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Crop yield response to water

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Crop yield response to water

FAO IRRIGATION AND DRAINAGE PAPER
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by

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Foreword

Sustainable management and utilization of natural resources is part of the *Global Goals* of FAO Member Countries and essential to the mandate of FAO.

The latest FAO assessment of the state of the world's land and water resources clearly indicated that these resources, already scarce today, will be increasingly scarce as we move into the future, threatening food security. In fact, the outstanding food demand projected for the next decades, due to the world population growth and to the anticipated shift in consumption patterns, will face very limited opportunities for further land expansion and the finite availability of fresh water resources. Such a food demand may be satisfied only if we are able to act effectively and sustainably on both sides of the *food* equation, i.e., *production* and *consumption*, and on the inter-linkages between these two variables, including trade, distribution and access.

Efforts are being made by FAO to address major issues on the *production* side, on the fairness of trade, on the *consumption* side (reduction of post-harvest losses and food waste; promoting nutritious and healthy diets) and other emerging challenges. Among these emerging challenges are: *food price volatility*, revealing the vulnerability of some countries in their dependency on imports, leading to increase production inside their national boundaries; *climate change*, causing greater uncertainties on rainfall patterns, thus requiring higher levels of adaptation and increased resilience of the local production systems; *transboundary* rivers and *competing demands* for land and water resources by other sectors of society and by ecosystems.

Under such circumstances, and looking into the future food demand, it is imperative that agriculture improve the efficiencies of use of the limited resources and ensure substantial *productivity* gains. In the case of water, scarcity is a major threat to the sustainability of food production in many areas of the world. The effective management of water in rainfed and irrigated agriculture is thus a major knowledge-based pathway to increase *productivity* and farmers' income. To combine increased productivity with sustainable management of natural resources, without repeating the mistakes made in the past, will be a challenge.

With the contribution of numerous experts, professionals and scientific institutions around the world, including a few *Institutes* of the *Consultative Group on International Agricultural Research* (CGIAR), "*Crop yield response to water*" is published at a time of high demand for assistance by member countries in order to implement effective water management strategies and practices that are environmentally safe and climate-resilient, and enhance sustainable water productivity and yield of their farming systems, therefore alleviating the risks of food insecurity.

José Graziano da Silva
Director-General
Food and Agriculture Organization
of the United Nations

Preface

The FAO *Land and Water Division* is engaged extensively in the enhancement of global agricultural performance. A part of this effort is the production of landmark publications and guidelines that address food production and water use problems using analytical methods that often serve as standards worldwide.

In the face of growing water scarcity, declining water quality, and the uncertainties of climate change, improving the efficiency and productivity of crop water use, while simultaneously reducing negative environmental impact, is of utmost importance in responding to the increasing food demand of the growing world population. To this end, irrigated and rainfed agriculture must adopt more knowledge-intensive management solutions.

Moreover, competing demands for water from other economic sectors and for ecosystem services will continue to grow. As agriculture is by far the largest consumer of water, efficiency and productivity gains in this sector would free significant amounts of water for other uses.

Abstracting from the scientific understanding and technological advances achieved over the last few decades, and relying on a network of several scientific institutions, FAO has packaged a set of tools in this *Irrigation and Drainage Paper* to better assess and enhance crop yield response to water. These tools provide the means to sharpen assessment and management capacities required to: sustainably intensify crop production; close the yield-gap in many regions of the world; quantify the impact of climate variability and change on cropping systems; more efficiently use natural resources; and minimize the negative impact on the environment caused by agriculture. These tools are invaluable to various agricultural practitioners including, but not limited to: water managers and planners; extension services; consulting engineers; governmental agencies; non-governmental organizations and farmers' associations; agricultural economists and research scientists.

Representing FAO's state-of-the-art work in water and crop productivity, it is our hope that this publication provides easy access to, and better understanding of, the complex relationships between water and food production and, in this way, help improve the management of our precious water resources.

Alexander Müller
Assistant Director-General
Natural Resources and Environment

Parviz Koohafkan
Director
Land and Water Division

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Acknowledgments

This publication has relied on inputs from a large number of people and institutions in various forms, including expert consultations, contributions at project workshops, experimental data and authorship.

Universities and national and international research institutions from many regions of the world have provided data and insights, which forms part of the vast amount of information and knowledge condensed in this state-of-the-art publication *Crop yield response to water.*

Particularly significant has been the involvement of key CGIAR Centres, specifically IRRI, ICARDA, ICRISAT, CIMMYT and CIP, and the FAO/IAEA Joint Division. Working together with the colleagues from these Centres has strengthened the institutional partnership and enhanced the synergy towards filling the gaps between scientific research and field implementation, theoretical knowledge and field practice, investigation and actual operation.

Most of these scientists, experts and colleagues are listed in this publication either as editors, authors or as scientists who have contributed with data and tests for the model *Aquacrop*. We are grateful to all of them for their highly valuable inputs.

We would like to thank the following experts who were involved in the initial stage of this endeavour: John Passioura (CSIRO, Canberra, Australia), Luigi Cavazza (University of Bologna, Italy), Hugh Turral (formerly IWMI, Colombo, Sri Lanka), John Annandale (University of Pretoria, South Africa), Dogo Seck (CERAAS, Dakar, Senegal), Lamourdia Thiombiano (FAO, Sub-Regional Office for Central Africa, Libreville, Gabon), Netij Ben-Mechlia (INAT, Tunis, Tunisia), Claudio Stockle (Washington State University, Pullman, United States), Florent Maraux (CIRAD, Montpellier, France), François Tardieu (INRA, Montpellier, France), Tsugihiro Watanabe (RIHN, Tokyo, Japan), Hiroshi Nakagawa (Ishikawa Prefectural University, Ishikawa, Japan), Long Nguyen (Joint FAO/IAEA Division, Vienna, Austria), Tim Wheeler (University of Reading, Reading, United Kingdom), Jan Doorenbos and Amir Kassam (formerly FAO, Land and Water Division, Rome, Italy) and Gerardo van Halsema (Wageningen University and Research Centre, Wageningen, The Netherlands). Their inputs have been determinant in correctly setting the initial condition of this work.

The support of colleagues at FAO at different stages has been indispensable for this publication. Special thanks go to Martin Smith, who started the process and later overviewed the various chapters, providing inputs and feedback to the editors to improve harmonization among the chapters and between the present and past FAO publications. Martin was ably assisted by Giovanni Munoz and Robina Wahaj. Shortly after the initial phase, an intense period of work started and we are particularly grateful to Gabriella Izzi and Lee K. Heng who managed the extensive experimental data set collected for calibration, maintained the liaison between all the collaborators, and contributed considerably to the various calibration and tests of *Aquacrop*. After one year of diligent effort at FAO, Lee moved to the FAO/IAEA Joint Division in Vienna, but continued to cooperate enthusiastically on model calibration and testing. Gabriella moved to the World Bank after two years of intense work on the model at FAO. More recently, support has been provided by Michela Marinelli, Patricia Mejías Moreno and Jippe Hoogeveen. We thank them for their continuous help and critical exchange in the completion of this product.

The design and accurate execution of the layout and editing of the manuscript are critical for this publication, requiring meticulous attention to the numerous details in the text, graphs, pictures, drawings, equations, symbols and citations. For their professional and immensely patient devotion to these tasks, we would like to thank the FAO collaborators Gabriele Zanolli, Paolo Mander, Rosemary Allison and Jim Morgan. A very special recognition goes to Margherita Bongiovanni for providing artistic, beautiful and accurate botanical illustrations of the crops.

Finally, we thank the former Assistant Director-General of Agriculture and Consumer Protection Department, Ms Louise Fresco, for her early endorsment and support of the iniciative, and both the Land and Water Division, Mr Parviz Koohafkan, and the Assistant Director-General of Natural Resources Management and Environment Department, Mr Alexander Müller, for their strong and continuous support of the 'Water' programme making possible this publication and the development of the model *Aquacrop*.

Without this collective and interdisciplinary effort, this outcome could not have been achieved.

Acronyms of institutions

CER:	Canale Emiliano Romagnolo, Italy
CNR:	Consiglio Nazionale delle Ricerche, Italy
CMMYT:	Centro Internacional de Mejoramiento de Maíz y Trigo, Mexico
CIP:	Centro Internacional de la Papa, Peru
CONICET:	Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina
CRA:	Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Italy
CRI:	Cotton Research Institute, Uzbekistan
CSIRO:	Commonwealth Scientific and Industrial Research Organisation, Australia
DSIR:	Department of Scientific & Industrial Research, India
EEAD-CSIC:	Estación Experimental Aula Dei - Consejo Superior de Investigaciones Científicas, Spain
EMBRAPA:	Empresa Brasileira de Pesquisa Agropecuária, Brazil
FAO:	Food and Agriculture Organization of the United Nations, Italy
GRI:	Golan Research Institute, Israel
GRC:	Geisenheim Research Centre for Viticulture and Grapevine Breeding, Germany
IAM-B:	Mediterranean Agronomic Institute of Bari, Italy
IAEA:	International Atomic Energy Agency, Austria
IAS-CSIC:	Instituto de Agricultura Sostenible - Consejo Superior de Investigaciones Científicas, Spain
ICARDA:	International Center for Agricultural Research in the Dry Areas, Syria
ICREA:	Institució Catalana de Recerca i Estudis Avançats, Spain
ICRISAT:	International Crops Research Institute for the Semi-Arid Tropics, India
INIA:	Instituto Nacional de Investigaciones Agropecuarias, Chile
INRA:	Institute National de la Recherche Agronomique, France
INTA:	Instituto Nacional de Tecnologia Agropecuaria, Argentina
IRD CEFE-CNRS:	Institut de Recherche pour le Développement Centre d'Ecologie Fonctionnelle & Evolutive - Centre National de la Recherche Scientifique, France
IRRI:	International Rice Research Institute, Philippines
IRTA:	Institut de Recerca i Tecnologia Agroalimentaries, Spain

ISPA:	Istituto di Scienze delle Produzioni Alimentari, Italy
IVIA:	Instituto Valenciano de Investigaciones Agrarias, Spain
KESREF:	Kenya Sugar Research Foundation, Kenya
LARI:	Lebanese Agricultural Research Institute, Lebanon
LLNL:	Laurence Livermore National Laboratory, USA
SARDI:	South Australian Research and Development Institute, Australia
SASRI:	South African Sugarcane Research Institute, South Africa
SIA:	Servicio de Investigación Agraria, Spain
USDA-ARS:	United States Department of Agriculture – Agricultural Research Service, USA
WB:	World Bank, USA
VLIR-UOS:	Flemish Inter-University Council, Belgium
ZIS:	Zhanghe Irrigation System, China

List of principal symbols and acronyms

B	Dry biomass, of shoot for non-root crops, and of shoot plus storage root or tuber for root crops [tonne/ha or kg/m^2]
C_a	Mean atmospheric CO_2 concentration for the actual year [ppm]
$C_{a,o}$	Mean atmospheric CO_2 concentration for the year 2000 [ppm]
cc_o	Canopy size of the average seedling at 90% emergence [cm^2]
CC	Green canopy cover [percent or fraction]
CC*	Green canopy cover adjusted for micro advection [percent or fraction]
CC_{meas}	Canopy cover measured [percent or fraction]
CC_{sim}	Canopy cover simulated [percent or fraction]
CC_o	Initial canopy cover, canopy cover at 90% emergence [percent or fraction]
CC_{pot}	Potential canopy cover [percent or fraction]
CC_x	Maximum green canopy cover [percent or fraction]
CDC	Canopy decline coefficient [percent or fraction of canopy decline per unit time]
CGC	Canopy growth coefficient [percent or fraction of canopy growth per unit time]
CN	Curve number or surface runoff coefficient
[CO_2]	Carbon dioxide concentration of the atmosphere [ppm]
CWSI	Crop water stress index
d	Day
d_p	Plant density [plants per unit surface]
d_{ref}	Reference plant density [plants per unit surface]
D_r	Soil water depletion of the root zone [mm]
DAE	Days after emergence [day]
DAP	Days after planting [day]
DI	Deficit irrigation
DP	Deep percolation [mm per unit time]
DU	Distribution uniformity
E	Soil evaporation [mm per unit time]
E_{dz}	Surface evaporation from the rest of the soil surface outside the emitter wetting pattern [mm per unit time]
$E_{Stage\ I}$	Soil evaporation at Stage I (wet soil surface) [mm per unit time]
$E_{Stage\ II}$	Soil evaporation at Stage II (drying soil surface) [mm per unit time]
E_{wz}	Surface evaporation from the soil wetted by the emitters [mm per unit time]

ECe	Electrical conductivity of the saturated soil-paste extract [dS/m]
ECe_n	Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts occurring) [dS/m]
ECe_x	Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect) [dS/m]
ET	Evapotranspiration [mm per unit time]
ET_a	Actual evapotranspiration [mm per unit time]
ET_c	Crop evapotranspiration under standard conditions [mm per unit time]
ET_x	Maximum evapotranspiration [mm per unit time]
ET_o	Reference evapotranspiration [mm per unit time]
f_{age}	Reduction coefficient describing the effect of ageing on $K_{c,Trx}$ [1/d]
f_{cc}	Fraction of the orchard ground surface occupied by the cover crop
f_{CO2}	CO_2 factor for atmospheric CO_2 normalization
f_{HI}	Adjustment factor for HIo
FC	Field capacity
FI	Full irrigation
FDR	Frequency domain reflectometry
FTSW	fraction of transpiring soil water
g_s	Stomatal conductance [m/s]
G	Ground cover fraction of the tree canopy
GDD	Growing degree days [°C d]
GIR	Gross irrigation requirement [mm or m3/ha per unit time]
GIS	Geographical information systems
HI	Harvest index [percent or fraction]
HI_o	Reference harvest index [percent or fraction]
I	Infiltration [mm per unit time]
K_c	Crop coefficient
K_{cb}	Basal crop coefficient representing Kc for a dry soil surface having little evaporation but full transpiration
K_{cc}	Cover crop coefficient
K_{ext}	Radiation extinction coefficient
K_p	Pan coefficient (for the pan evaporation method to determine ET_o)
$K_{r,t}$	Empirical coefficient relating the ET_c of an orchard of incomplete cover to that of a mature orchard
K_{sat}	Saturated hydraulic conductivity [mm per unit time]
$K_{s,e}$	Empirical soil evaporation coefficient
K_y	Yield response factor

