main reasons why paddy fields are flooded is that most rice varieties realize better growth and produce higher yields in flooded farmland than in dry field.

In most cases, the water layer of some centimeters in a field is established usually after transplanting of rice seedlings and maintained until few weeks before harvesting. The typical water management of paddy field with standard depth of flooding for each growing stage is shown by FAO [10], and it is summarized in **Table 1** with supplemental explanation of GriSP [1].

Actual water management practices on water application and flood depth control are affected by field conditions including:

1. cultivar of rice,
2. climate and weather,
3. soil profile (water holding capacity, permeability, fertility, etc.),
4. fertilizer and chemicals (pesticide and herbicide),
5. irrigation water availability (timing and quantity),
6. drainage capacity (water conductivity of soil profile, groundwater table, etc.),
7. farm machinery,
8. labor inputs, and
9. other farming techniques.

In the improved paddy field with stable water supply and enough drainage capacity, independent water management practices of farmers are implemented, where the farmers can apply and drain water whenever they want and they introduce advanced techniques and materials.

Cultivation Stage	Growth Phase	Typical Duration	Standard Flood Depth	Remarks
		days	mm	
Field Preparation		7 - 10	none	before transplanting, 200 mm application for saturating soil profile
Early Season	Vegetative	60(55-85)	100	first roughly one-third of the vegetation stage
			20 - 50	second roughly two-thirds of the vegetation stage
Mid Season	Reproductive	30 (15-45)	100	Stages of heading and flowering
Late Season	Ripning	30(15-45)		first roughly one-fourth of the maturing stage
			none	second roughly one-fourths of the maturing stage

Table 1. Typical water management of paddy field with standard depth of flooding.

Under these conditions, the field water condition including flooding period and depth is controlled considerably. For some periods, they drain water intentionally resulting in no submergence for some periods, which is to be called intermittent irrigation or flooding [11]. If this water management is practiced, water movement in the area would be accelerated, and it affects local hydrological regime.

3.2. Advantages and disadvantages of water ponding in paddy fields

The fact that rice is cultivated under water ponding condition in most cases implies the water ponding has the advantages even if it requires much water. Main advantages of the water ponding are listed as follows:

1. stable water supply to rice,
2. suppression of weeds,
3. control of harmful insects,
4. control of temperature of rice and field (warm up and cool down),
5. supply of nutrients and control of fertilizer effects,
6. supply of necessary minerals,
7. avoidance of adverse effects of continuous cultivation,
8. leach out of accumulated salts, and
9. enhanced productivity of soil cultivation or plowing.

Most of these advantages come from stable water ponding on the field and could be potentially replaced with other materials or methods than water except stable “water” supply listed as No. 1 above.

On the other side, the water ponding induces some adverse effects on rice production and local environment. They include:

1. soil reduction due to longer submergence resulting in shortage of oxygen and emission of undesirable gases like hydrogen sulfide and methane,
2. requirement of much works to maintain ponding in the fields,
3. much water requirement for maintaining ponding resulting in water resource development,
4. difficulty on introduction of heavier machineries due to increased soil water contents,
5. growth of undesirable insects like malarial mosquito, and
6. influence on local climate due to much evapotranspiration and modified ground surface temperature.

Consequently, taking both merits and drawbacks of water ponding into account integrally in addition to field irrigation and drainage conditions, actual water management in the fields for each growing stage is performed.

http://dx.doi.org/10.5772/intechopen.80581

4. Water management and water requirement of paddy fields

4.1. Water requirements for paddy irrigation

Water ponding in the fields requires much water. Water requirements of paddy fields compose mainly of transpiration of rice plant, evaporation from ponding water or soil surface, and percolation into soil profile. In some cases, requirement to reestablish water layer after intentional drainage and to implement flow-through irrigation for saving management labor or for control of temperature might be included.

For planning and designing the irrigation facilities and the water use plan, water requirement is basically estimated base on evapotranspiration of rice field. The actual water lost in the field through other paths, including seepage into the deeper soil profile under the root zone part and run off or spill out into the drain through the field outlet, is often recognized as the "loss," rather than "requirement."

Table 2 shows the total water requirements for one irrigation season reported by JSIDRE [12]. The total requirements range from 500 mm in Senegal to 3900 mm in Kazakhstan or 4500 mm in East Africa. This wide range is caused fundamentally by the significant difference in the seepage rates, which are estimated as none at minimum and more than 30 mm/day at maximum. The effects of water management on water requirements are to be regarded. Water requirement of paddy field in dry area is sometimes much and sometimes less than paddy field in the humid region. For example, as mentioned above, water requirement of paddy field in Egypt or Kazakhstan is relatively much, where consumption for evapotranspiration is large with drier climate, while limited water availability constrains increased water use.

Country or Region	Water Requirement mm/season	Remarks
Senegal	500 - 1,000	percolation: almost nil
Northwest China	900 - 1,500	direct sowing; 1,200 to 1,500 mm, transplanting; 900 to 1,050 mm
Brazil	1,000	equivalent to 8.6 mm/d
Texas, USA	1,200	intake: 759 mm, rainfall: 432 mm
Italy	1,600	
Australia	1,500 - 1,700	evapotranspiration: 1,200 mm
India	1,680	percolation: 1,200 mm
Cote d'Ivoire	1,920	percolation: 5 mm/d
Egypt	1,800 -2,200	
Japan	1,500 - 2,500	wide range of percolation: nil to 50 mm/d
Malaysia	2,810	evapotranspiration: 1,570 mm
Kazakhstan	3,930	
East Africa	4,500	intake: 3,600 mm, rainfall: 900 mm

(Note: Listed in order of the total amounts, source: JSIDRE in [12])

Table 2. Water requirement of paddy field per irrigation season [11].

5. Implication of paddy fields in local hydrological regime

5.1. Impacts of paddy cultivation and fields on local environment

Water ponding for rice production needs much water and also irrigation and drainage system to supply and withdraw much water to and from the fields. While the system, of course, should function well for local rice production, it could also perform for improvement of local environment. It is called as "multi-function" of paddy cultivation or paddy irrigation. The functions are fundamentally based on (1) widespread establishment of stable and shallow water body for some specific period, (2) stable water supply, and (3) adjustment of local hydrological regime.

The outcomes of the multifunction include the followings [3]:

1. reduction of flood damage in a region or basin with water storage in the fields and acceptance of flood water,
2. control of soil erosion with bunds of flat fields,
3. stable groundwater recharge with continuous percolation from water layer on the fields,
4. mitigation of local climatic variability especially drastic temperature changes based on higher specific heat of water ponded in the field,
5. establishment of conditions for fish cultivation, and
6. establishment of habitats for wildlife including aquatic flora and fauna.

These are the outcomes of paddy fields as the artificial wetlands, which are the land with surrounding ridges and the infrastructures for irrigation and drainage, as well as their management institutions and organizations in local society.

While there are many exact cases of the multifunction in the world rice cultivation areas, as the typical case with the function No. 3, the paddy fields in the Kumamoto Region, Kyushu of Japan, are to be introduced. The Kumamoto is famous as a "Groundwater City," where almost 1 million local residents depend their daily lives on the groundwater, which also enables irrigation and industry in the region. It is the fact that the groundwater is a treasured resource to support regional activities, and the stable groundwater is recharged by the percolation from the paddy fields located in the upper basin (see **Figure 1**). Now, 11 municipalities in the region share this groundwater.

In 2012, to conserve the hydrological system, the local residents, private sector representatives, and the local municipal governments established the organization "Kumamoto Groundwater Foundation." There, the function of paddy fields for stable groundwater recharge is widely recognized, and then the conservation of paddy cultivation is one of the main challenges for sustainable groundwater management. For these challenges and outcomes, the Kumamoto City received the "Water for Life Award" from the United Nations in 2013.