$K_{c,Tr}$	Crop transpiration coefficient
$K_{c,Tr\ x}$	Crop transpiration coefficient for when the canopy fully covers the ground (CC = 1) and stresses are absent
Ke	Soil evaporation coefficient for fully wet soil surface
Ke_x	Soil evaporation coefficient for fully wet and non-shaded soil surface
Kr	Evaporation reduction coefficient
Ks	Stress coefficient
$Ks_{b,c}$	Cold stress coefficient for biomass production
$Ks_{pol,c}$	Cold stress coefficient for pollination
$Ks_{pol,h}$	Heat stress coefficient for pollination
Ks_{aer}	Water stress coefficient for water logging (aeration stress)
$Ks_{exp,w}$	Water stress coefficient for canopy expansion
Ks_{sen}	Water stress coefficient for canopy senescence
Ks_{sto}	Water stress coefficient for stomatal closure
LAI	Leaf area index [m^2 leaf area/m^2 soil surface]
LAI_{ref}	LAI of the same crop planted at a reference density
LWP	Leaf water potential [MPa]
NIR	Net irrigation requirement [mm per unit time or m^3/ha per unit time]
p	Fractional depletion of TAW
p_{upper}	Upper threshold of p (no water stress: Ks = 1)
p_{lower}	Lower threshold of p (maximum water stress: Ks = 0)
P	Precipitation or rainfall [mm]
PAR	Photosythetically active radiation [μmol per m^2 of surface per s]
PRD	Partial root drying
PWP	Permanent wilting point
RDI	Regulated deficit irrigation
RAW	Readily available soil water in the root zone [mm]
REW	Readily evaporable water at the top of the soil profile [mm]
RUE	Radiation use efficiency [Kg of biomass per MJ of intercepted solar radiation]
RO	Surface runoff [mm per unit time]
SDI	Sustained (or continuous) deficit irrigation
t	Time [GDD or d]
T	Air temperature [°C]
T_{base}	Base temperature (below which crop development does not progress) [°C]
T_c	Canopy temperature [°C]
$T_{max} = T_x$	Daily maximum air temperature [°C]

$T_{min} = T_n$	Daily minimum air temperature [°C]
$T_{n,cold}$	Minimum air temperature at upper threshold for cold stress affecting pollination [°C]
$T_{x,heat}$	Maximum air temperature at lower threshold for heat stress affecting pollination [°C]
T_{opt}	Crop optimal daily temperature [°C]
T_{upper}	Upper temperature (above which crop development no longer increases with an increase in air temperature) [°C]
Tr	Crop transpiration [mm per unit time]
Tr_{cc}	Cover Crop transpiration [mm per unit time]
Tr_x	Maximum crop transpiration (for a well watered crop) [mm per unit time]
TAW	Total Available soil Water (between FC and PWP), equivalent to the soil water holding capacity in the root zone [mm/m]
TDR	Time domain reflectometry
TE	Transpiration efficiency [Kg of biomass per unit of water transpired]
VPD	Air vapor pressure deficit [kPa]
wz	Fraction of the soil surface wetted by the emitters
Wr	Soil water content of the root zone expressed as an equivalent depth [mm]
WP	Crop biomass water productivity [tonne of biomass per ha and per mm of water transpired or kg of biomass per m^3 of water transpired]
WP*	WP normalized for ET_o and air CO_2 concentration [tonne /ha or kg/m^2]
$WP_{B/ET}$	WP as the ratio of biomass to ET [kg/m^3]
$WP_{B/Tr}$	WP as the ratio of biomass to Tr [kg/m^3]
$WP_{fresh\ Y/ET}$	WP as the ratio of yield measured as fresh biomass to ET [kg/m^3]
$WP_{lint/ET}$	WP as the ratio of lint (of cotton) to ET [kg/m^3]
$WP_{sucrose/ET}$	WP as the ratio of sucrose (for sugar cane) to ET [kg/m^3]
$WP_{Y/ET}$	WP as the ratio of yield (as dry matter) to ET [kg/m^3]
$WP_{Y/Tr}$	WP as the ratio of yield (as dry matter) to Tr [kg/m^3]
X	Irrigation depth [mm]
X_R	Required irrigation depth [mm]
Y	Yield [tonne/ha or kg/ha]
Y_a	Actual yield [tonne/ha or kg/ha]
Y_x	Maximum yield [tonne/ha or kg/ha]
Z_e	Effective rooting depth [m]
Z_x	Maximum effective rooting depth [m]
Z_n	Minimum effective rooting depth [m]
θ	Volumetric soil water content [m^3 of water / m^3 of soil]
Ψ_{stem} = SWP	Stem water potential [MPa]
Ψ_{leaf} = LWP	Leaf water potential [MPa]

1. Introduction

Food production and water use are inextricably linked. Water has always been the main factor limiting crop production in much of the world where rainfall is insufficient to meet crop demand. With the ever-increasing competition for finite water resources worldwide and the steadily rising demand for agricultural commodities, the call to improve the efficiency and productivity of water use for crop production, to ensure future food security and address the uncertainties associated with climate change, has never been more urgent.

To examine the pathways for increasing the efficiency and productivity of water use, the yield response of crops to water must be known. This relationship is complex in nature and various attempts have been made to provide simplified, though sound, approaches to capture the basic features of the response.

FAO's first publication that presented a relationship between crop yield and water consumed was *Irrigation and Drainage Paper* No. 33 *Yield Response to Water* (Doorenbos and Kassam, 1979). This approach, discussed in Chapter 2, is based on one single equation relating the relative yield loss of any crop (either herbaceous or woody species) to the relative reduction of water consumption, i.e. evapotranspiration, by way of a coefficient (k_y), which is specific for any given crop and condition. This approach has provided a widely-used standard for synthetic water production functions, still in use today. This simplification, however, made this approach more suitable for general planning, project design and rapid appraisal purposes, often providing a first-order approximation.

Over the last three and half decades, new knowledge has enlighten processes underlying the relationship between crop yield and water use and technology has improved. Further, novel needs have emerged related to the planning and management of water in agriculture, including those arising from climate change. FAO has, therefore, revisited the approach to quantify crop yields in response to water use and water deficit. The end product of this effort is a crop simulation model named *AquaCrop*, which balances accuracy, simplicity and robustness and is described in Chapter 3. The conceptualization and development of this modelling approach is the result of a number of years of consultation and collaboration with scientists, crop specialists and practitioners worldwide, consolidating the vast amount of knowledge and information available since 1979.

AquaCrop uses the original equation of Doorenbos and Kassam (1979) as a point of departure and evolves from it by calculating the crop biomass, based on the amount of water transpired, and the crop yield as the proportion of biomass that goes into the harvestable parts. An important evolution is the separation of the non-productive consumption of water (soil evaporation) from the productive consumption of water (transpiration). Furthermore, the timescale of the original equation is seasonal, or growth-stages that are weeks long in duration, while the timescale used in *AquaCrop* is daily, in order to better represent the dynamics of crop response to water. Finally, the model allows for the assessment of responses under different climate change scenarios in terms of altered water and temperature regimes and elevated carbon dioxide concentration in the atmosphere. *AquaCrop* simulates growth, productivity and water use of a crop day-by-day, as affected by changing water availability and environmental conditions. The results of calibration and testing of the model so far provide grounds for confidence in its performance.

The development of standard crop parameters has made the model accessible to several types of users in different disciplines and for a wide-range of applications. *AquaCrop* is mainly aimed at practitioner-type end users such as those working for extension services, consulting engineers, irrigation districts, governmental agencies, nongovernmental organizations, and various kinds of farmer associations for use in the development of irrigation schedules and management decisions. Economists and policy specialists can also use this model for planning and scenario analysis. In addition, research scientists should find the model valuable as a tool for analysis and conceptualization. Overall, *AquaCrop* allows proper investigation of strategic planning and management to improve the efficiency and productivity of water use in herbaceous crop production. It is not designed for use with trees and vines.

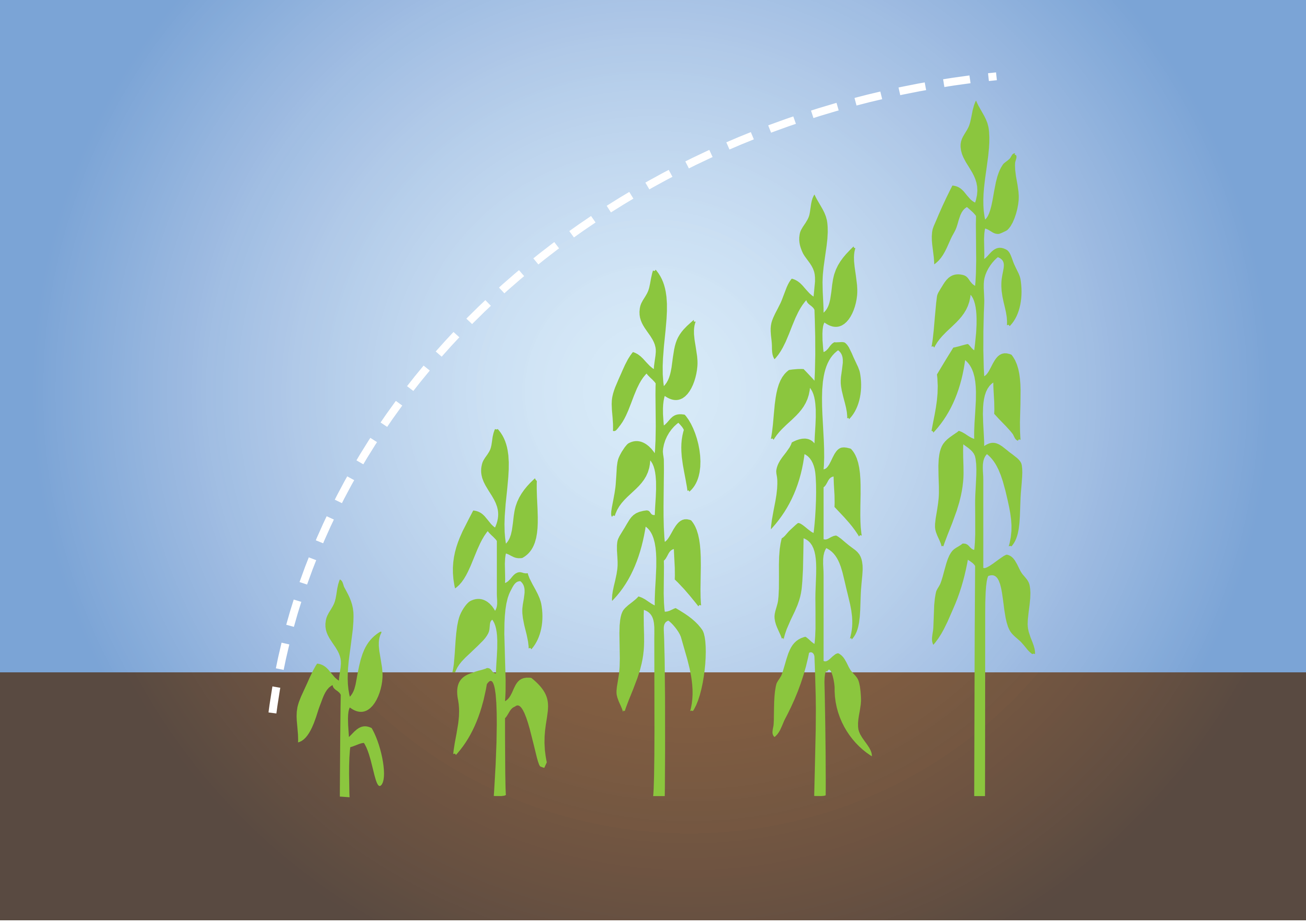
Chapter 3 not only describes *AquaCrop* but also provides samples of applications for specific purposes and guidelines for calibration.

Chapter 3 also provides the agronomic features of the sixteen crops for which the model has been calibrated and validated. The crops covered are: wheat, rice, maize, soybean, barley, sorghum, cotton, sunflower, sugarcane, potato, tomato, sugar beet, alfalfa, bambara groundnut, quinoa and tef. Additional crops will soon be calibrated and their agronomic features described. The goal is to provide an overview of each crop's physiology and agronomy for users interested in applying the model to a particular crop at a given location. Furthermore, the overview can serve as a reference when calibrating the model for different crop classes. The description of each crop includes crop growth and development, water use and productivity, responses to water deficits and expected yields.

Fruit production has risen in importance over the past decades for increasing the productivity and competitiveness of small-scale farmers around the world. Fruit not only provides better income opportunities for growers, but is also pivotal in providing more healthy diets to consumers. The yield response to water of fruit trees and vines forms the second major part of this *publication*, presented in Chapter 4. The complexity of tree crops resulting from carry-over effects from one year to the next and the large divergence among cultivars, however, precluded using a relatively simple modelling approach, as that used for herbaceous crops. Therefore, a *Guideline* is presented instead, which includes a *general section* on the irrigation of fruit trees and vines, and a special section covering physiological and agronomic features of each individual crop species. While the *general section* provides the technical background and guidelines for efficient irrigation management, the sections on individual crops give specific responses to water, with a common format, covering the following key items: growth and development, crop water requirements, yield response to water supply, and recommended strategies for deficit irrigation. The focus of Chapter 4, in fact, is to synthesize available data and to generate production functions to glean opportunities in many cases for reducing water supply without yield or net income penalties. Particular attention in this chapter is paid to safeguarding farmers' net income and, in some cases, to enhancing fruit quality. Crops covered in Chapter 4 include olive, citrus, apple, plum, almond, pear, peach, walnut, pistachio, apricot, avocado, sweet cherry, grapevine and kiwi. As more information becomes available, other fruit and plantation crops will be described and made available to users via the Internet.

Finally, Chapter 4 provides some closing remarks and the way forward from this FAO *I&D Paper* No. 66. A compact disc accompanies this publication, where the user will find most of the information products and guidelines relevant to her/his work.

This new publication will provide the practitioner with strengthened skills to: assess the effect of water shortages on crop production; investigate the impact of climate change on crop yield; compare the results of several water allocations plans; optimize irrigation scheduling (either full, deficit or supplementary); and enhance management strategies for increased water productivity and water savings.



Yield response to water: the original FAO water production function

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2. Yield response to water: the original FAO water production function

GENERAL DESCRIPTION

FAO addressed the relationship between crop yield and water use in the late seventies proposing a simple equation where relative yield reduction is related to the corresponding relative reduction in evapotranspiration (ET). Specifically, the yield response to ET is expressed as:

$$\left(1-\frac{Y_a}{Y_x}\right)=K_y\left(1-\frac{ET_a}{ET_x}\right) \quad (1)$$

where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual evapotranspiration, and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses. Equation 1 is a water production function and can be applied to all agricultural crops, i.e. herbaceous, trees and vines.

The yield response factor (K_y) captures the essence of the complex linkages between production and water use by a crop, where many biological, physical and chemical processes are involved. The relationship has shown a remarkable validity and allowed a workable procedure to quantify the effects of water deficits on yield.

This approach and the calculation procedures for estimating yield response to water were published in the *FAO Irrigation and Drainage Paper* No. 33 (Doorenbos and Kassam, 1979), which was considered one of FAO's milestone publications, and were used widely worldwide for a broad range of applications.

In this Chapter, the procedures used to quantify the yield response to water deficits using Equation 1 are briefly described. To get fully acquainted with the original procedures, the K_y use and related applications, the reader is referred to the original publication.

THE YIELD RESPONSE FACTOR (K_y)

The K_y values are crop specific and vary over the growing season according to growth stages with:

K_y >1: crop response is very sensitive to water deficit with proportional larger yield reductions when water use is reduced because of stress.

K_y <1: crop is more tolerant to water deficit, and recovers partially from stress, exhibiting less than proportional reductions in yield with reduced water use.

K_y =1: yield reduction is directly proportional to reduced water use.

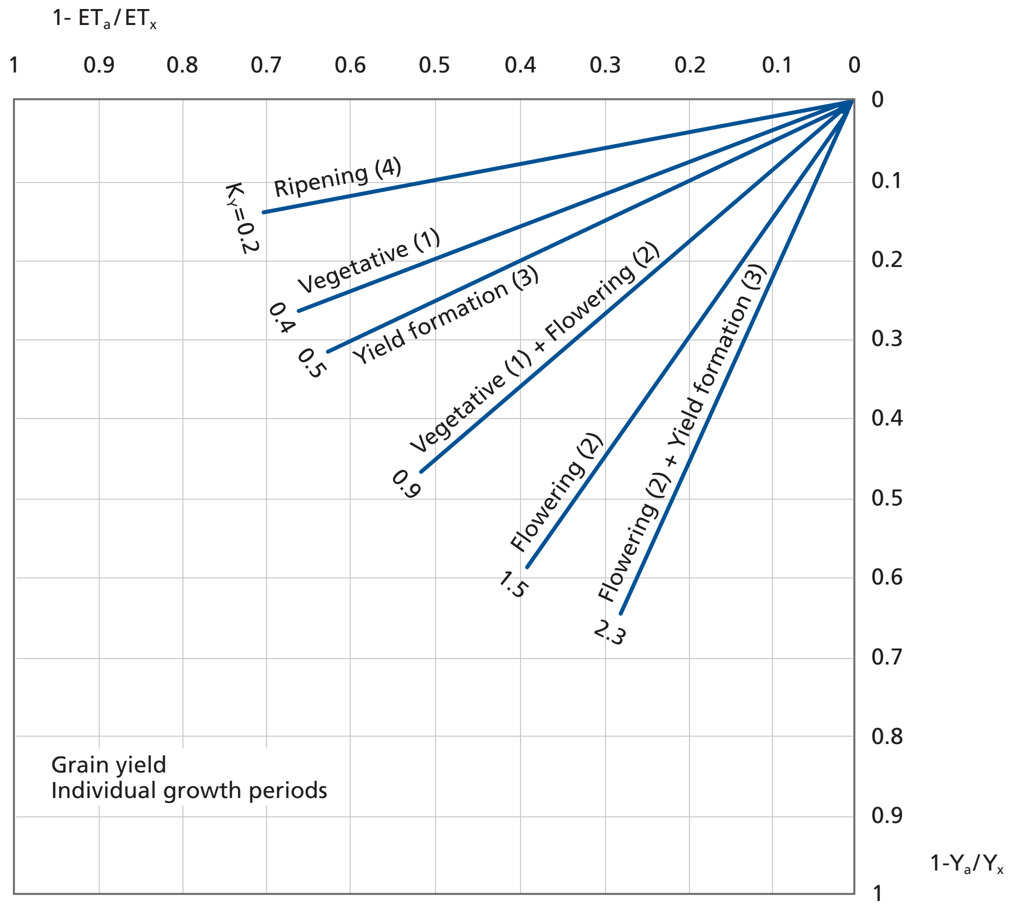
Based on the analysis of an extensive amount of the available literature on crop-yield and water relationships and deficit irrigation, K_y values were derived for several crops (Table 1).

TABLE 1 Seasonal K_y values from *FAO Irrigation and Drainage Paper No. 33*.

Crop	K_y	Crop	K_y
Alfalfa	1.1	Safflower	0.8
Banana	1.2-1.35	Sorghum	0.9
Beans	1.15	Soybean	0.85
Cabbage	0.95	Spring wheat	1.15
Cotton	0.85	Sugarbeet	1.0
Groundnuts	0.70	Sugarcane	1.2
Maize	1.25	Sunflower	0.95
Onion	1.1	Tomato	1.05
Peas	1,15	Watermelon	1.1
Pepper	1.1	Winter wheat	1.05
Potato	1.1		

The analysis of deficit irrigation studies also allowed, for a majority of crops, the development of crop response functions when water deficits occur at different crop stages. As illustrated for maize in Figure 1, yield response will differ largely depending on the stage the water stress occurs. Typically flowering and yield formation stages are sensitive to stress, while stress occurring during the ripening phases has a limited impact, as in the vegetative phase, provided the crop is able to recover from stress in subsequent stages.

FIGURE 1 Linear water production functions for maize subjected to water deficits occurring during the vegetative, flowering, yield formation and ripening periods. The steeper the slope (i.e. the higher the K_y value), the greater the reduction of yield for a given reduction in ET because of water deficits in the specific period.



CALCULATION PROCEDURES

The calculation procedure for Equation 1 to determine actual yield Y_a has four steps:

i. Estimate maximum yield (Y_x) of an adapted crop variety, as determined by its genetic makeup and climate, assuming agronomic factors (e.g. water, fertilizers, pest and diseases) are not limiting.
ii. Calculate maximum evapotranspiration (ET_x) according to established methodologies and considering that crop-water requirements are fully met.
iii. Determine actual crop evapotranspiration (ET_a) under the specific situation, as determined by the available water supply to the crop.
iv. Evaluate actual yield (Y_a) through the proper selection of the response factor (K_y) for the full growing season or over the different growing stages.

MAXIMUM YIELD (Y_x)

The *FAO I&D No. 33* recommended procedures for estimating maximum yield either from available local data for maximum crop yields or based on the calculation of maximum biomass and a corresponding harvest index, following two different procedures:

I. Wageningen procedure (De Wit, 1968; Slabbers, 1978)
II. Ecological zone approach (Kassam, 1977)

These procedures for yield estimation were developed in the late sixties and seventies. The considerable advances in agronomy and crop physiology, though, allow for the use of more precise methods to estimate maximum yields.

MAXIMUM CROP EVAPOTRANSPIRATION (ET_x)

Procedures for determining ET_x were based on FAO guidelines for crop-water requirements (ET_c), and the ET_x component of Equation 1, which is equal to ET_c, was determined through the product of the reference-crop evapotranspiration (ET_o) times the crop coefficient (K_c), i.e.

(2)
$$ET_x = K_c \, ET_o$$

Original procedures for determining ET_o are described in *FAO I&D No. 24* (Doorenbos and Pruitt, 1977), offering different equations for its calculation according to the available climate data. K_c values were provided for a large number of crops and procedures to determine ET_c over the growing season. Subsequently, revised procedures for calculating ET_o were introduced in *FAO I&D No. 56* (Allen et al., 1998), according to the FAO Penman-Monteith equation, which has now become the standard for estimating reference crop evapotranspiration.

ACTUAL CROP EVAPOTRANSPIRATION (ET_a)

It is very difficult to estimate the actual crop evapotranspiration with precision. *FAO I&D No. 33* provided tables from which ET_a could be estimated from data on evapotranspiration rate, available soil water and wetting intervals. The tables however proved cumbersome and later were replaced by more accurate ET_a calculations based on daily water balance calculations and digital computation methods.

Water balance calculations allow the level of available soil water in the root zone to be determined on a daily basis. As long as soil water is readily available for the crop, then $ET_a = ET_x$. When a critical soil moisture level is reached, defined as a fraction of the total available soil water content (p), transpiration is reduced because the stomata close and thus $ET_a < ET_x$, until the level of soil water in the root zone reaches the permanent wilting point, when ET_a is assumed to be zero. This critical soil-water content is estimated from soil, crop and rooting characteristics and from the ET_o rate. Depletion of soil-water content between p and the permanent wilting point will result in a proportional reduction of ET_a.

FAO I&D No. 56 provides detailed procedures to assess the impact of stress on reduced evapotranspiration based on the water balance calculations with parameters on critical soil-water content values and rooting depth.

ACTUAL CROP YIELD (Y_a) AND YIELD REDUCTION

Based on the estimated Y_x and the calculated ET_x and ET_a , actual yield (Y_a) may be determined using Equation (1).

However, in many planning and management studies requiring the estimation of yield in relation to the water availability, the yield reduction is expressed in relative terms, e.g. as a fraction or percentage $\left(1-\frac{Y_a}{Y_x}\right)$ rather than absolute (Y_a).

As a matter of fact, the errors in estimating actual yields with water production functions are quite important, given the empirical nature of the relationships and the uncertainty of estimating the parameters discussed above.

COMPUTERIZED CALCULATION PROCEDURES (CROPWAT)

The use of the water production functions, Equation (1), is facilitated using the CROPWAT model (Smith, 1992) that provides computation procedures to determine yield reductions based on the FAO *I&D* No. 33 approach using daily water balance calculations. CROPWAT has been widely used as a practical management tool for irrigation scheduling and to estimate yield reductions under water deficit condition. Standard values for crop parameters (K_c, p, rooting depth, etc.) and K_y values are included in the model and can be modified to adjust to local conditions.

CROPWAT includes various modules to calculate reference evapotranspiration from daily, decade or monthly climatic data, crop-water requirements and irrigation water requirements from climatic and crop data, as well as scheme water supply for varying cropping patterns. CROPWAT was designed as a practical tool to carry out standard calculations for design and management of irrigation schemes, and for improving irrigation practices. It may also be used for irrigation scheduling under full or deficit irrigation conditions and for this, it uses the yield response factors derived from the crop-water production functions synthesized in FAO *I&D* No. 33. In order to allow the calculation from a wide-range of countries a climatic database CLIMWAT (Smith, 1993) has been included in the CROPWAT software, based on agro-meteorological data compiled by the FAO agro-meteorological service with over 3 200 stations from 144 countries and spanning the years from 1961 to 1990.

LIMITATIONS AND APPLICATIONS OF FAO I&D NO. 33

Procedures for estimating yield response to water developed in FAO *I&D* No. 33 have been very popular among economists and engineers, and have been used in several practical applications at field, scheme, regional and national level. For many years, this water production function approach has been the standard for planning and was an input to many economic models dealing with water allocation. It is still useful when a quick, first approximation of yield reduction related to water limitations is needed, especially when both herbaceous crops, trees and vines have to be considered simultaneously. Recent examples of applications can be found at basin scale (e.g. Xiaojuan *et al.*, 2011), at field scale (e.g. Yacoubi *et al.*, 2010) and in decision support systems (e.g. Gastélum *et al.*, 2008).

While the *FAO I&D No. 3*3 approach is solidly based on crop-water use principles, the simplification introduced by using one empirical yield response factor (K_y) to integrate the complex linkages between production and water use for crop production, limits its applicability for making accurate estimates of yield responses to water. Moreover, factors other than water such as nutrients, different cultivars, etc. also affect the response to water. In fact, adjustments for site-specific conditions would be needed if greater accuracy is sought. Determination of K_y values after adaptive research has been carried out in numerous studies for various crops and under different environments. Results showed a wide range of variations of K_y values and suggest that the within-crop variation in K_y may be as large as that between crops (Stanhill *et al., 1985*).

As an example of the differences in K_y values from different studies, it is instructive to compare the results under a cooperative research programme carried out by the International Atomic Energy Agency (IAEA) against the original K_y values of the *FAO I&D No. 33*. Table 2 summarizes the comparison of K_y values as published in the *FAO Water Report No. 22*, *Deficit Irrigation*, 2002.

Despite the robustness of the production function approach, the differences in K_y values between the two publications are important, and no specific trend can be extracted from the deviations in the K_y values under different conditions. It can be concluded that application of the water production function approach has proved useful for general planning, design and operation of irrigation projects and for the rapid assessment of yield reductions under limited water supply. It has found applications from water supply allocation among crops during periods of water shortage to various studies at national or regional scales, where generalized crop conditions prevail.

For improved strategies and practices related to on-farm water management aiming to increasing efficiency and productivity of water use, Equation 1 is of limited use and more accurate predictions are required for yield response under actual field conditions. *AquaCrop* (Chapter 3), provides a valid alternative for herbaceous crops, as the incorporation of advanced knowledge of crop-water relationships allows a more accurate modelling of actual crop growth and yield formation processes under various soil water availability, climate and soil fertility conditions.

TABLE 2 Comparison of K_y values between *FAO Irrigation and Drainage Paper No. 33* and IAEA investigations (FAO, 2002) at different stages of crop development. Tr-0000=water deficit occurring during the whole season; Tr-0111=water deficit occurring during initial crop stage; Tr-1011=water deficit occurring during crop development; Tr-1101=water deficit occurring during midseason; Tr-1110=water deficit occurring during late season. Where different values of K_y are reported by IAEA for the same crop, they refer either to experimental results of different countries or to experimental results of different locations within the same country.