Paddy fields are providing wild lives with their habitats, as shown as the function No. 6 above. As one of the examples, the paddy fields in the Kohoku region of Japan, the northern shore of

http://dx.doi.org/10.5772/intechopen.80581

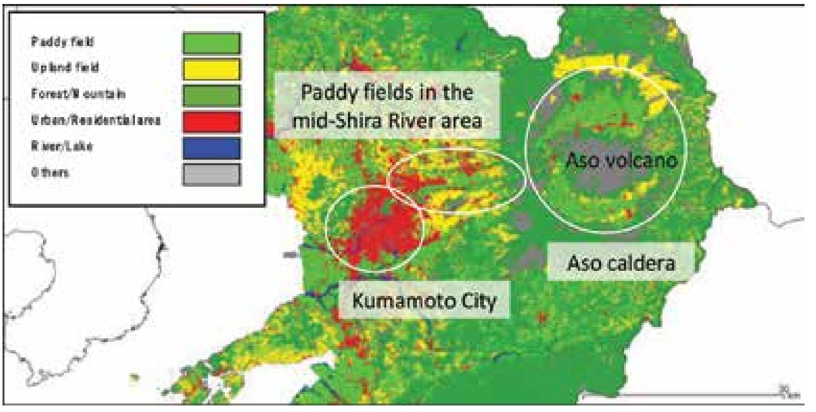

Figure 1. Paddy fields in the Kumamoto region of Japan recognized as water resource for the regional groundwater (source: Hama et al. [13]).

Photo 1. Buick swans flying onto paddy fields in the Kohoku region of Japan.

the Lake Biwa that is one of the Ramsar sites of Japan, are working as the areas for feeding the migratory birds Buick Swan. According to the detailed field observation, birds fly only to the paddy plots with water ponding, after harvesting (see **Photo 1**) [14].

5.2. Impacts of paddy fields in the dry region: the cases of Egypt and Kazakhstan

In the dry region of the world, paddy fields have been developed extensively. There, paddy cultivation and irrigation might create local "water rich condition" in regional dry environment. This impact of the artificial modification on local hydrological regime could be much larger and critical to the sustainability of cultivation and irrigation development. This is to be the typical case of the artificial and temporal wetland and suitable opportunity to reevaluate the implication of paddy fields.

Here, brief overviews of the cases of Egypt and Kazakhstan are introduced including the summary by GRiSP in the following [1].

Egypt is one of the typical countries that produce rice in dry area. It has a fast growing population with 82.5 million in 2011 leading to increased food demand. Almost all of water demand in Egypt is supplied by the Nile River, of which water is used extensively to irrigate crops including rice. Rice is one of the staple crops in Egypt and consumed 38.6 kg milled rice per person per year in 2009. Rice is grown in the summer on about 600,000 ha, mainly in the northern Nile Delta. The yield is quite high, about 9 t/ha in 2000, due to abundant solar energy and fertile alluvial soils.

The area for rice is officially regulated by the government due to limited water resources, while farmers prefer cultivating rice for its higher profit. The areas for rice producing located in the northern Nile Delta have potential risk of soil salinization. Paddy cultivation has been functioning to leach out accumulated salts in the soil profile. Salt leaching in arable soils can be supported by prevailing sub-surface drainage systems (e.g., [15, 16]).

In Kazakhstan, of which most of the land is classified as steppe or desert with annual average precipitation of 100–200 mm, wheat is a predominant crop in the northern part, whereas rice, cotton, fodder, and fruit are produced in the southern part in summer season. Its cropped area had increased due to rapid land reclamation mainly in the Syr Darya Basin since the 1950s to the 1980s, and the irrigated land became one of the big food supplying sources of the Soviet Union and Eastern Europe in that period. While rice occupies only 5–6% of the irrigated area, its water requirement is about 15% of the total irrigation requirement in that period. Most of the rice cropping area in Kazakhstan is distributed mainly in the Kzyl-Orda area of the Lower Syr Darya River Basin and some in the Ili River basin. The present total rice area is about 113,000 ha, which is equivalent to 17% of the total irrigated area. In the irrigated area in Kazakhstan, the crop rotation system is dominantly practiced with several rotation patterns, and rice is grown usually in this crop rotation system.

In Kazakhstan, large-scale irrigated agriculture has been developed since the 1960s with crop rotation including rice. In the irrigation scheme, water is applied only to paddy fields, which consists about 30% of the total scheme, and paddy fields are continuously ponded. Basically upland crop is not irrigated directly, while water required in upland fields is supplied through much percolation from paddy fields. The efficiency of conveyance and distribution is quite low due to not lined canals running through sandy soil.

Water requirement of paddy fields is around 3000 mm. Seepage from irrigation canals and deep percolation from paddy fields raise local groundwater table, and it functions as water source for upland fields surrounding the paddy fields. According to the study of the Tottori University Group, this water distribution system induces soil salinization (see [17]). In upland fields, salts accumulate during crop production with upwards water movement, while most of them are leached out when that field is cultivated with rice and flooded continuously for the rice growing season.

The large amount of water requirement for the large irrigation schemes, including much loss from the systems, needs much water diversion from the Syr Darya River, which is the main water resource in this dry region. This large quantity of diversion is recognized as the main reason for serious desiccation of the Aral Sea.

6. Significance of paddy fields in the environment

6.1. Paddy fields in local hydrological regime

Considering the limited availability of water resources, generally, it is reasonable to recognize that paddy cultivation in dry region is not realistic or acceptable in terms of sustainability of economics and environment in many cases. Actually, most of the paddy fields are developed in the humid region with much rainfall and much available water resources. It brings that paddy fields are suitable to humid condition. This is not wrong, while it simultaneously brings another question on significance of "suitability."

The Japanese paddy fields have been reclaimed and developed historically and recently improved much with large investments for advanced irrigation and drainage system (see [18]). With advanced farming techniques including the introduction of modern cultivars, nutrients, chemicals, machineries, and so on, they are proud of higher yield and productivity of rice production as well as the qualities. It needs, however, much lasting investments and labors to maintain the systems. They are always facing risks of flood and drought damages, and the cool and hot weather damages during rice growing season. There, the paddy fields and the system are maintained by everlasting human activities as hard as possible, which have developed the infrastructures, institutions, and interconnectedness in the society. This situation has been developed under the condition of climate and small-scale topography and river system, which are relatively controllable comparing with the continental conditions. Thinking over these history and present system, we can ask "Are the paddy fields in Japan suitable to its natural condition?" Some paddy fields in other regions can produce considerable yield without any hard investment, while its yield is not so high. This could be recognized as "naturally" suitable.

The point to be recognized here is just that the "suitability" of the paddy fields to the natural, and climate condition is not to be evaluated absolutely. It needs comprehensive conclusion, especially assessment in terms of sound hydrological cycle of the region or basin. Paddy cultivation and fields are to be arranged appropriately in the hydrological regime of the region. Then, consequently, we might find "suitable" and "sustainable" development of paddy fields in each region including dry area, which are to be located in right place in the local hydrological system.

6.2. Impacts of reduced paddy fields on local environment

In the past few decades, in some developed countries and regions with long history of rice production, like Japan, Taiwan, and Korea, the area of paddy fields has been reducing, due to the changes of dieting system according to economic development and globalization, as shown in **Figures 2** and **3**. This reduction of paddy area might result in losing their multifunction with reduced rice production.

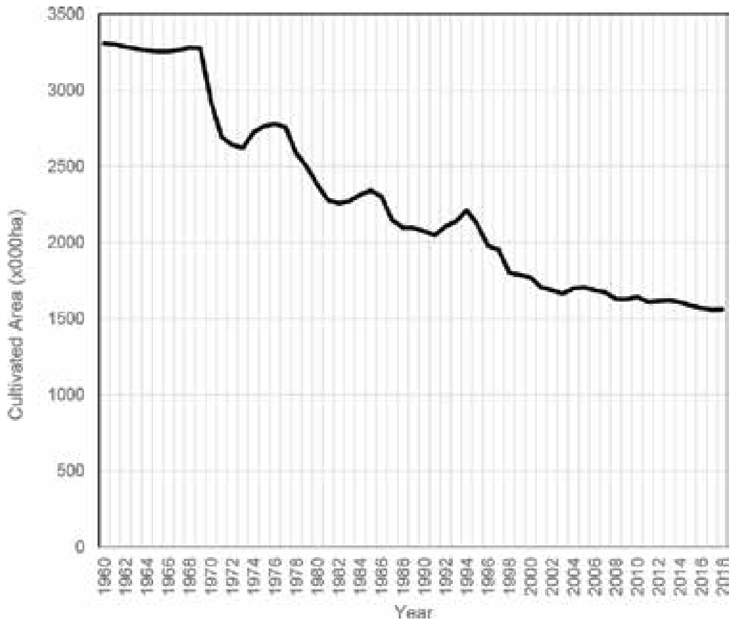

Figure 2. Changes of paddy cultivation area in Japan (source: [9, 19]).