Crop	Tr-0000			Tr-0111			Tr-1011			Tr-1101			Tr-1110		
	FAO	IAEA	(%)	FAO	IAEA	(%)	FAO	IAEA	(%)	FAO	IAEA	(%)	FAO	IAEA	(%)
Beans	1.15	0.59	-49	0.20	0.38	90	1.10	1.75	59	0.75	1.44	92	0.20	0.06	-70
	1.15	1.43	24	0.20	0.56	180	1.10	1.35	23	0.75	0.87	16	0.20	0.17	-15
Cotton	0.85	1.02	20	0.20	0.75	275	0.50	0.48	-4				0.25		
	0.85	0.71	-16	0.20	0.80	300	0.50	0.60	20		0.05				
	0.85	0.99	16				0.50	0.76	52						
Groundnut	0.70			0.20			0.80	0.74	-8	0.60			0.20		
Maize	1.25	1.33	6	0.40			1.50			0.50			0.20		
Potato	1.10			0.60	0.40	-33		0.33		0.70	0.46	-34	0.20		
Soybean	0.85			0.20	0.56	180	0.80	1.13	41	1.00	1.76	76			
Sugarcane	1.20			0.75	0.20	-73		1.20		0.50	1.20	140	0.10		
	1.20			0.75	0.40	-47		1.20		0.50	1.20	140			
Sunflower	0.95	0.91	-4	0.40	1.19	198	1.00	0.94	-6	0.80	1.14	43			
Spring wheat	1.15	1.32	15	0.20	0.55	175	0.65	0.90	38	0.55	0.44	-20		0.25	
Winter wheat	1.00	0.87	-13	0.20	2.54	1170	0.60	0.81	35	0.50	0.48	-4		0.62	

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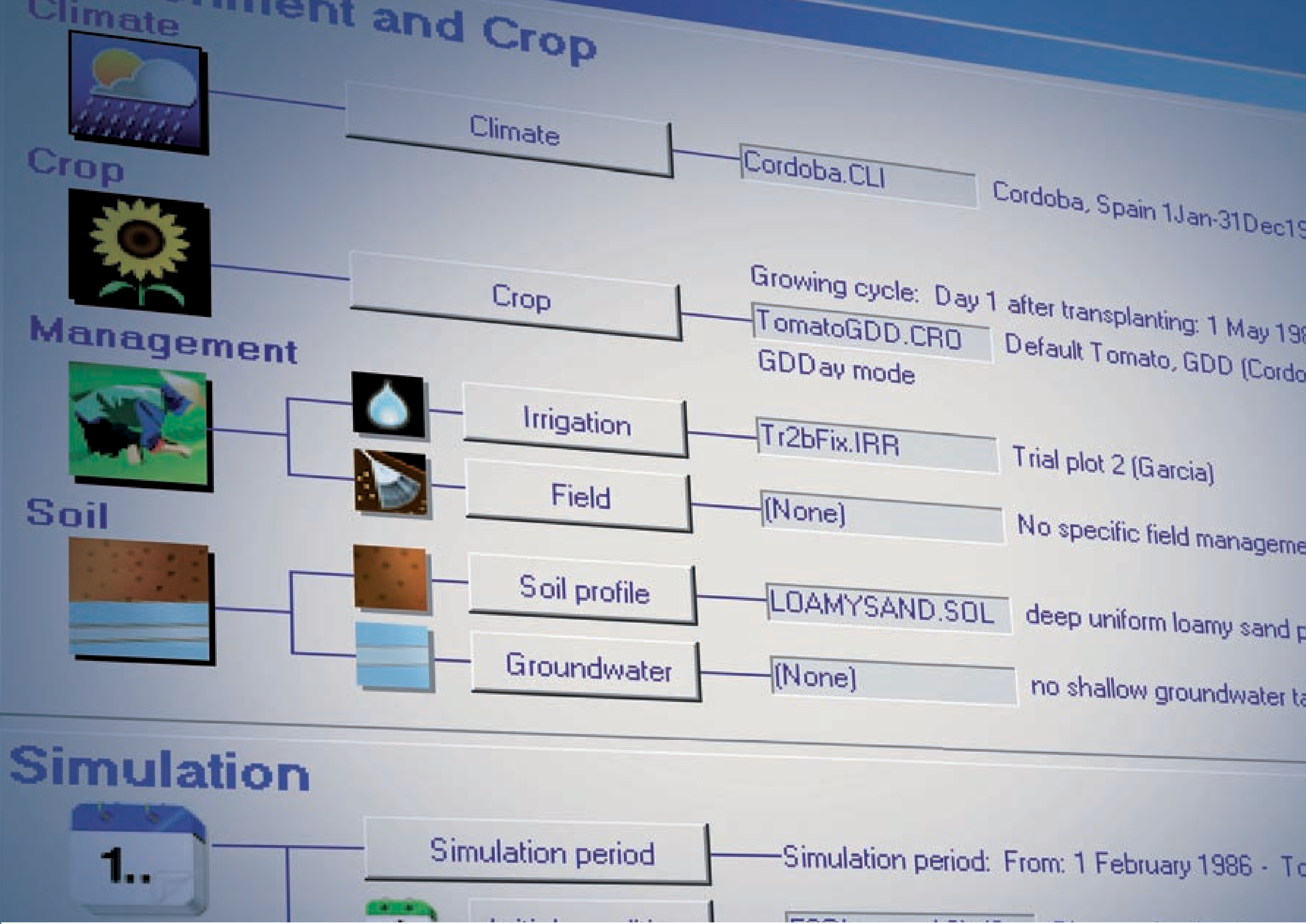

Yield response to water of herbaceous crops: the *AquaCrop* simulation model

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3. Yield response to water of herbaceous crops: the *AquaCrop* simulation model

This Chapter presents the main features of *AquaCrop*, the dynamic crop-growth model developed to predict yield response to water of herbaceous crops. The scientific basis of *AquaCrop* has been previously described (Steduto *et al.*, 2009; Raes *et al.*, 2009; Hsiao *et al.*, 2009) and only the basic concepts and fundamental calculation procedures are briefly explained here, along with additional descriptions related to the input requirements, the user interface and the model outputs. Sample applications are provided to illustrate the usefulness of *AquaCrop* for benchmarking, irrigation scheduling, and for studying the effect of various soils, crop management practices, and the impact of climate change, on crop yield and water productivity. Finally, guidelines for parameterizing, calibrating and validating *AquaCrop* are presented. For further insights on the operation of the model and on the full algorithms details, the reader is referred to the *AquaCrop Reference Manual* (Raes *et al.*, 2011).

3.1 *AquaCrop*: concepts, rationale and operation

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EVOLVING CONCEPTS IN YIELD RESPONSE TO WATER

Intercepted solar radiation is the driving force for both crop transpiration and photosynthesis. A direct relation exists therefore between biomass production and water consumed through transpiration. Water stress and reduced transpiration result in a reduced biomass production that normally also reduces yields. The yield response to water approach adopted in the FAO *Irrigation and Drainage Paper* No. 33 (Doorenbos and Kassam, 1979) linked a reduction in evapotranspiration to a proportional reduction in yield. As discussed in Chapter 2, the approach suffers drawbacks as a result of the aggregation of variables, i.e. final yield rather than its components and evapotranspiration rather than transpiration only. As a result, the yield response factor has proved, in several cases, to be significantly variable.

Maintaining the original concept of a direct link between crop water use and crop yield, the *AquaCrop* model evolved from the FAO *I&D Paper* No. 33 approach (Equation 1, Chapter 2) by separating non-productive soil evaporation (E) from productive crop transpiration (Tr) and estimating biomass production directly from actual crop transpiration through a water productivity parameter. The changes lead to the following equation, which is at the core of the *AquaCrop* growth engine:

(1)
$$B = WP \cdot \Sigma Tr$$

Where, B is the biomass produced cumulatively (kg per m^2), Tr is the crop transpiration (either mm or m^3 per unit surface), with the summation over the time period in which the biomass is produced, and WP is the water productivity parameter (either kg of biomass per m^2 and per mm, or kg of biomass per m^3 of water transpired).

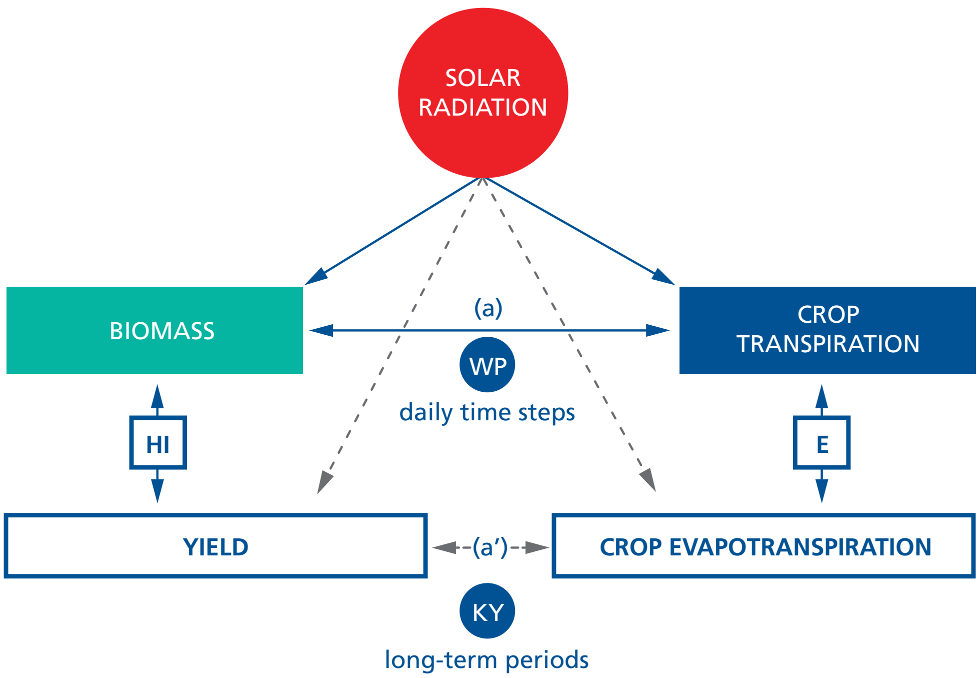
For most crops, only part of the biomass produced is partitioned to the harvested organs to give yield (Y), and the ratio of yield to biomass is known as harvest index (HI), hence:

(2)
$$Y = HI \cdot B$$

The underlying processes culminating in B and in HI are largely distinct from each other. Therefore, separation of Y into B and HI makes it possible to consider effects of environmental conditions and stresses on B and HI separately.

Understanding of crop-water-yield relationships has improved markedly since 1979 and made the step-up from Equation (1) of Chapter 2 to Equation (1) and (2) of this Chapter possible. WP, when normalized for evaporative demand, behaves conservatively (Steduto *et al*, 2007). That is, normalized WP (designated as WP*) remains virtually constant over a range of environments. This has fundamental implications for the robustness of the model, which is further enhanced by quantification of the harvest index day-by-day over the yield formation period. Improved knowledge of plant responses to water stress on short time scales (from second to hours), enhanced computation capacity, and more accurate procedures to determine daily soil water status made it possible to simulate in daily time steps. This allowed the important change from a static approach to a dynamic growth model. A schematic representation of the evolution of *AquaCrop* from Equation (1) of Chapter 2 to Equation (1) and (2) of this Chapter is shown in Figure 1.

FIGURE 1 Evolution of *AquaCrop* from Equation (1) of Chapter 2, based on the introduction of two intermediary steps: the separation of soil evaporation (E) from crop transpiration (Tr) and the attainment of yield (Y) from Biomass (B) and harvest index (HI). The relationship **(a')**, linking yield to crop evapotranspiration, is expressed through Equation (1) of Chapter 2 via the K_y parameter and normally applies to long-term periods. The relationship **(a)**, linking biomass to crop transpiration, is expressed through Equation (1) of this Chapter via the WP parameter and has a daily time step.



STRUCTURE AND COMPONENTS OF *AQUACROP*

AquaCrop is a dynamic model that simulates the attainable yield of herbaceous crops as a function of water consumption. In addition to its core functions, represented by equations (1) and (2), an extensive set of additional model components have been incorporated that includes:

- the **climate**, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration;
- the **crop**, with its development, growth and yield processes;

- the **soil**, with its water (and salt) balance;
- the **management,** with practices including irrigation, fertilization and mulching.

AquaCrop allows simulations of yield response to water under various management and environmental conditions, including climate change scenarios but, like most crop models, it does not account for the effects of pests and diseases.

These fundamental model components of *AquaCrop*, and their functions, are briefly described in this Section. For more detailed information, the user is referred to the *AquaCrop Reference Manual* (Raes *et al.*, 2011), which is regularly updated as the model develops.

The climate

The atmospheric environment is identified by four daily weather variables: maximum and minimum air temperatures (T_x and T_n, respectively), rainfall and the evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_o) to be calculated according to the FAO Penman-Monteith equation (Allen *et al.*, 1998). In addition, the annual mean carbon dioxide concentration (CO_2) of the atmosphere is required. Temperature influences crop development (phenology). Additional effects of more extreme temperatures are reduction of WP (hence biomass accumulation) when it is too cold, and reduction in pollination (hence HI) when it is either too cold or too hot. Rainfall, irrigation and ET_o are determinants of water balance of the soil root zone and water stress. Atmospheric CO_2 concentration affects WP, canopy expansion and stomatal conductance. T_x, T_n, ET_o and rainfall are derived from typical records of agrometeorological stations. Aside from its continuous rise over years, atmospheric CO_2 varies with an annual cycle and also with location. These variation are small and of minimal significance in terms of impact on crops. For simplicity, *AquaCrop* provides as default values the annual mean atmospheric CO_2 concentration from 1902 to the last year measured at Mauna Loa Observatory in Hawaii. Users may enter their own data set or the forecasted CO_2 following pre-determined climate change scenarios.

The crop

The crop component of the model includes the following subcomponents: phenology, canopy cover, rooting depth, crop transpiration, soil evaporation, biomass production, and harvestable yield.

After emergence, the crop grows and develops over its growth cycle by expanding its canopy and deepening its root system, transpiring water and cumulating biomass, while progressing through its phenological stages. The harvest index (HI) alters the portion of biomass that will be harvestable. It is important to note that in *AquaCrop*, beyond the partitioning of biomass into yield, there is no other partitioning among the various plant organs. This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the most difficult to model. The relationships between root and shoot (biomass) or canopy in *AquaCrop* are not direct. Instead, root deepening rate is slowed by an empirical function once the stress becomes severe enough to initiate partial stomatal closure.