The Japanese case of the reduction of paddy field area and its consequences are quickly reviewed. Japan had tried to establish complete self-sufficiency of rice historically, especially after the World War II. And then, it is finally realized in the 1960s, after long development investigation for improvement of paddy cultivation and fields including farming techniques and infrastructures of it.

Just after the reach to complete self-sufficiency, it had faced to the problem of over production of rice, which was caused by higher yield of rice, reduction of rice consumption with increased consumption of other food, including bread, meat as well as vegetables. The government asked farmers to convert their farm fields from rice to other crops with some portion of their farming plots, providing some subsidies. The rapid industrialization and urbanization also require paddy fields in the plain to be transferred to urban use. Consequently, the area of rice cultivation area has been decreasing as from about 3.3 million ha in 1960 to 1.56 million ha in 2017. It is a drastic reduction (**Figure 2**). During the same period, the rice consumption per capita per year of Japan has drastically reduced from about 127 to about 68 kg (**Figure 3**) [19].

With these changes, it could be easily recognized that the water ponding area, that is temporal water body or wetland, has reduced to the half of the peak, and the hydrological environment has been affected. It also means the degradation of multifunction of paddy fields. The wildlife is losing their habitats, and the biodiversity and the ecosystem developed historically have been modified.

In Japan, another problem is a reduction of farmers and their successors, which is another constraint to conserve paddy areas. The reduction of paddy fields means not only reduction of

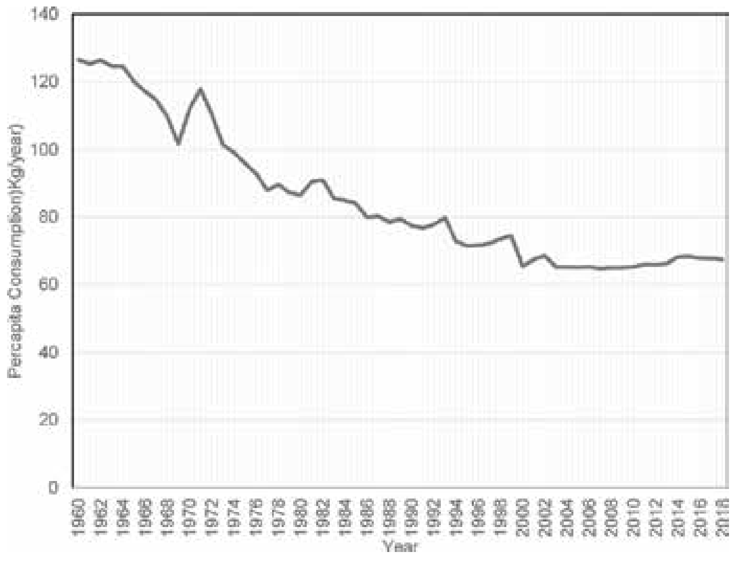

Figure 3. Changes of rice consumption in Japan (source: [9, 19]).

rice production but also induces the changes of paddy irrigation system in the basin. The significance of paddy fields is to be reevaluated and reappreciated in terms of conserving the natural environment and sustaining the rural society and culture. The Japanese governments are challenging to revitalize agriculture and communities in rural areas, with some policy for conserving ecology and environment in rural area. The similar situation of reduced rice consumption and paddy fields are seen in Korea and Taiwan.

7. Summary: concluding remarks

In this chapter, implication of paddy cultivation and paddy fields is reviewed, focusing on flooding in the fields including its reasons and consequences.

It is clear that paddy fields, paddy cultivation, and paddy irrigation need much water, land reclamation and preparation, and system to distribute water. Therefore, they have developed infrastructure, institution as well as interconnectedness of the farmers and other stakeholders.

Significance of paddy fields as the artificial, temporal/seasonal wetland is to be assessed in comprehensive manner with aspects of agriculture, eco-environment, and hydrology. Since they use much water and might alter the local water balance and ecoenvironmental system with adverse effects, they are to be arranged appropriately in the hydrological and environmental regime of the region. Local communities established with paddy fields are to be organized continuously as the base for the society and culture and the potential to manage the future changes of environments.

In addition, it is urgent to reevaluate the role and implication of paddy cultivation and fields in the local system under the changing climate.

Acknowledgements

Discussion in chapter about implication of paddy cultivation and field has been elaborated with communication in the society on paddy field including the International Society of Paddy and Water Environment Engineering (PAWEES). This study is partially supported by the Sosei and Togo Programs of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), and the KAKENHI Grant Number JP16H02763 of Japan Society for Promotion of Science (JSPS).

Author details

Tsugihiro Watanabe

Address all correspondence to: watanabe.tsugihiro.4v@kyoto-u.ac.jp

Graduate School of Global Environmental Studies, Kyoto University, Kyoto, Japan

References

[1] GRiSP (Global Rice Science Partnership). Rice Almanac. 4th ed. Los Baños (Philippines): International Rice Research Institute (IRRI); 2013

[2] Groenfeldt D. Multifunctionality of agricultural water: Looking beyond food production and ecosystem services. Irrigation and Drainage. 2006;**55**:73-83

[3] Matsuno Y, Nakamura K, Masumoto T, Matsui H, Kato K, Sato Y. Prospects for multifunctionality of paddy rice cultivation in Japan and other countries in monsoon Asia. Paddy and Water Environment Engineering. 2006;**4**:189-197

[4] Mekong River Commission. Multi-Functionality of Paddy Fields Over the Lower Mekong Basin. MRC Technical Paper No. 26; 2010

[5] Cambridge Dictionary Cambridge Advanced Learner's Dictionary & Thesaurus. Available from: https://dictionary.cambridge.org/dictionary/english/paddy-field [Accessed: 01-06-2018]

[6] Collins English Dictionary. Available from: https://www.collinsdictionary.com/dictionary/english/paddy-field [Accessed: 01-06-2018]

[7] The Free Dictionary. Available from: https://www.thefreedictionary.com/paddy-field [Accessed: 01-06-2018]

[8] Oxford Living Dictionaries. Available from: https://en.oxforddictionaries.com/definition/paddy [Accessed: 01-06-2018]

[9] Merriam-Webster. Available from: https://www.merriam-webster.com/dictionary/paddy [Accessed: 01-06-2018]

[10] FAO. Irrigation Water Management: Irrigation Scheduling, Training Manual No. 4; 1989

[11] Watanabe T. Irrigation water requirement. In: The Japanese Society of Irrigation, Drainage and Reclamation Engineering (JSIDRE), editor. Advanced Paddy Field Engineering. Tokyo: Shinzan-sha Sci. & Tech; 1995. pp. 31-50

[12] Tabuchi T, Hasegawa S, editors. Paddy Field of the World. Tokyo: The Japanese Society of Irrigation, Drainage and Reclamation Engineering (JSIDRE); 1995

[13] Hama T, Imafuji K, Kuwahata S, Kawagoshi Y, Ishida K. Role of paddy fields on ground water resource in Kumamoto. In: Proceedings of PAWEES 2017 International Conference; November 2017; Taichung

[14] Watanabe T. Management of paddy field condition for migratory birds linking together with lake environment conservation. In: Proceedings of Taal 2007—The 12th World lake Conference; Jaipur. 2007. pp. 882-888

[15] Abou El Hassan WH, Watanabe T, Freeg MR. Cross-scale hydro-dynamics and effects of paddy cultivation on water management and productivity. In: Proceedings of the International Dryland Development Conference (ICDD); August 2016; Alexandria

[16] Ondrasek G, Rengel Z, Petosic D, Filipovic V. Land & water management strategies for the improvement of crop production. In: Parvaiz A, Saiema R, editors. Emerging Technologies and Management of Crop Stress Tolerance Vol. 2—A Sustainable Approach. London: Elesvier; 2014. pp. 291-310

[17] Shimizu K, Takahashi N, Kitamura Y, Anzai T. Paddy rice irrigation and water requirements with upland crop rotation system in the lower Ili River Basin, Kazakhstan. In: Proceedings of the International Dryland Development Conference (ICDD); August 2016; Alexandria

[18] Hasegawa S, Tabuchi T. Well facilitated paddy fields in Japan. In: Hasegawa S, Tabuchi T, editors. Paddy Fields in the World. Tokyo: The Japanese Society of Irrigation, Drainage and Reclamation Engineering (JSIDRE); 1995. pp. 103-124

[19] Ito S. World Food Statistics and Graphics: Available from: http://worldfood.apionet.or.jp/graph/index-e.html [Accessed: 01-06-2018]

Chapter 10

Traditional Water Meadows: A Sustainable Management Type for the Future?

Constanze Buhk, Jens Schirmel,
Gerlach Rebekka and Oliver Frör

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79429

Abstract

Traditional meadow irrigation techniques were once widespread throughout Europe and served as a method of grassland intensification before the era of mineral fertilization. Close to Landau (Palatinate), Germany, there are several hectares of traditionally irrigated water meadows that are irrigated twice a year in parts since the medieval age or irrigation has been reinitiated since the 1990. In a research project "WasserWiesenWerte", we analyzed the ecological and socio-economic value of meadow irrigation. We compared extensively to semi-intensively used meadows with fertilizer application between 0 and 80 kg N/ha per year which were either irrigated or nonirrigated. The results were very motivating. Biomass production is increased by about one-third with irrigation. At the same time, several species groups did not decrease in frequency and diversity in the meadows under irrigation. In contrast, some especially rare species seemed to even profit. Ditch structures turned out to be especially important refuges for sensible meadow species and added a large quantity of additional species to the landscape diversity. We propose that the revitalization of traditional irrigation techniques should be considered when extensively managed grassland—especially hay meadows—are prone to either intensification or abandonment.

Keywords: biodiversity conservation, ditch structures, extensive grassland management, hay meadows, hay quality, land-use intensification, traditional meadow irrigation, recreational value, traditional water meadows

1. Introduction

Species rich grasslands are among the most threatened ecosystems in Europe [1–3]. They suffer either from abandonment or intensification—both processes lead to species loss [4, 5].

However, to sustain future ecosystem services, stability, and high quality living environments, biodiversity is a crucial good and has to be protected and promoted according to the Convention on Biological Diversity treaties setup by the UN [6]. To conserve large scale meadow landscapes in a modern world, innovative ideas are needed to combine nature conservation and economic aspects [7].

Since the medieval ages, but especially around 1900, a widespread technique throughout Europe to improve hay yields was traditional meadow irrigation [8]. Short-term flooding of the meadows via irrigation and drainage ditches twice to three times a year was done to use the fertilization effect of the stream water and to achieve an elongation of the vegetation period [9]. With World War II followed by the need for massive food production and the development of mineral fertilizers in 1950, most irrigation systems were abandoned, and meadows were transformed to crop land [10]. Today, only a few actively traditionally irrigated water meadows exist [9]. A landscape with active traditional meadow irrigation is the Queich River Plain East of the city of Landau in Palatinate, Germany. In the research project "WasserWiesenWerte", we studied the economic and ecological values of 18 water meadows in contrast to 18 nonirrigated meadows along the Queich river (Palatinate, Germany) as well as the socio-economic value of the landscape. We asked the following questions: is it possible to reduce the amount of fertilizers applied under irrigation keeping hay yields high and hay quality good? Which is the effect of irrigation on biodiversity of plants and animals living on meadows? How do species of conservation concern react to traditional irrigation? Does landscape attractiveness increase to combine the economic and ecological values with high recreational and touristic value? Could this traditional technique of intensification be a way out of the dilemma that farmers need to either heavily fertilize or abandon extensive meadows to find economically viable management solutions?

In many parts of Europe remains of former traditional meadow irrigation systems can still be found. However, the potential of the technique might be overlooked in many places.

2. Traditional water meadows

2.1. Traditional water meadows in Europe

Traditional irrigation techniques in grasslands were widely used until about the middle of the twentieth century [8], this is, when the techniques were replaced with modern systems using electric power supply and sprinkler irrigation and liquid manure or mineral fertilization to improve economic output of grasslands. Traditional methods of intensification, like traditional meadow irrigation techniques, are based on gravity and the natural movement of water from a river or stream [8, 9]. Meadows are either deliberately inundated by the damming of adjacent streams or ditches or the water slowly trickles over the surface of a slope. The time of inundation is usually kept short ("flash inundation"). The relief of the irrigated area is crucial to allow fast drainage, to avoid adverse effects of stagnant water [8, 11].

The widespread use of traditional meadow irrigation throughout Europe was by far not focused to dry areas only [8]. The positive effects found are not only restricted to the water supply but also to soil quality, making available of nutrients, pest control or elongating the growing period [9]. From Finland and Sweden in the North to Southern Spain or Sicilia in the South as well as from France in the West to Eastern Romania, traditional water meadow techniques were applied [8].

There is a large variety of management practices depending on region and natural settings. A rough separation of the techniques can be done into practices used in mountainous regions in contrast to techniques applied in valley floors and flat areas [8]. The application of traditional meadow irrigation in mountainous areas is often especially straightforward as the water is directed into ditches that follow the contour lines and the natural inclination of the hillslope which is sufficient to avoid stagnant water conditions. Irrigation systems in flat areas often were constructed with major effort as the surface level had to be adapted thoroughly. A ditch system allowing water division as well as a drainage system has to be constructed.

Traditional meadow irrigation clearly differs from modern sprinkler irrigation. The soil is not just wetted from above but soaks thoroughly. Above ground plant parts are often not even wet after irrigation, but soil water is effectively filled up to the local water holding capacity. The negative effects of large water drops splashing onto the soil surface closing soil pores, compacting the soils, and eventually leading to soil erosion—which are often problems under sprinkler irrigation—are avoided. Further, large water losses by the evaporation from the plant surfaces are reduced. It could be shown that traditional irrigation techniques are leading to a renewal of ground water resources [8] and increases water retention in the landscape. The potential negative argument traditional irrigation methods would be a waste of water that do not necessarily hold, if such secondary effects are included into the evaluation [8, 12, 13].

2.2. Traditional water meadows along the river Queich

While traditional water meadows in the region of Palatinate still covered one-third of the whole meadow area in 1936, hardly any traditionally irrigated meadows remained by 1960 [14]. This was not due to the low effectiveness of the systems, but it was the result of a large change in agriculture with abandonment on the one hand and intensification and transformation to arable land on the other hand. Many small farms were given up, food production on arable fields became extremely important during and after World War II, and the maintenance of irrigation systems was labor intensive. Since the introduction of mineral fertilizers after 1950, there seemed to be no need to keep on using meadow irrigation techniques as an alternative method to improve yields seemed to have been found.

The study region is part of the Upper Rhine Rift Valley located between the cities of Landau (49°19′N, 8°12′E) and Germersheim (49°22′N, 8°36′E) in the lower Queich valley. It belongs to the FFH habitat directive area "Queichniederung" [15]. The area under flush irrigation today has a size of more than 400 ha and is the largest actively traditional irrigated meadow landscape in Germany and one of the largest in Europe [9]. In parts (about 90 ha), meadow irrigation in the area continued since the medieval age. The larger parts were reactivated since 1996. The streams responsible for the large scale irrigation system are the river Queich and its side streams Fuchsbach and Spiegelbach. They originate from the Palatinate Forest region, a mountain range built from acidic sandstone from the Buntsandstein period.