Phenology

The stages of crop development and their duration are characteristics frequently differentiating cultivars of the same crop from each other, and needs to be specified by the user for the cultivar in question. *AquaCrop* uses the *growing degree days* (GDD) as the internal default clock to account for effects of temperature regimes on phenology. The simulation runs and displays, however, in daily (calendar) time step. GDD is calculated following procedures described by McMaster and Wilhelm (1997), but with the exception that the minimum temperature (T_n) is not changed to be equal to the base temperature when it drops below the base temperature in the calculation. This is believed to represent better the damaging or inhibitory effects of cold on plant processes.

AquaCrop is applicable to all major herbaceous crop types: fruit or grain crops; root and tuber or storage-stem crops; leafy or floral vegetable crops, and forage crops typically subjected to several cuttings per season. For all but forage crops, the key developmental stages are: emergence, start of flowering (anthesis) or root/tuber/storage-stem initiation, time when maximum rooting depth is reached, start of canopy senescence, and physiological maturity. For forage cops, the list may be shortened to only emergence or start of regrowth in spring, time of cuttings, and start of senescence.

Genetic differences among species require calibration of the model for each species. Although some crop cultivars may require some adjustment of parameters in the calibrated model, in addition to phenology, calibration and validation using data from different studies in different parts of the world have given confidence that most of the fundamental parameters considered to be conservative (virtually constant) will be applicable even to different cultivars. The calibrated parameters available should at least serve as solid starting values, and can be adjusted if good data sets, used to test the values, indicate clearly a need. In this regard, it must be pointed out that calibrations should be done with data obtained from crops grown without any mineral nutrient limitation, as deficiencies of major nutrients (N, P, and K) do alter, to some extent, a number of the conservative parameters in *AquaCrop*.

Canopy development

Canopy cover (CC), more precisely green canopy cover, is a crucial feature of *AquaCrop*. Its expansion, ageing, and senescence, along with its conductance as controlled by stomata, determine the amount of water transpired, which in turn determines the amount of biomass produced. Expressing amount of foliage in terms of canopy cover (in fraction or percentage) and not as leaf area index (LAI) is one of the distinctive features of *AquaCrop*. This results in a significant simplification of the simulation, allowing the user to enter actual values of CC, even if only estimated visually. Moreover, CC is easily obtained from remote-sensing sources, either to check the simulated CC or as input for *AquaCrop*.

For the first half of the CC increase or development curve, an exponential equation, analogous to the equation for relative growth rate, is used for the simulation. Specifically,

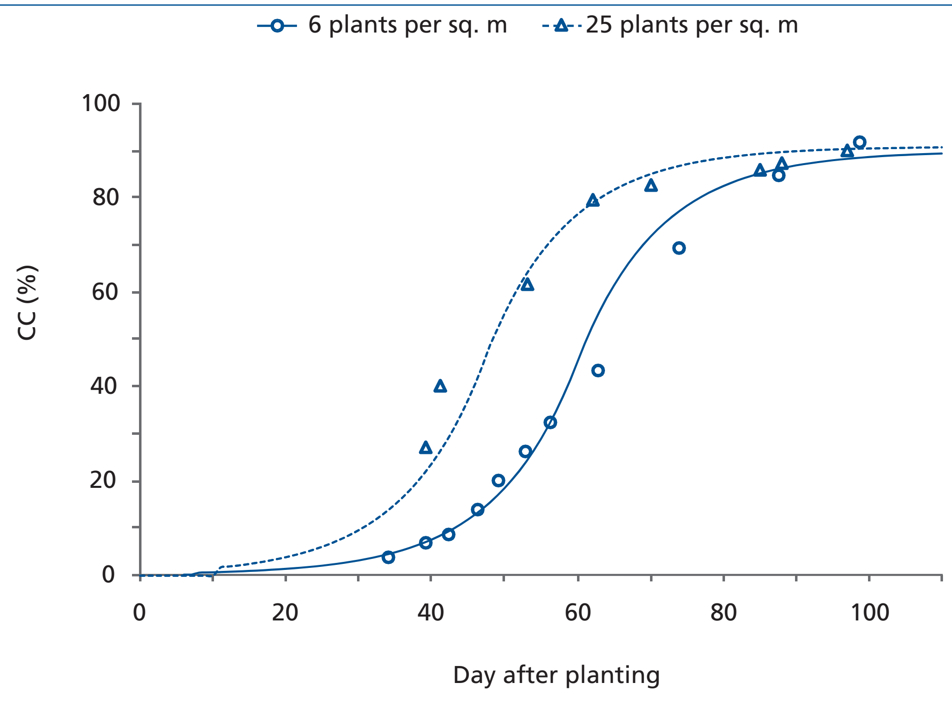
(3)

$$CC = CC_O \cdot e^{CGC \cdot t}$$

where CC is the fractional coverage of the soil by the canopy at time t, CC_o is initial CC (at t = 0) also in fraction, and CGC is canopy growth coefficient in fraction or percentage of existing CC at time t. CC_o is a composite of canopies of individual plants and is calculated by multiplying plant density by the mean canopy size per plant (cc_o). This feature is used by the model to account for effects of plant density on canopy size. For simulations starting at emergence, cc_o is defined as the canopy size for the average seedling at the time of 90 percent emergence. For a number of crop species the value of cc_o has been assessed and found to be conservative; only small adjustments may be required for specific cultivars. CGC is also conservative, as long as time is expressed as GDD. This was demonstrated for a number of crop species when the same CGC gave good prediction of canopy development over time for a number of cultivars at different locations around the world (e.g. Hsiao *et al.*, 2009; Heng *et al.*, 2009, for maize).

CC calculated with Equation (3) over the canopy development period is compared with measured values in Figure 2. Also shown is the difference in canopy development due to plant density. As noted earlier, the fact that CC_o is the product of cc_o and plant density provides a simply but fundamentally based procedure to account for variations in density.

FIGURE 2 An example of canopy development simulated with Equation 3 and 4 (lines) as compared with measured canopy data (symbols), for two different cotton plant densities. Dashed and solid lines represent 25 and 6 plants/m^2, respectively. Simulations were run with the same CGC and cc_o. The measured data were obtained from two different cultivars, one at low density and the other at high density, grown in different years at two different locations in California. Source: T.C. Hsiao and R. Radulovich, unpublished data.



The concept underlying Equation (3) (Bradford and Hsiao, 1982) is based on the reasoning that when green canopy cover is sparse, the growth of canopy, being dependent on the existing canopy size to capture radiation and carry out photosynthesis, should be proportional to the canopy size existing on that day. This led to the use of an exponential growth equation with a constant coefficient to simulate canopy development up to half of the maximum CC. When canopy grows further and covers more than half of the soil, radiation capture and photosynthesis begin to increase less than in proportion to the increase in CC because of mutual shading among the plants.

Therefore, Equation (3) no longer applies and for the second half of canopy development, CC follows an exponential decay equation,

$$CC = CC_x - (CC_x - CC_0) \cdot e^{-CGC \cdot t} \quad (4)$$

where CC_x is the maximum canopy cover for optimal conditions. *AquaCrop* simulates with Equation (3) up to the point when CC = 0.5 CC_x, then switches to simulate with Equation (4) until CC_x is reached. Default values for CC_x are provided for the calibrated crops, based on various studies. Since CC_x is determined also by plant density, a farm management option, the user should adjust the default CC_x to the actual field situation.

As the crop approaches maturity, CC enters a declining phase resulting from leaf senescence. The decline of green canopy cover in *AquaCrop* is characterized by an empirical canopy decline coefficient (CDC), with units of fractional reduction in CC per unit of time, and can be adjusted to either lengthen or shorten the time span required to go from the start of senescence to the time when no green canopy remains (CC = 0).

The starting time for canopy senescence is critical because it determines the duration of the canopy when it is most effective in photosynthesis. As senescence starts both transpiration and photosynthesis decline, and biomass accumulations slow. Canopy senescence should be considered to start at the time when leaf senescence (indicated by yellowing) becomes significant, but only when canopy cover of the soil is incomplete and LAI is no more than 3 to 4.

Calibration of senescence requires accurate field observation or measurement of LAI during the late phase near maturity, as there is no effective way to assess green canopy cover during this phase because of the interference by the yellow or dead leaves. LAI can be converted to CC using equations in the literature arrived at by regressing CC against LAI (see Section 3.3). The progression of CC over a full crop cycle under non-stress conditions, as simulated with Equation (3) and (4) and CDC, and as measured on a crop, is depicted in Figure 3.

Root deepening

Root water uptake in *AquaCrop* is simulated by defining effective rooting depth (Z_e) and the water extraction pattern. Z_e at planting to near emergence is the soil depth from which the germinating seed or the young seedling can extract water. For water balance calculation by *AquaCrop*, a minimum effective rooting depth of 0.2 to 0.3 m (Z_n) at the beginning is generally considered appropriate. Studies show that under favourable conditions, roots deepen at a relatively constant rate up to the time when fruit/grain begin to accumulate the major portion of photosynthetic assimilates. At this time root deepening is likely to slow. *AquaCrop* simulates this with an exponential function that makes the deepening of the root zone faster after planting in an early stage than later in the life-cycle of the crop (Figure 4).

Under optimal conditions, with no soil restrictions, the maximum effective rooting depth (Z_x) is expected to be reached near the end of the crop's life cycle, around the beginning of canopy senescence. If, at a certain depth, a soil layer is restricting root growth, roots will deepen at the normal rate until the restrictive layer is reached and then stops completely (Figure 4). Also a shallow groundwater table will limit rooting to the depth of the water table.

FIGURE 3 An example of the progress of green canopy cover through a crop life-cycle under non-stress conditions, for maize.

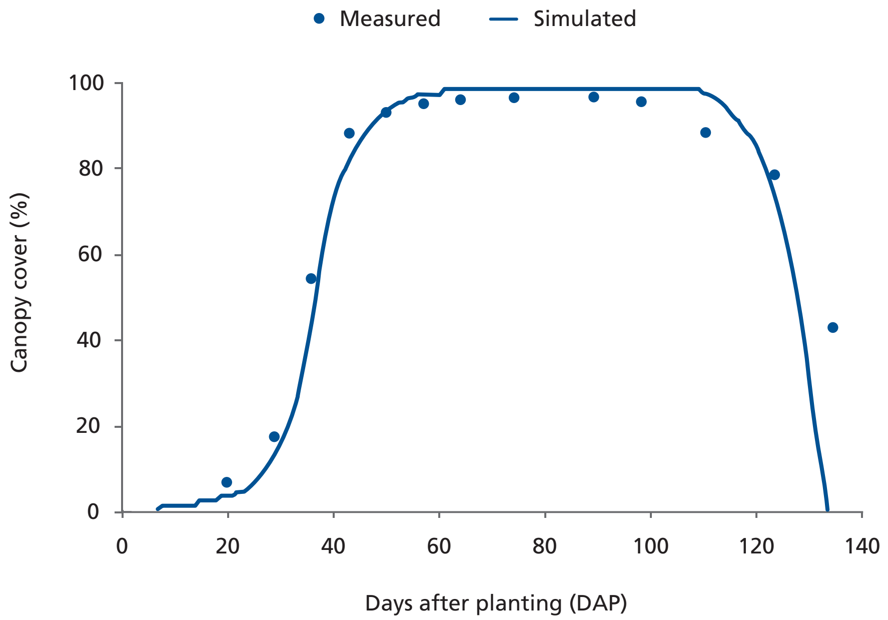
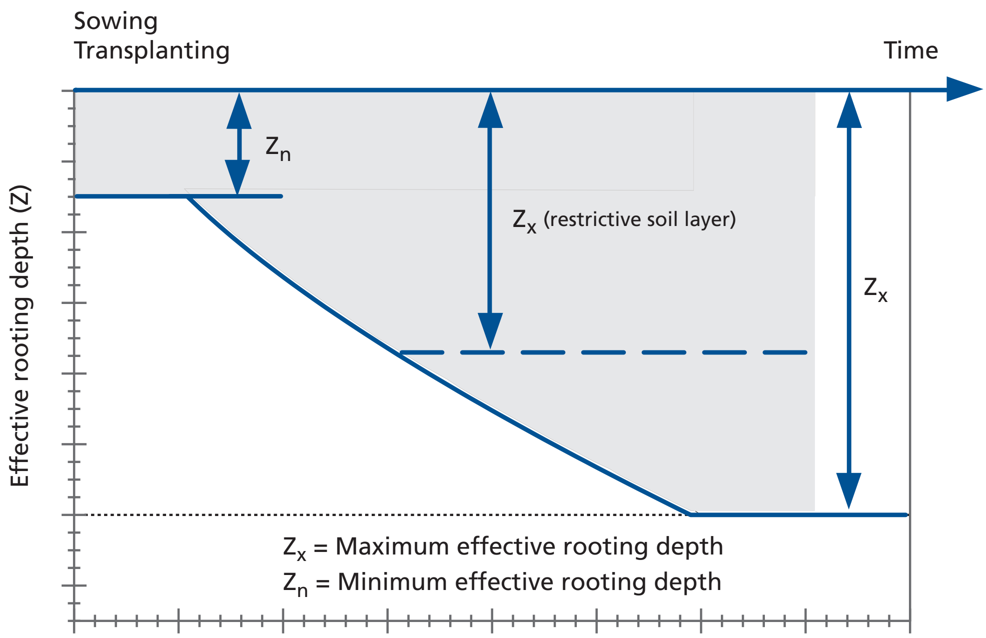


FIGURE 4 Schematic representation of a generalized rooting depth with time, in the presence (dashed line) and absence (full line) of a restrictive soil layer limiting root development.



Water extraction by roots follows the common pattern used in simulations. Namely, 40 percent, 30 percent, 20 percent, and 10 percent of the required water is taken from the upper to the lower quarter of Z_e, when water content is adequate. The pattern can be changed by the user, in cases warranted by specific physical or chemical characteristics of the soil.

Crop transpiration

Transpiration per unit land area is dependent on the fraction of land area covered by the canopy (CC) when there is insufficient stress to limit stomatal opening. The dependence is not strictly linear, because inter-row micro-advection supplies energy to the canopy in addition to that supplied by radiation, causing Tr to be somewhat more than being proportional to CC when CC is substantially incomplete. *AquaCrop* adjusts for this by assuming a slightly larger effective canopy cover with an empirical equation, developed from literature data. Tr is calculated from ET_o with crop transpiration coefficient, denoted by $K_{c,Trx}$, defined as the crop coefficient (K_c) for transpiration when the canopy fully covers the ground (CC is close to and approaching 1.0) and stresses are absent. The effective CC is then multiplied by $K_{c,Trx}$ and ET_o to arrive at Tr. Restriction of Tr by water stress is elaborated on later in this section.

After maximum canopy cover (CC_x) is reached and before the onset of senescence, the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity. This is simulated by applying an ageing coefficient (f_{age}) that decreases $K_{c,Trx}$ by a constant and slight fraction (e.g. 0.3 percent) per day. After senescence is triggered, transpiration and photosynthetic capacity of the canopy drop more markedly with time.

Soil evaporation

Evaporation is mostly from the wetted soil surface unshaded by the canopy. *AquaCrop* calculates soil evaporation (E) separately from Tr, and for simplicity assumes that E takes place only from unshaded soil and is slightly less than being proportional to (1-CC) as the results of the adjustment for inter-row advection. The other key factor determining E is the wetness of the soil surface layer. When the soil surface is fully wet, E proceeds at the potential rate determined by the energy supply, and is about 10 percent more than the rate of ET_o. This phase is known as Stage I evaporation and lasts from less than to a little more than 1 day, and can be adjusted in the model. As the soil surface begins to dry and water vapour pressure at the surface drops, E declines exponentially with the decline of the soil water in the top soil (a very thin surface layer). This phase is known as Stage II evaporation. *AquaCrop* simulate this by multiplying the potential E rate with an exponentially declining coefficient.

As the canopy senesces, it still shades the soil, but not as effectively, because canopy structure begins to disintegrate and dead leaves may be lost. The model continues to base soil E on CC_x, but applies a simple factor to reduce the sheltering effect of the dying canopy.

Biomass production

The biomass water productivity (WP) is central to the operation of *AquaCrop* (Equation 1) and has shown a remarkable conservative behaviour (remaining nearly constant) when normalized for different evaporative demands. This has been demonstrated already in early studies of, among others, de Wit (1958) and was further advanced in studies by Tanner and Sinclair (1983), Hsiao and Bradford (1983) and Steduto *et al.* (2007).

The WP parameter introduced in *AquaCrop* is normalized for atmospheric evaporative demand, defined by ET_o, and for the CO_2 concentration of the atmosphere. The normalized biomass water productivity (WP*) proved to be nearly constant for a given crop when mineral nutrients are not limiting, regardless of water stress except for extremely severe cases. Calibration of WP and normalization for evaporative demands has been based on the equation:

$$WP^* = \left[\frac{B}{\sum \left(\frac{Tr}{ET_O} \right)} \right]_{[CO_2]} \qquad (5)$$

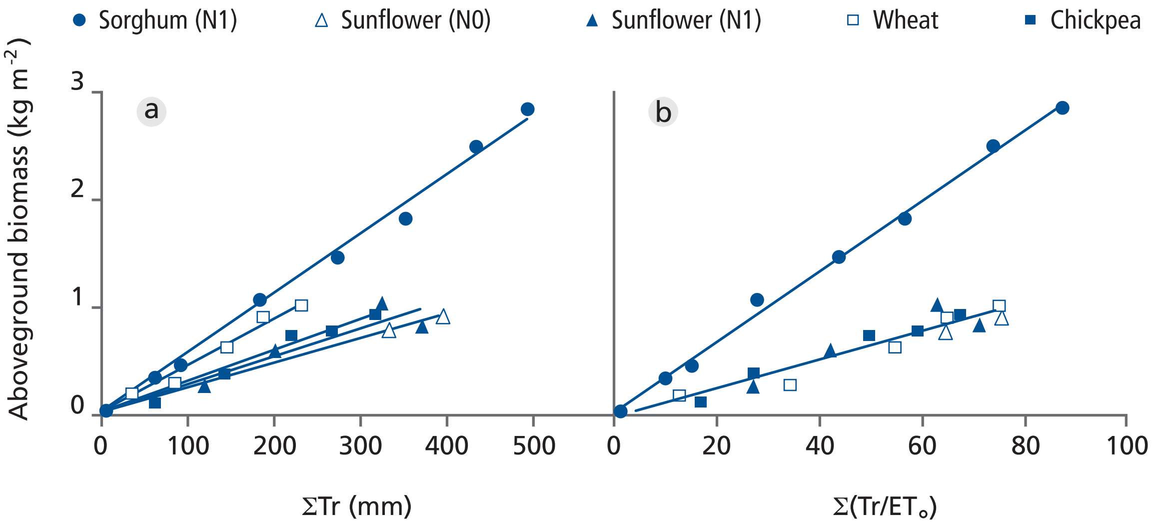
The summation is taken over the time intervals spanning the period when B is produced. $[CO_2]$ outside the bracket indicates that the normalized value is for a particular air CO_2 concentration. For most crop species, WP* increases as air CO_2 concentration increases, allowing the simulation of impact on yield under various CO_2 and climate change scenarios. The equation is directly applicable when Tr and ET_o data are for daily time intervals. When Tr and ET_o are available for time interval larger than daily, the normalization requires caution. Background information and more details on normalization, including that for CO_2 concentration, are given in Steduto *et al.* (2007).

In the literature WP is commonly normalized for evaporative demand using air vapour pressure deficit (VPD) instead of ET_o. The choice of using ET_o was made because it has been demonstrated to be superior and accounts for advective energy transfer, which is ignored using VPD (Steduto *et al.*, 2007). WP* is conservative for a given level of mineral nutrition, but may be reduced by nutrient deficiencies, particularly nitrogen. The calibrated WP* in the model for various crops are for situations where nutrients are ample. For nutrient limited situations, the model provides categories of soil fertility stress ranging from mild to severe nutrient deficiencies, with corresponding lower default WP* values.

The conservative nature of WP* is demonstrated in Figure 5, where cumulative B vs. cumulative Tr are plotted in (a), and cumulative B vs. cumulative normalized Tr (Tr/ET_o) in (b), over the season for sweet sorghum (a C_4 crop), sunflower, wheat and chickpea (all three are C_3). It is seen in Figure 5a that the regression lines for different crops are linear but with different slopes. This means WP is constant for each crop but differs among the crops. In Figure 5b it is seen that normalization by ET_o has coalesced the lines for the three C_3 crops into one, meaning their WP* are very similar. In this study sunflower was grown in May-August, wheat in February-May, and chickpea in April-June. So growth of these crops occurred in periods differing in atmospheric evaporative demand. Normalizing by ET_o accounted for the difference in evaporative demand and showed that the three crops have very similar intrinsic water productivity (very similar WP*).

The single value of WP*, as show in Figure 5b, is used for the entire crop cycle for most of the crops. However, for crops with yields high in fat and protein content, more photosynthetic assimilates or energy is required per unit of dry matter produced after flowering and during the grain/fruit filling stage. For such crops, *AquaCrop* uses a single value for the WP* up to flowering, then declining gradually towards a lower WP* value to account for yield composition.

FIGURE 5 Relationship (a) between aboveground biomass and cumulative transpiration (ΣTr) and (b) between aboveground biomass and cumulative normalized transpiration [Σ(Tr/ET$_o$)], during the cropcycle of sunflower (under two N levels and up to anthesis), sorghum, wheat, and chickpea (redrawn from Steduto and Albrizio, 2005).



Harvestable yield

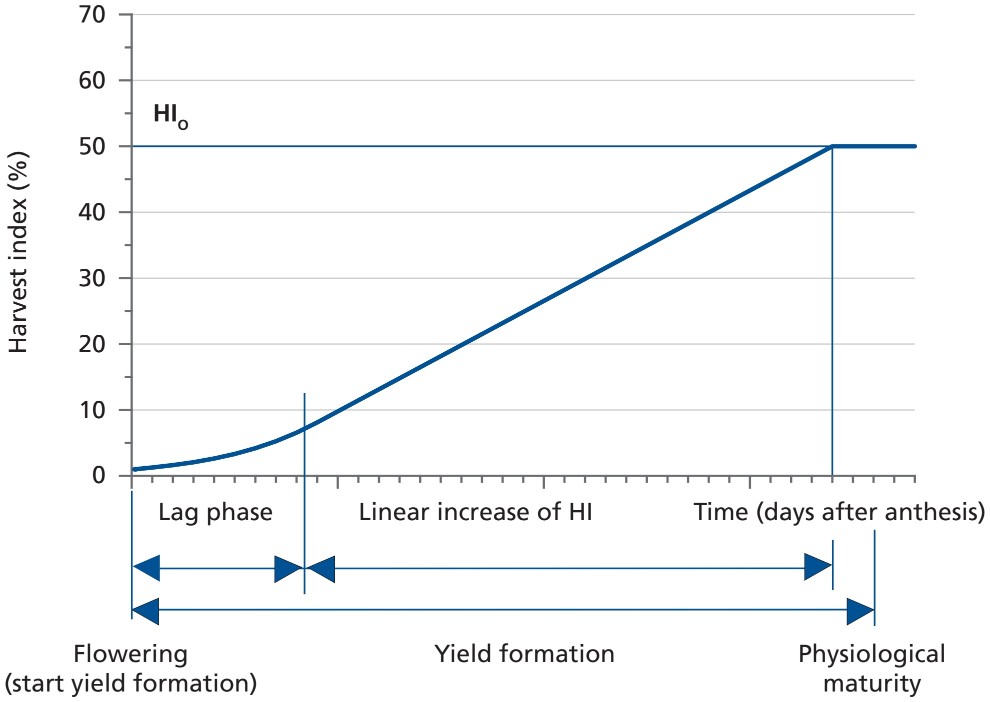
The partition of biomass into yield part (Y) is simulated by means of a harvest index (HI). For fruit or grain crops, published data on different species indicate there is a linear increase with time in the ratio of fruit or grain biomass to total above-ground biomass, from the time not too long after pollination and fruit set until maturity or near maturity. In common usage, HI is this ratio at maturity or harvest time. In *AquaCrop*, this ratio at earlier stages is also referred to as HI, for simplicity. For fruit/grain crops, HI is set to increase from zero at flowering, first over a short lag phase, when the increase starts slowly but accelerates with time, followed by a steady phase with the highest, but at constant rate of, increase (Figure 6). For root/tuber crops, HI is the ratio of the storage organ biomass to the total biomass (root plus shoot). The limited published data on root/tuber crops indicate that instead of increasing linearly after a lag phase, HI increases quickly shortly after storage organ initiation, then gradually slows until maturity. So HI is described by a logistic curve for these crops.

A reference point is needed for the upper range of HI. This point, termed reference HI (HI$_o$), is the HI representative of well-developed cultivars adapted to their environments and grown under optimal conditions without limiting inputs. Calibrated HI$_o$ can be changed based on good data for a particular cultivar. The progression of HI for fruit/grain crops is exemplified in Figure 6.

The soil

In *AquaCrop* the soil is described by a soil profile and the characteristics of the groundwater table (if any). In *AquaCrop* the soil can be subdivided vertically up to five layers of variable depth, each layer (or horizon) accommodating different soil physical characteristics: the soil-water content at saturation; the upper limit of water content under gravity (commonly referred as field capacity (FC) for easy of reference); the lower limit of water content where a crop can reach the permanent wilting point (PWP); and the hydraulic conductivity at saturation (K$_{sat}$). From these characteristics *AquaCrop* derives other parameters governing soil evaporation,

FIGURE 6 Building up of harvest index from flowering until physiological maturity for fruit and grain producing crops with indication of the reference harvest index (HI_o).



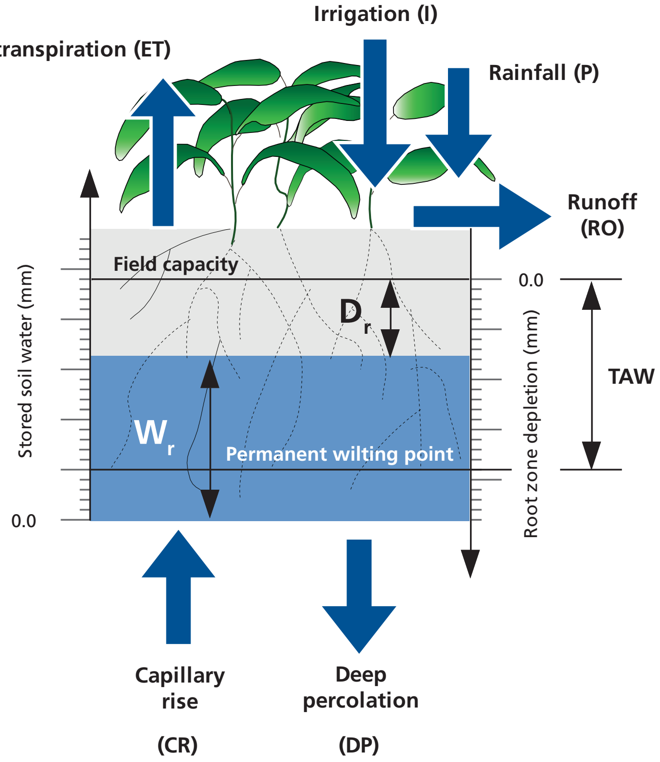
internal drainage and deep percolation, surface runoff, and capillary rise. The considered characteristics of the groundwater table are its depth below the soil surface and its salinity. The characteristics can remain constant during the season or vary throughout the simulation period.

By keeping track of the incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evapotranspiration and deep percolation) water and salt fluxes at the boundaries of the root zone, the amount of water and salt retained in the root zone can be calculated at any moment of the season (Figure 7).

When calculating the soil-water balance, the amount of water stored in the root zone can be expressed as an equivalent water depth (Wr) or as root zone depletion (D_r). The total available soil water (TAW) is the amount of water held in the root zone between field capacity and permanent wilting point. At field capacity root zone depletion (D_r) is zero, and at permanent wilting point Dr is equal to TAW.