Altogether, there are nine active sluices along the river Queich, one along Fuchsbach and two along the Spiegelbach. In the area, a large system of sluices, irrigation ditches, and drainage ditches was constructed (**Figure 1**). Two to three times a year, the irrigation follows the meadows downstream. Starting with the first sluice, the water is dammed slowly and flows into a main ditch (**Figure 2**). From here, there are several secondary ditches and even smaller distribution ditches to cover the area. Side sluices remain closed at the beginning of the irrigation but are opened successively as the water slowly covers the adjacent meadow areas (**Figure 3**). Water soaks slowly into the soil. When a section is well irrigated, the side sluices are opened and the water continues to flows to meadows further down the ditch. The first irrigation usually transports organic material from the river and the ditch to the sluices. The material is removed to guarantee the permeability of the ditch (**Figure 3**). With the successive opening of the side sluices, the water proceeds to wander over the meadows. Every main sluice is closed for 2–4 days, depending on the size of the irrigation area. The remaining water slowly flows into drainage ditches that drain back into the river. Simultaneously to the reopening of the first main sluice, the next main sluice further downstream is closed to use the increased water volume to irrigate the next sections. The irrigation follows an exact plan and is organized by the adjacent communities and farmer associations. They are based on the land owners' irrigation water rights that origin from ancient times. The sluices are never closed completely but allow a steady water flow to not affect the ecology of the stream ecosystem. A minimal water level is to be guaranteed. This avoids conflicts with other water users. In very dry periods, this may lead to a reduced size of the irrigation as the areas located at the far ends of the distribution ditches may not be reached by the water during the irrigation days of the respective section [9].

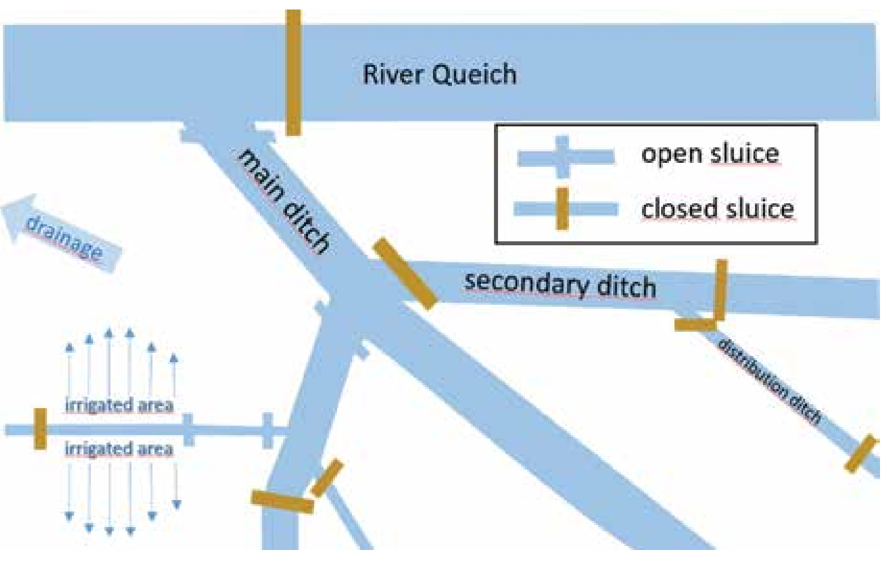

Figure 1. Scheme of the irrigation system found along the river Queich (redrawn and adapted from [8]). See text for explanation.

Figure 2. Main sluice (near Mörlheim) along the river Queich (right side of the photo). The sluice is closed which allows water to flow into a main ditch (upper left side of the photo; photo: Martin Alt).

Figure 3. Irrigated meadows to the left and to the right during spring irrigation. Side sluices are closed until the adjacent meadows are irrigated. The water level is not rising high above the surface during irrigation but soaks the soils from the sides (photo: Martin Alt).

The majority of the meadows are irrigated twice a year. The first irrigation starts by mid-April and ends by mid-May. The second period starts from mid-July and ends by mid-August. Historically, autumn irrigation also played an important role. This was done mainly to increase the organic debris that was transported with the water on the meadows to be used as fertilizers the next spring. Further, it was used as a rodent and mole control agent. Autumn irrigation is also known in the area to be effective to reduce the poisonous autumn crocus (*Colchicum autumnale*) in the area. Today, the autumn irrigation is not practiced any more. The amount of debris and nutrients that is transported with the river water today is very low, thanks to the existence of treatment plants.

3. Ecological, economic, and socio-economic values of traditional meadow irrigation

In our research project, the potential value of the traditional meadow irrigation in the Queich valley for species conservation and biodiversity, for the farmers' income, and for the recreational and touristic value were studied. The ecological value was mainly studied by comparing irrigated and nonirrigated meadows. All studied meadows were selected along a fertilization gradient from 0 to 80 kg N/ha per year. The following parameters were measured:

- Plant diversity and vegetation composition
- Diversity and species composition of several animal groups (butterflies, carabids, grasshoppers, snails, and woodlice)
- The activity of soil fauna
- Soil nutrient status, organic substance, and water retention capacity
- The quality and nutrient supply with the irrigation water
- The biomass (hay) production from two cuts over a period of 2 years
- Hay quality
- Additional income of the farmers based on the traditional meadow irrigation.
- Vegetation composition in ditches compared to other edge structures and the quality of differently managed forms of ditches
- The attractiveness for visitors of the area

Vegetation composition as well as plant diversity is clearly influenced by irrigation [16, 17]. The effect varies from year to year, but there seems to be rather an increase in plant species diversity than a decrease [16]. Mineral nitrogen fertilization, in contrast, turned out to be clearly negative on species richness though the nitrogen input of the studied meadows was low to moderate with up to 80 kg N/ha per year. This is especially relevant, as **biomass production** increased on average by about one-third under irrigation, while only half of this effect was measured for the influence of fertilization [18]. This demonstrates that an increase in biomass production does not necessarily lead to plant species loss. This well-known effect of fertilization induced biomass increase [4] does not necessarily occur if biomass is increased due to traditional meadow irrigation. Species composition is changing under irrigation allowing more space for herbs growing in low zones near the ground. Especially, semi-rosette and rosette plants increased under irrigation as did legumes [17]. The impact of the ratio of the cover of grasses to herbs is not consistent between the datasets. While in earlier datasets, grasses seemed to be reduced under irrigation [17], later analyses showed the contrary trend. However, the effect to increase grasscover in contrast to herbs is in both datasets higher under fertilization than under irrigation.

It is difficult to explain the positive effect on productivity as probably a large number of effects sum up and interact. Interestingly, the water retention capacity of soils of irrigated meadows was higher (marginally significant) than of nonirrigated meadows, while fertilization had a significantly negative effect on the water retention (**Figure 4**). The same pattern (positive irrigation effects and negative fertilization effects) is found regarding the water content after field sampling determined gravimetrically several weeks after spring irrigation (**Figure 4**). A linear model including irrigation as a fixed factor and amount of N fertilization in kg N/ha as a covariate gives the following results: water retention capacity [% vol.] (irrigation $p = 0.063$; N fertilization $p = 0.046$) and water content of the field samples in late spring (irrigation $p < 0.001$; N fertilization $p = 0.093$). The capacity to store water from precipitation in times without irrigation is therefore higher. As humidity in soils (not stagnant conditions) lead to high microbial activity and activity of other soil organisms [18], this may explain a continuous supply with nutrients on the water meadows in contrast to the other meadows which temporarily suffer from drought. Measured nutrients showed no significant pattern as the diversity of soil conditions overlaid the pattern we expect to be induced by the management. Fertilization did show a negative effect on soil fauna activity in spring but not during autumn sampling [18]. Nutrient supply of nitrogen and phosphorus with the irrigation water is probably insignificant, as analyses of the water suggest low nutrient input with the irrigation water (**Table 1**). While nitrate, nitrite, ammonium, and phosphate inputs are very low, the input of some minerals especially boron, magnesium, and chloride are high. They seem to have their origin in the sewage water from several treatment plants along the river as analyses of the outflow of two treatment plants in the area suggest (**Table 1**, bottom lines). As a consequence, soils of irrigated meadows had significantly elevated values of magnesium (positive irrigation effect $p = 0.013$) and boron (positive irrigation effect $p = 0.019$; negative fertilization effects 0.053; **Figure 5**). Chloride in the soils was not measured. Irrigation water pH was high (**Table 1**) and may contributed to decrease acidification processes. Soil pH, however, was not significantly increased under irrigation but stabilized. Variance of soil pH between nonirrigated meadows was clearly higher in contrast to irrigated meadows.