To accurately describe surface runoff, the retention and movement of water and salt in the soil profile, soil evaporation and crop transpiration throughout the simulation period, *AquaCrop* divides both the soil profile and time into small fractions. *AquaCrop* divides the soil profile into 12 soil compartments with thickness Δz and runs with a time step Δt of 1 day. As such the one-dimensional vertical water and salt flow and root water uptake can be solved by means of a finite difference technique. Each of the 12 soil compartment has the hydraulic characteristics of the soil layer to which it belongs (Figure 8). The default size of the compartments (0.10 m) is automatically adjusted to cover the entire root zone. For deep root zones, ΔZ is not constant

FIGURE 7 The root zone depicted as a reservoir with indication of the equivalent water depth (Wr) and root zone depletion (D_r).

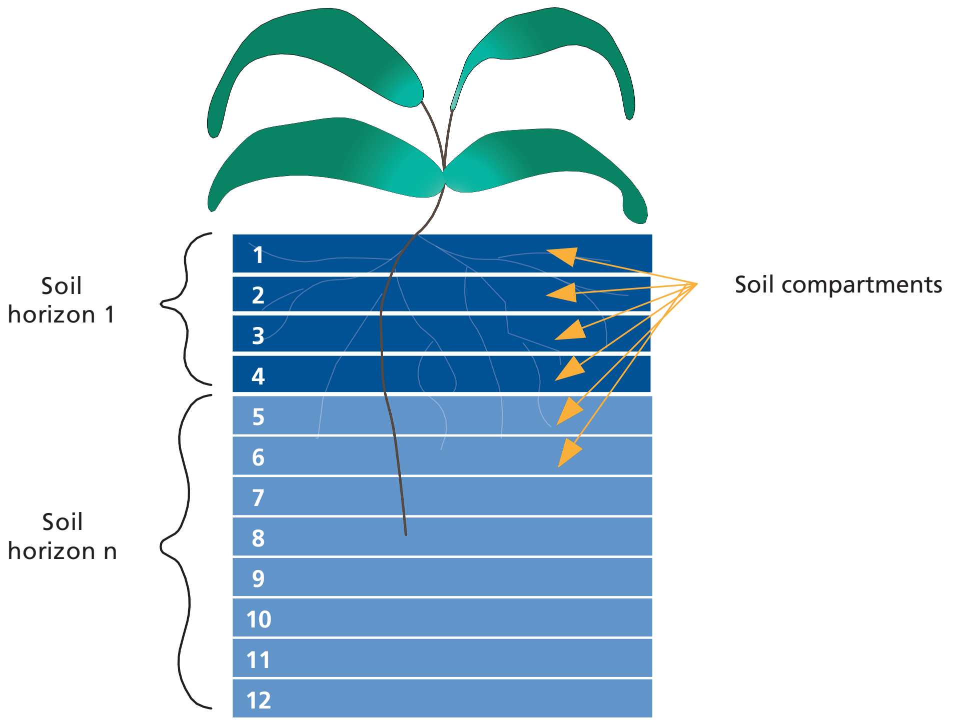


but increases exponentially with depth, so that infiltration, evaporation and transpiration from the top soil layers can be described with sufficient detail.

To simulate water movement in and out of the soil profile, *AquaCrop* considers surface runoff, infiltration, capillary rise, soil evaporation and crop transpiration. To simulate the redistribution of water into a soil layer, the drainage out of a soil profile, and the infiltration of rainfall and/or irrigation, *AquaCrop* makes use of an exponential drainage function that describes the declining water movement between saturation and field capacity. Upward water movement from a groundwater table to the soil profile is described by an exponential relationship between the capacity for capillary rise and the height above the groundwater table. The amount of water that moves upward depends not only on the depth of the groundwater table but also on the wetness of the top soil and the hydraulic characteristics of the soil layers. By considering the water fluxes in response to the processes listed above, the soil-water content is updated at the end of the daily time step in each of the 12 compartments (for full details see Raes *et al.*, 2011).

While performing the water balance, *AquaCrop* also deploys the salt balance. Salts enter the soil profile by capillary rise from a saline groundwater table or together with the irrigation water. Salts are leached out of the soil profile by excessive rainfall or irrigation. Vertical salt movement in a soil profile is described by assuming that salts are transferred downwards by soil-water flow in macro pores as simulated by the drainage function. Since the solute transport in the macro pores bypass the soil water in the matrix, a diffusion process is considered to describe the transfer of solutes from macro pores to the soil matrix. Therefore the soil

FIGURE 8 A soil profile with more than one soil horizon and 12 soil compartments. The total number of compartments remains always 12, regardless of the number of horizon (varying from 1 to 5).



compartments are divided into a number of cells where salts can be figuratively stored. A cell is a representation of a bundle of pores with a specific diameter. The driving force for the horizontal diffusion is the salt concentration gradient that exists between the water solution in the cells at a particular soil depth. To avoid the building up of high salt concentrations at a particular depth, vertical salt diffusion is also taken into account. The driving force for this vertical redistribution process is the salt concentration gradient that builds up at various soil depths in the soil matrix.

The management

AquaCrop encompasses two categories of **management** practices: the **irrigation management**, which is quite complete in its various features, and the **field management**, which is limited to selected aspects and is relatively simple in approaches.

Irrigation management

Here options are provided to assess and analyse crop production and water management and use, under either rainfed or irrigated conditions. Management options include the selection of water application methods (sprinkler, surface, or drip either surface or underground), defining the schedule by specifying the time, depth and quality of the irrigation water of each application, or let the model automatically generate the schedule based on fixed time interval, fixed depth per application, or fixed percentage of allowable water depletion. An additional feature is the estimation of full water requirement of a crop in a given climate.

Field management
Three aspects are considered here: (i) fertility of the soil for growing the crop, whether native or by fertilization; (ii) mulching of the soil to reduce soil evaporation; and (iii) use of soil bunds (small dykes) to pond water or control surface runoff and enhance infiltration.

Effects of fertility on crop growth and productivity are not directly simulated. Instead, *AquaCrop* provides default adjustments of the pivotal crop parameters for several limiting fertility categories, ranging from near optimal to poor. The adjustments are multipliers, used to reduce: (1) CGC; (2) CC_x; (3) CC, from the time when CC_x is reached to maturity, but only gradually; and (4) WP*. These adjustments are based on the pattern of canopy evolution, photosynthesis, and WP at different fertility levels reported in several studies (e.g. Wolfe *et al.*, 1988). To make the adjustments more reliable, biomass production data and observed canopy development, obtained at different fertility levels, should be used to do a local calibration, as provided for in *AquaCrop*.

Mulching is considered only for its effect on reducing soil E, and is to be specified by the user in terms of the percentage of soil surface covered and effectiveness of the mulching material.

The last management aspect concerns soil bunds and runoff. A bund and its height can be specified to prevent runoff and force all water from rain or irrigation to infiltrate the soil. Equally important, bunds allow the simulation of crops under ponding water such as paddy rice. For soils that are especially permeable, it is also possible to choose 'no runoff' without building bunds.

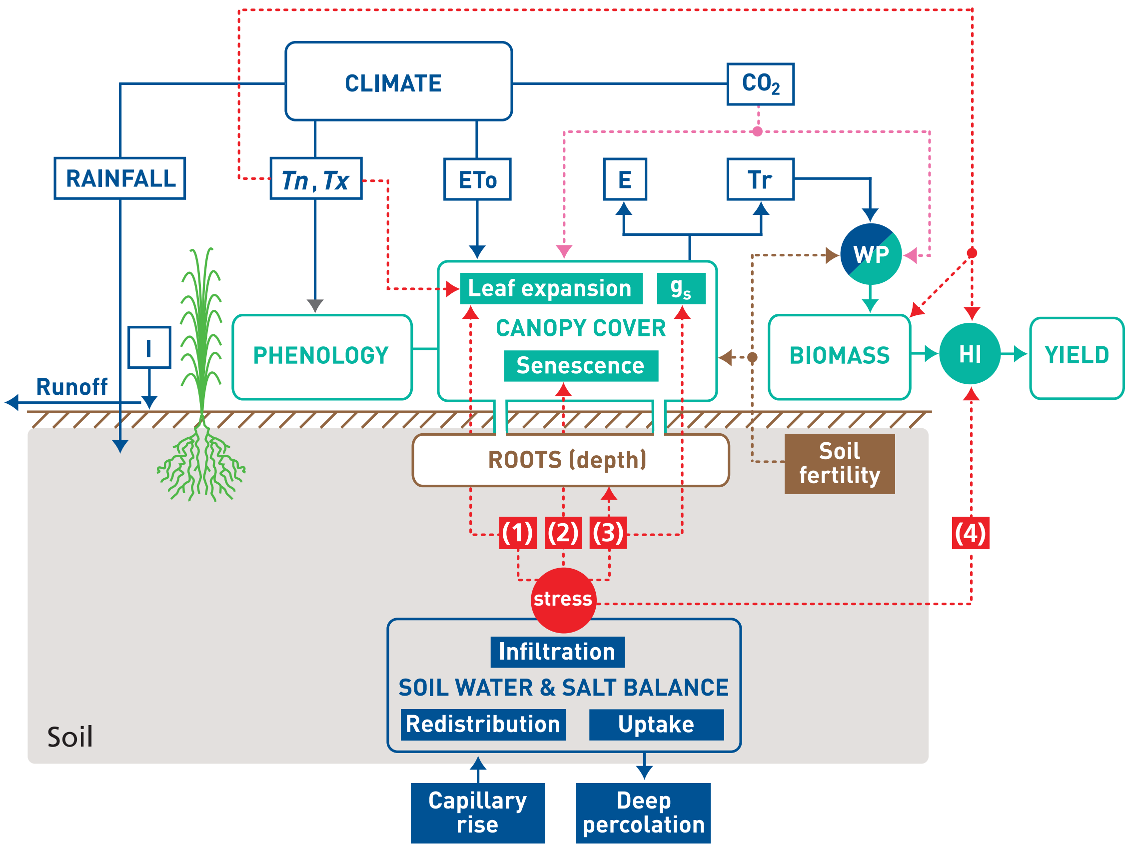
THE DYNAMICS OF CROP RESPONSES TO STRESSES IN *AquaCrop*

Environmental abiotic stresses such as water and temperature can have major negative impacts on canopy development, biomass production and yield, depending on timing of occurrence, severity and duration. In addition, stress from soil salinity or low soil fertility may have similar negative impacts, but be less dynamic in terms of speed of response and recovery. *AquaCrop* is designed to simulate crop responses first to water, but with sufficient attention also to temperature. *AquaCrop* takes an indirect approach to the deficiencies of mineral nutrients or the presence of salts in the root zone, avoiding attempts to simulate nutrient balances and their complex cycles that would make the model too complex. This indirect approach is outlined in the *Fertility and Salinity stress* section below.

The structural components of *AquaCrop*, including stress responses, and the functional linkages among them, are shown schematically in the diagram of Figure 9, to serve as a framework for the following discussion.

Stress response functions
Any type of stress is described in *AquaCrop* by means of a stress coefficient (Ks) which is an indicator of the relative intensity of the effect on a specific growth process and growth stage. In essence, Ks is a modifier of its target model parameter, and varies in value from one (no stress) to zero (full stress).

FIGURE 9 Chart of *AquaCrop* showing the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield. Continuous lines indicate direct links between variables and processes. Dotted lines indicate feedbacks. Symbols are: I, irrigation; T_n, minimum air temperature; T_x, maximum air temperature; ET_o, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; g_s, stomatal conductance; WP, water productivity; HI, harvest index; CO_2, atmospheric carbon dioxide concentration; (1), (2), (3), (4), water stress response functions for leaf expansion, senescence, stomatal conductance and harvest index, respectively. Modified from Steduto *et al.* (2009).



Above the upper threshold of a stress indicator, the stress is non-existent and Ks is 1. Below the lower threshold, the effect is maximum and Ks is 0 (Figure 10). For water stresses, the thresholds are soil water depletions (D_r) from the root zone. The upper threshold refers to the soil water that can be depleted before the stress starts to affect the process, while the lower threshold is the root zone depletion at which the stress inhibits the process completely. Indicators for air temperature stress are growing degrees, minimum air temperatures (cold stress) or maximum air temperatures (heat stress), while the electrical conductivity of the soil water in the root zone (ECe) determines salinity stress. When running a simulation, the degree of soil fertility selected as the Field management practice is the indicator for soil fertility stress. It varies from 0 percent, when soil fertility is non-limiting (Ks = 1), to a theoretical 100 percent when soil fertility stress is so severe that crop production is no longer possible (Ks = 0).

The relative stress level and the shape of the Ks curve determines the magnitude of the effect of the stress on the process between the thresholds. The relative stress is 0.0 at the upper threshold and 1.0 at the lower threshold (Figure 10). The shape of most of the Ks curves are typically convex, and the degree of curvature is set during model calibration.

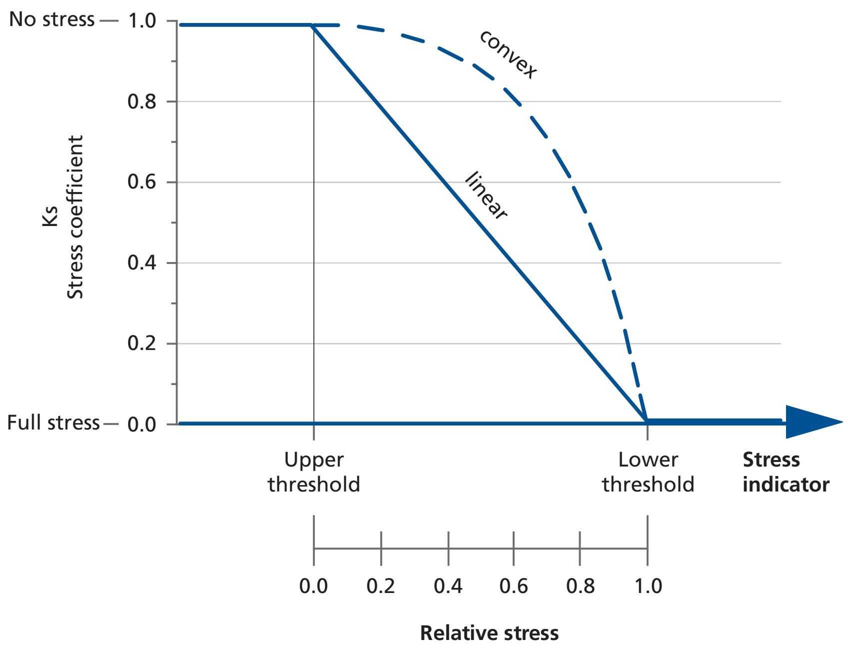
Water stress

AquaCrop distinguishes stresses related to *deficit* and to *excess* water. In this publication, water stress routinely refers to the stress caused by a lack of water, and stress caused by excessive water is referred to as aeration stress. Water stress effects on productivity and water use processes are simulated by impacting: (1) canopy growth; (2) stomata conductance; (3) canopy senescence; (4) root deepening, and (5) harvest index. The normalized water productivity is assumed to be not impacted, based on extensive evaluation of the literature. The discourse that follows discusses the first three impacted processes together, and includes root depending at the end. Harvest index, a complex subject, is covered on its own in the last section on water stress.