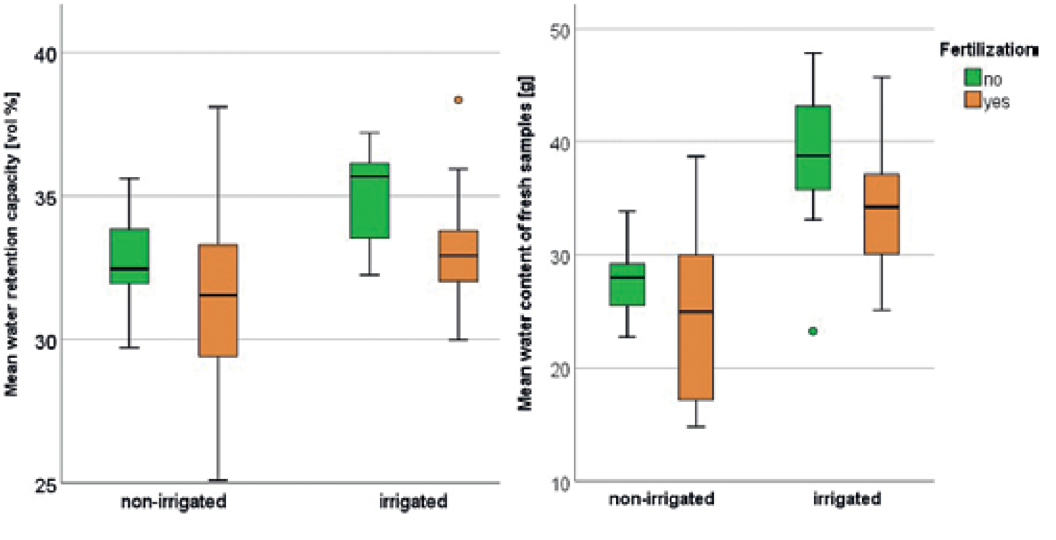

Figure 4. Water retention capacity and water content after field sampling in the month of May.

Day	Site	EC	pH	T	Cl	NO_3	PO_4	SO_4	Na	NH_4	K	Ca	Mg	Al	B	Cu	Fe	Mn	Pb	Zn
18-Apr	OB 1	328	8.0	10.8	26.9	5.1	0.0	23.1	17.7	0.0	3.7	30.9	7.7	3.6	47.9	1.2	4.5	40.0	0.5	3.6
18-Apr	OB 2	330	8.0	9.7	19.8	3.7	0.0	17.3	12.4	0.0	2.7	24.9	6.1	4.0	41.5	2.1	4.8	30.3	1.3	3.1
20-Apr	OB 3	358	8.2	8.8	18.9	3.6	0.0	21.0	13.4	0.0	2.7	28.1	6.3	3.6	45.5	0.8	5.5	25.3	1.7	3.2
28-Apr	OH 1	400	8.1	11.4	31.8	7.2	0.0	41.8	26.3	0.0	5.8	36.0	7.6	3.7	43.0	1.2	3.7	36.3	0.0	4.4
2-May	OH 2	442	7.8	12.2	30.9	2.7	0.0	32.1	23.4	0.0	6.2	25.5	6.0	4.1	50.9	1.5	11.6	6.9	0.5	5.0
4-May	KH 1	445	7.7	12.5	40.5	5.4	0.0	46.8	34.5	0.9	8.5	43.1	9.8	4.9	72.0	0.9	9.3	7.8	0.0	7.1
4-May	KH 2	443	7.8	12.9	42.0	5.6	0.0	44.1	36.5	0.9	11.8	40.6	9.5	4.6	77.5	1.6	9.2	16.5	0.3	7.1
5-May	BH 1	500	7.8	15.5	43.8	5.7	1.0	60.4	45.2	0.9	13.5	31.3	9.2	4.3	73.8	1.6	11.2	37.6	0.0	4.3
5-May	BH 2	496	7.8	15.5	21.3	3.2	1.0	35.4	21.8	0.0	4.0	26.9	3.6	4.3	56.3	1.6	9.7	4.4	0.0	5.3
5-May	BH3	551	7.7	16.5	26.5	3.3	1.0	41.4	50.2	0.9	17.0	46.7	10.7	7.2	63.7	1.8	17.5	10.9	0.3	10.4
Mean		429	7.9	12.6	30.2	4.6	0.3	36.3	28.1	0.4	7.6	33.4	7.7	4.4	57.2	1.4	8.7	21.6	0.5	5.4
sd		75	0.2	2.6	9.3	1.5	0.5	13.3	13.0	0.5	5.0	7.8	2.2	1.1	13.6	0.4	4.2	13.9	0.6	2.3
Sewage plant 1		754	7.5	14	65	4.2	0.8	77	51	1.6	12	42	7.0	5.4	54	1.2	11	83	1.1	13
Sewage plant 2		1104	7.2	15	151	2.3	0.0	49	90	3.0	22	70	15.4	8.5	260	1.3	50	33	0.8	31

Table 1. Water chemical characteristics measured in irrigation ditches during irrigation in different areas during spring irrigation in 2017. Legend: EC (electric conductivity in μs/cm), T (temperature in °C), most nutrients are presented in mg/l irrigation water. Al, B, cu, Fe, Mn, Pb, and Zn are presented in μg/l. Nitrite was below detection limit and is not shown. The last lines show mean values measured in the outflows of two local sewage treatment plants in the area at four different points of time in spring 2017.

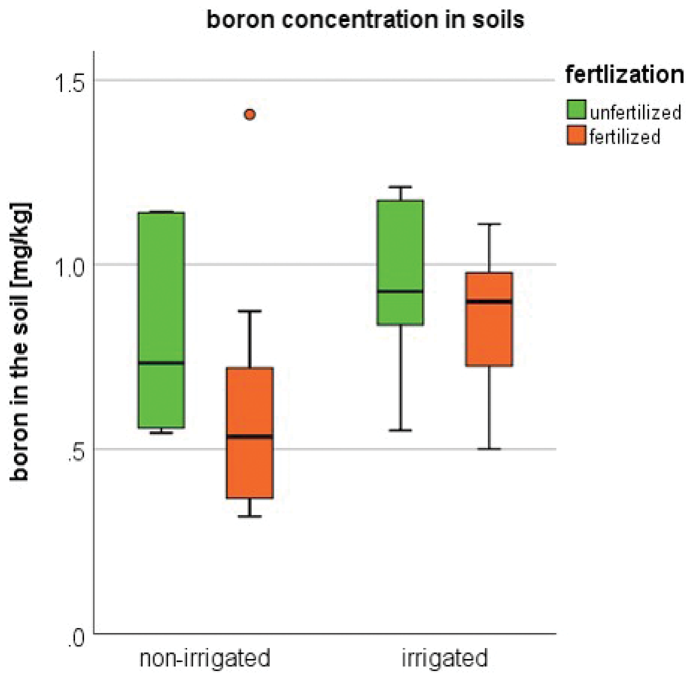

Figure 5. Boron concentration in soils in relation to irrigation and fertilization impact.

Nutrient input—especially of the micro-nutrient boron—may also contribute to the vegetation shift of irrigated meadows and to the conservation of species richness though biomass production is clearly enhanced [19]. For the micro-nutrient boron, there exists only a narrow window between deficiency and toxicity and different plant species groups and even genotypes within the same species tend to react differently to low or elevated boron values [20, 21]. Grasses tend to suffer from boron toxicity at lower concentrations as compared to several herbal species, especially legumes [20, 22], which could explain the observed vegetation shift [16, 17].

Hay quality does not differ significantly between irrigated and nonirrigated meadows [18]. The energy content of the hay produced on any of the meadows (irrigated and/or fertilized) would not be sufficient to serve as basic food for modern high productivity cattle. However, the food is perfect quality hay for horses or extensively raised cattle of older breeds. The quality mainly reflects the development phase of the vegetation when cut and is little affected by the management itself [18].

The elevated productivity lead to significant higher **income of the farmers** under traditional irrigation compared to farmers producing hay on nonirrigated meadows [18]. Astonishingly, the use of mineral fertilizers did not increase the income in a significant way. Nonirrigated and nonfertilized meadows did not draw any profits and their profitable management depended on governmental subsidies within agri-environmental schemes. Irrigation helped to improve the profit in most cases to reach a positive balance without the necessity to receive subsidies [18].

The hay in the region is primarily produced for horses which are very abundant in the rich outskirt of larger industrial areas. The economic analysis comprised a quantitative survey with farmers assessing their land-use practices as well as associated costs and revenues.

The **composition and diversity of the fauna** also responds to irrigation. Irrigation clearly changed invertebrate species assemblages of carabids, grasshoppers, and spiders toward more moisture-dependent species and probably increased overall diversity at the landscape scale [23]. Although irrigated meadows have a higher biomass than nonirrigated ones, effects of traditional meadow irrigation on species richness of invertebrates were generally weak and taxon-dependent. Irrigation had no significant effect on species richness of butterflies, carabids, spiders, and woodlice in lowland meadows [23, 24]. Effects on grasshoppers are not clear and differed among years and were either neutral [23] or slightly negative [24]. However, irrigation turned out to be important for species of conservation concern. The number of endangered carabid species and individuals was two to three times higher in irrigated meadows than in nonirrigated ones. Moreover, irrigation increased flower richness of the meadows [18], which in turn favored the occurrence of endangered butterfly species [18]. Thus, irrigation can have indirect positive effects on invertebrates via the provision of important resources. In contrast to irrigation, only weak effects of fertilization were found on invertebrate diversity [23]. However, functional diversity of grasshoppers was strongly negatively affected by fertilization [24]. Thereby, even relatively moderate fertilizer inputs (in our study system up to 80 kg N/ha per year) reduced functional diversity of grasshoppers, while this effect was not obvious when solely considering species richness. Moreover, increasing fertilizer applications reduced the number of specialized butterflies, while generalists were not affected [18]. To conclude, traditional meadow irrigation is compatible with invertebrate biodiversity conservation in European grasslands.

Next to measures at the single meadow or patch scale, traditional meadow irrigation should also be evaluated concerning its effect on the landscape scale as **species diversity of the landscape** is mainly influenced by the heterogeneity of different habitats in the area and not just by the richness of a single meadow. This became obvious observing species of snails in ditches and on the meadows themselves. While the species richness and composition at the meadows is low with about 7 species per m^2, the species and individual numbers increased to on average over 15 species in ditches with maximum values of over 20. Here, the snails profited from the high heterogeneity of site conditions in the ditches with dry and sunny as well as humid or even wet sites in the ditches and similar heterogeneity of organic debris and nutrients that were clearly higher in irrigation ditches as compared to drainage ditches. Even two red list aquatic snail species could be regularly found in the irrigation ditches. They survive in local puddles that remain wet most of the year [18].

Several organisms are mobile and cannot be studied at single meadows. This is the case with white storks. Their population development since the reactivation of major parts of the meadows is very well documented [25]. The white storks profit from the irrigation, as they find plenty of food during spring, when the juveniles need plenty of food close to their nests (**Figure 3**), and in late summer, when storks prepare to fly south. Many storks raised in the area of meadow irrigation emigrate to other regions in previous years, which shows that the donor effects [25]. Other bird species might decrease as their nesting sites are flooded. However, as there are several areas and patches that are not irrigated, the diversity is obviously not decreasing as bird observations in the area demonstrate [15].

Similar to the snails, the vegetation composition along **ditches** was heterogeneous and species rich [26]. Overall plant diversity in the ditches contributed one-third of the total species pool. This means that about one-third of all the species found in the sampled quadrats were found in ditches only. Many species of herbs typically found in extensively used grasslands seemed to use the rims of the ditches as refuges from the semi-intensively used meadows and were common here, while sometimes only sparsely found in the meadows themselves (**Figure 6**) [26]. Locally, species preferring wet habitat increase overall richness (**Figure 7**). The quality of the ditches for plant diversity varied according to ditch size, sedimentation, and successional stage. The larger and deep trapezoid well maintained ditches had highest richness in contrast to smaller and strongly overgrown and silted up ditches [26]. However, the large variety of differently maintained ditches finally made up the very high overall diversity found in the landscape. This is the result of the diverse management techniques and frequencies used by the different communities concerned. Commonly, the ditches are mown or mulched once a year (usually in late winter) and maintained with excavators once every two to more than every 10 years depending on the community and ditch location [26].

The **touristic and recreational value** was assessed by conducting a travel cost analysis with visitors of the meadows in the Queich valley. The touristic and recreational value was estimated to be between 0.38€ and 2.54€ per visit depending on whether the opportunity costs of time were taken into account or not. Since most of the visitors were from the direct vicinity of

Figure 6. Drainage ditch with the defined area for a vegetation analyses (blue line). Ditches play an important role in overall biodiversity as they provide various different niches and serve as refuge for sensible plants and animals which escape from more intensive meadow management techniques. The corresponding data is published in [26] (photo: Melanie Meier).

Figure 7. Irrigation ditch after first cut in June. Remaining standing water from the last irrigation in may serves as a habitat and food source for a large variety of organisms. It clearly contributes to the heterogeneity of the landscape (photo: Melanie Meier).

the meadows, most people did not incur real financial costs to visit the meadows. About 20% of the visitors use the meadows more than 100 times per year for recreational purposes. The main activities in the meadows are cycling, walking, watching nature, and excursions with children. More than 60% of the visitors state that they would have stayed at home if they had not had the chance to go to the meadows on the day they were interviewed. This shows the substantial value of the meadows for the local population. However, more than 40% of the visitors traveled more than 20 minutes, 15% even more than 1 h to visit the meadows. About 3% of the visitors stayed overnight in the area and came to visit the meadows mainly to watch the gathering of the white stork population in spring and early autumn. Next to the storks, the beauty of the semi-open landscape as such, the diversity and the traditional irrigation infrastructure are mentioned to attract the visitors (**Figure 8**).

Apart from these mentioned socio-economic values, the value of the **cultural heritage** can be considered to be substantial. In a two-volume book, Leibundgut and Vonderstrass [9]

http://dx.doi.org/10.5772/intechopen.79429

Figure 8. Beautiful landscape with high recreational and touristic value. The high numbers of storks also attract visitors. The active traditional irrigation system also contributes to our cultural heritage (photo: Martin Alt).

described the role and the extension of meadow irrigation in Europe. On the European level, a group of actors from Switzerland, Germany, Belgium, Austria, the Netherlands, Sweden, Great Britain, and France is currently working on an application of irrigated meadows as UNESCO world heritage sites. This shows the importance of those irrigated meadows still have in some regions. Obviously, meadow irrigation systems are popular and bear witness to a century long innovation and tradition. On the other hand, the once widely spread meadow irrigation systems are now found only very locally. In the area of the Queich valley, the local interest group Queichwiesen comprised of a very diverse group of actors like representatives of local administration, environmental NGOs, and farmers jointly pursues the acknowledgement of the irrigation meadows in the world heritage list.

4. Conclusions

Traditional meadow irrigation proved to increase productivity in a very effective and more sustainable way than mineral fertilization did. Summarizing our manifold data on flora, fauna, and soil characteristics, the management method creates multifunctional habitats and production sites. They offer multiple ecosystem services of all four categories defined in the Millennium Ecosystem Assessment report by the UN: supporting, provisioning, regulation as well as cultural services [27]. We explain this by the positive effect of this management practice on soil carbon or humus [28] and the related positive effect on soil organisms [29]. Next to the multiple services for productivity and biodiversity found at the single meadows, there are larger scale services provided at the landscape scale. The heterogeneity of the irrigation, the variety of habitats that are created by the ditches (irrigation and drainage), and the mixture with other habitats in the region provide a beautiful landscape for animal life and human well-being (recreation and tourism).

Acknowledgements

We thank the DBU (German Environmental Foundation) for funding of the WasserWiesenWerte project as well as the Federal State of Rhineland-Palatinate, Ministry of Science (MBWWK) for the funding of activities within the framework of "AufLand" research initiative. For their contributions in data acquisition, we thank various students of the University Koblenz-Landau. Further, we thank the communities, the Landschaftspflegeverband Südpfalz as well as many of their farmers for their valuable cooperation.

Conflict of interest

We declare that there are no conflicts of interest.

Author details

Constanze Buhk[1*], Jens Schirmel[2], Gerlach Rebekka[3] and Oliver Frör[4]

*Address all correspondence to: buhk@uni-landau.de

1 Institute for Environmental Sciences, Geoecology and Physical Geography, University of Koblenz-Landau, Landau, Germany

2 Institute for Environmental Sciences, Ecosystem Analyses, University of Koblenz-Landau, Landau, Germany

3 Institute for Environmental Sciences, Geoecology and Physical Geography/Environmental Economics, Germany

4 Institute for Environmental Sciences, Environmental Economics, University of Koblenz-Landau, Landau, Germany

References

[1] Habel JC, Dengler J, Janišová M, Török P, Wellstein C, Wiezik M. European grassland ecosystems: Threatened hotspots of biodiversity. Biodiversity and Conservation. 2013;**22**:2131-2138

[2] Henle K, Alard D, Clitherow J, Cobb P, Firbank L, Kull T, McCracken D, Moritz RFA, Niemelä J, Rebane M, Wascher D, Watt A, Young J. Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe–a review. Agriculture, Ecosystems and Environment. 2008;**124**:60-71. DOI: 10.1016/j.agee.2007.09.005

[3] Wesche K, Krause B, Culmsee H, Leuschner C. Fifty years of change in central European grassland vegetation: Large losses in species richness and animal-pollinated plants. Biological Conservation. 2012;**150**:76-85. DOI: 10.1016/j.biocon.2012.02.015

[4] Zechmeister HG, Schmitzberger I, Steurer B, Peterseil J, Wrbka T. The influence of land-use practices and economics on plant species richness in meadows. Biological Conservation. 2003;**114**:165-177. DOI: 10.1016/S0006-3207(03)00020-X

[5] Isselstein J, Jeangros B, Pavlu V. Agronomic aspects of biodiversity targeted management of temperate grasslands in Europe-a review. Agronomy Research. 2005;**3**:139-151

[6] Convention on Biological Diversity. Decision Adopted by the Conference of the Parties to the Convention of Biological Diversity at its Tenth Meeting [Internet]. 2010

[7] Tscharntke T, Tylianakis JM, Rand TA, Didham RK, Fahrig L, Batáry P, Bengtsson J, Clough Y, Crist TO, Dormann CF, Ewers RM, Fründ J, Holt RD, Holzschuh A, Klein AM, Kleijn D, Kremen C, Landis DA, Laurance W, Lindenmayer D, Scherber C, Sodhi N, Steffan-Dewenter I, Thies C, van der Putten WH, Westphal C. Landscape moderation of biodiversity patterns and processes - eight hypotheses. Biological Reviews. 2012;**87**: 661-685. DOI: 10.1111/j.1469-185X.2011.00216.x

[8] Leibundgut C, Kohn I. European traditional irrigation in transition part I: Irrigation in times past - a historic land-use practice across Europe. Irrigation and Drainage. 2014;**63**:273-293. DOI: 10.1002/ird.1826

[9] Leibundgut C, Vonderstrass I. Traditionelle Bewässerung - ein Kulturerbe Europas. 1st ed. Langenthal: Merkur Druck; 2016

[10] Leibundgut C, Kohn I. European traditional irrigation in transition part II: Traditional irrigation in our time - decline, rediscovery and restoration perspectives. Irrigation and Drainage. 2014;**63**:294-314. DOI: 10.1002/ird.1825

[11] Ondrasek G, Rengel Z, Petosic D, Filipovic V. Land and water management strategies for the improvement of crop production. In: Parvaiz A, Saiema R, editors. Emerging Technologies and Management of Crop Stress Tolerance: A Sustainable Approach. Elsevier; 2014. pp. 291-313

[12] Guillet D. Rethinking irrigation efficiency: Chain irrigation in northwestern Spain. Human Ecology. 2006;**34**:305-329. DOI: 10.1007/s10745-006-9020-6

[13] Merot A, Wery J, Isbérie C, Charron F. Response of a plurispecific permanent grassland to border irrigation regulated by tensiometers. European Journal of Agronomy. 2008;**28**:8-18. DOI: 10.1016/j.eja.2007.04.004

[14] Fiedler K-H. Die Wiesenbewässerung im Saarland und in der Pfalz [Dissertation]. Saarbrücken: Universität des Saarlandes; 1965

[15] Keller P. Die Queichniederung – Portrait einer Landschaft. Mainz: Gnor; 2013

[16] Müller IB, Buhk C, Lange D, Entling MH, Schirmel J. Contrasting effects of irrigation and fertilization on plant diversity in hay meadows. Basic and Applied Ecology. 2016;**17**:576-585

[17] Müller IB, Buhk C, Alt M, Entling MH, Schirmel J. Plant functional shifts in central European grassland under traditional flood irrigation. Applied Vegetation Science. 2016;**19**:122-131

[18] Buhk C, Schirmel J, Frör O, Gerlach R. WasserWiesenWerte: Wiesenbewässerung - Eine produktive Bewirtschaftungsform mit hohem Wert für Mensch und Natur?: Final Report of DBU Project AZ 31109 [Internet]; 2017

[19] Steidinger B. Qualitative differences in tree species distributions along soil chemical gradients give clues to the mechanisms of specialization: Why boron may be the most important soil nutrient at Barro Colorado Island. The New Phytologist. 2015;**206**:895-899. DOI: 10.1111/nph.13298

[20] Gupta UC, Jame YW, Campbell CA, Leyshon AJ, Nicholaichuk W. Boron toxicity and deficiency: A review. Canadian Journal of Soil Science. 1985;**65**:381-409

[21] Reid RJ, Hayes JE, Post A, Stangoulis JCR, Graham RD. A critical analysis of the causes of boron toxicity in plants. Plant, Cell & Environment. 2004;**27**:1405-1414. DOI: 10.1111/j.1365-3040.2004.01243.x

[22] Marschner H, Marschner P, editors. Marschner's Mineral Nutrition of Higher Plants. 3rd ed. Amsterdam, Boston, MA: Academic Press; 2012

[23] Schirmel J, Alt M, Rudolph I, Entling MH. Effects of traditional flood irrigation on invertebrates in lowland meadows. PLoS One. 2014;**9**:e110854. DOI: 10.1371/journal.pone.0110854

[24] Schirmel J, Gerlach R, Buhk C. Disentangling the role of management, vegetation structure and plant quality for Orthoptera in lowland meadows. Insect Science. 2018: In Press. DOI: 10.1111/1744-7917.12528

[25] Dorner I, Tietze DT. Die Wiederansiedlung des Weißstorchs Ciconia ciconia in Rheinland-Pfalz. Vogelwarte. 2015;**53**:99-110

[26] Meier M, Gerlach R, Schirmel J, Buhk C. Plant diversity in a water-meadow landscape: The role of irrigation ditches. Plant Ecology. 2017;**218**:971-981

[27] Assessment ME. Ecosystems and Human Well-Being: Synthesis [Internet]. 2005

[28] Banwart SA, Noellemeyer E, Milne E, editors. Soil Carbon: Science, Management and Policy for Multiple Benefits. CABI: Wallingford, Oxfordshire; 2015

[29] Wagg C, Bender SF, Widmer F, van der Heijden MGA. Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proceedings of the National Academy of Sciences of the United States of America. 2014;**111**:5266-5270. DOI: 10.1073/pnas.1320054111

Edited by Gabrijel Ondrašek

The agroecosystem is one of the most fascinating, purposely human-created functional units, by which human species made a huge leap from predators and nomads to food growers (agriculturists). Irrigation is one of the oldest and still one of the most effective agricultural practices for providing continuous and quality foodstuffs.

Published in London, UK

IntechOpen

ISBN 978-1-83881-743-5