Water stress response functions

For water stresses, the stress indicator is the root zone depletion (D_r), and the thresholds are soil water depletions from the root zone expressed as fractions (p) of the total available soil water (TAW). At the point when there is no depletion Ks = 1.0. As depletion progresses Ks does not drop below 1.0 until the upper threshold for stress effect is reached. This threshold is referred to as p_{upper}. Further increase in root zone depletion, brings about lower values of Ks, until the lower threshold (designated as p_{lower}) is reached, where Ks becomes zero and the stress effect is maximum (Figure 11). Further depletion below p_{lower} has no additional effect and Ks remains zero. For water stresses the shape of the curve can vary between very convex to mildly convex to linear. Conceptually, the more convex the curve, the higher is the crop's capacity to adjust and acclimate to the stress. A linear relationship indicates minimal or no

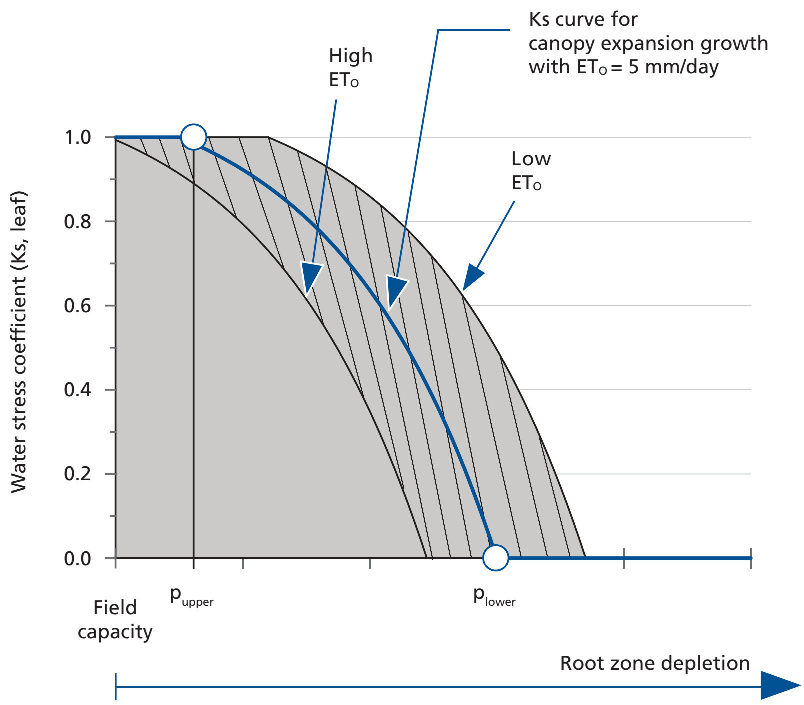
FIGURE 10 The stress coefficient (Ks) for various degrees of stress and for 2 sample shapes of the Ks curve.



acclimation. The stress thresholds, as well as the curve shape, are set by calibration and should be based on knowledge of the crop's drought resistance or tolerance.

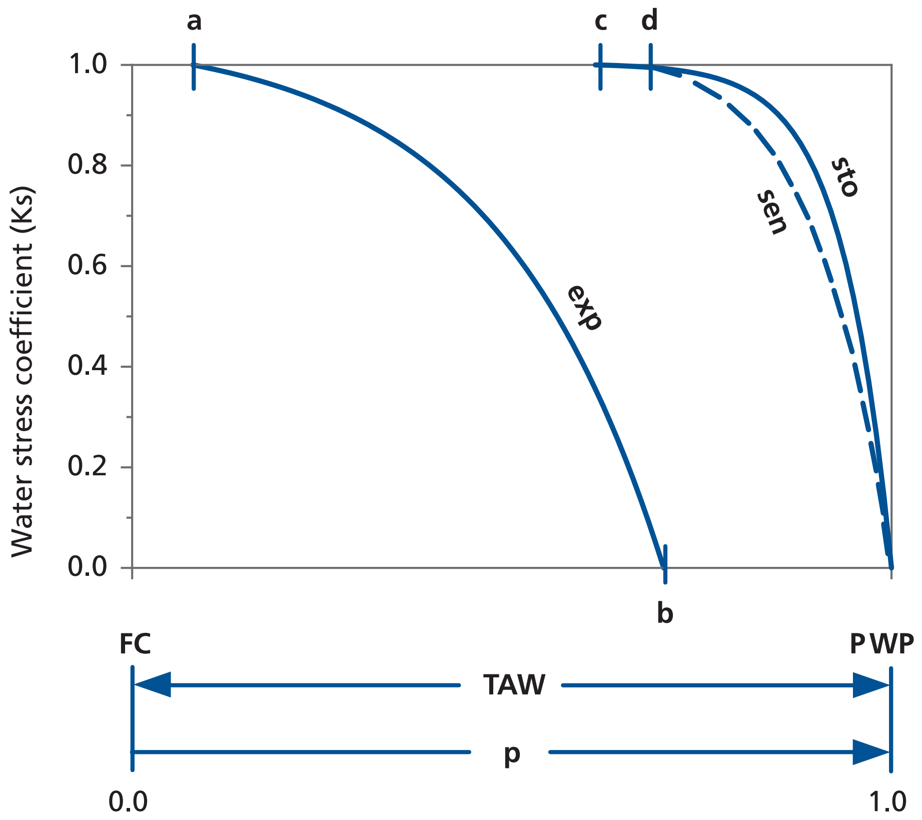
Being the middle link in the soil-plant-atmosphere continuum, the plant water status depends not only on soil-water status, but also on the rate of transpiration determined by atmospheric evaporative demand. The crop is more sensitive to soil-water depletion on days of high ET_o, and less on days of low ET_o. For simplicity, instead of modelling the soil-plant-atmosphere continuum, *AquaCrop* adjusts the thresholds of the Ks curve according to ET_o, a measure of evaporative demand. As the threshold is set for environments with ET_o = 5 mm/day, the model automatically adjusts the thresholds each day according to daily ET_o when running a simulation. The extent of the adjustment is depicted in Figure 11.

FIGURE 11 Sample Ks curve for canopy expansion. The thick blue line represents Ks for days when ET_o = 5 mm/day. The line on the left indicates that the value of Ks decreases (stronger stress effect) when ET_o increases, and the line on the right that Ks increases when ET_o decreases. The hatched area spans the range of adjustment as dictated by ET_o.



Of the first three processes affected by water stress, extensive studies have shown that expansion of the leaf (hence the canopy) is the most sensitive, and stomatal conductance is substantially less sensitive. Depending on the species, leaf (hence canopy) senescence may be equally or slightly less sensitive than stomatal conductance (Bradford and Hsiao, 1982). Setting of the three upper thresholds for water stress for a crop should be consistent with these observations. Differences in the Ks curves for the three processes can be seen in the example for maize in Figure 12.

FIGURE 12 The stress coefficient (Ks) curve for canopy expansion (exp), stomatal conductance (sto), and canopy senescence (sen) of maize as function of root zone water depletion (p). The upper threshold for expansion is indicated by **a**, and the lower threshold is indicated by **b**. The upper threshold for stomatal closure and canopy senescence are indicated by **c** and **d**, respectively. The lower threshold for both stomata and senescence are fixed at PWP in *AquaCrop* (reproduced from Steduto *et al.*, 2009).



Quantifying stress dynamics with Ks

Generally, Ks is used as a multiplier to modulate the processes in question. For canopy expansion, its CGC (Equation 3 and 4) is actually multiplied by its specific Ks. This has no effect on the value of CGC as long as **p** is small (little depletion) and Ks remains 1.0. As soil water depletion pass the upper threshold (point **a** in Figure 12), Ks drops to less than 1.0, causing a reduction in the calculated effective CGC, and the canopy development slows as a result. As water depletes further, canopy grows even slower because of further decreases in Ks, and stops completely when the depletion reaches the lower threshold (point **b** in Figure 12) where Ks = 0.

If there is no replenishment of water in the root zone, the final size of CC would be less than the specified CC_x. If the crop is indeterminant with the potential of growing leaves over much of its life-cycle, late replenishment of water would raise Ks above the lower threshold and restart canopy expansion. If the crop is determinant, however, late replenishment of water would not renew canopy expansion because the crop has no potential for leaf growth past the peak of the flowering period, and the model is programmed to end CC expansion.

As mentioned, stomata are considerably less sensitive to soil-water depletion than canopy growth, so its Ks is set not to decrease until the soil water is substantially more depleted. Tr is also calculated by multiplying with its Ks, and is not affected by water stress as long as root zone depletion is less than the upper threshold for its Ks. As more water depletes and the upper threshold (point **c** in Figure 12) is passed, Ks drops below 1.0 and calculated Tr becomes less than potential. Further depletion causes more reduction in Tr, and if it passes the upper threshold for senescence (point **d** in Figure 12), canopy starts to senesce and CC, made up of green foliage, decreases. If root zone water is replenished to above the upper thresholds at this point, stomata would open fully and Tr will increase, and canopy senescence will cease. Tr, however, will be lower than if there had not been water stress, because CC is now smaller. CC would increase gradually if the crop is at a stage when the potential for leaf growth is still there; otherwise CC would remain smaller, but would endure to the normal time of maturation if there is no additional depletion passing the upper threshold for senescence.

Senescence of the canopy can be triggered and accelerated by water stress any time during the crop life-cycle, provided the stress is severe enough. This is simulated by adjusting CDC, in units of fractional reduction of CC per unit of time, with an empirical equation based on Ks for senescence arranged in such a way that the value of CDC is zero when Ks is 1.0, but rises exponentially above zero when Ks falls below 1.0.

Root deepening is another process affected by water stress. It is well established that root growth is substantially less sensitive to water stress than leaves, and that the ratio of root to shoot is enhanced by mild to moderate water stress (Hsiao and Xu, 2000). In *AquaCrop* there is no link between roots and shoot (canopy and biomass) except indirectly via the effect of root zone water depletion on components of the production process. Specifically, deepening enlarges the root zone and reduces Dr (fractional water depletion) if the deeper soil layers are high in water content. This raises the value of particular Ks, leading to favourable changes in shoot processes. On the other hand, deepening into quite dry soil layers may actually increase Dr, because volume of the root zone becomes larger but there is little increase in its water the volume. Fractional depletion could then become larger with lower Ks and negative consequences on shoot processes.

Because root growth is less sensitive to water stress than leaves, root deepening is simulated in *AquaCrop* to proceed normally as root zone water depletes until p_{upper} for stomatal closure is reached. At this point, a reduction as a function of Tr (hence Ks for stomata) is applied to the deepening rate. In this simple way, the model mimics the increase in root-shoot ratio under mild to moderate water stress, because canopy expansion starts to be inhibited at a much higher fractional water content of the root zone than Tr. So roots grow better than the canopy, down at least to the upper threshold for stomata.

Water stress effects on harvest index

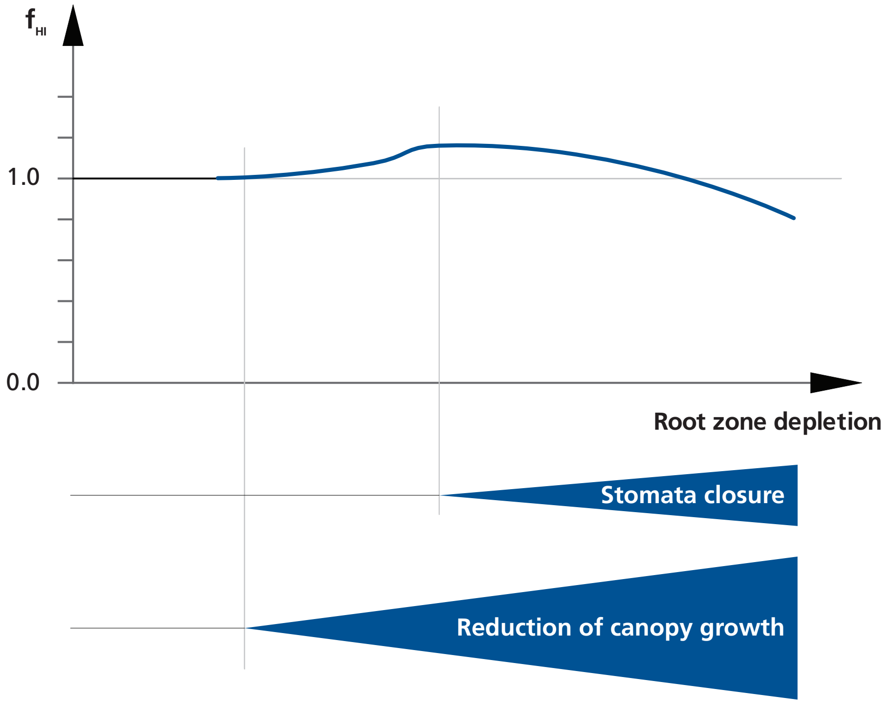
So far attention has been on processes leading to biomass production, on which yield depends (Equation 2). Yield also depends on HI, and the impact of water stresses on HI can be pronounced, depending on the timing and extent of stress during the crop cycle. Effects of water stress on HI can be negative or positive.

Two of the negative effects are more straightforward. One is the inhibition of water stress on pollination and fruit set (successful formation of the embryo). If the stress is severe and long enough, the number of set fruit (or grain) would be reduced sufficiently to reduce HI and limit yield, in some cases drastically. Under good conditions most, if not all crop species, have been selected with a tendency to set more fruit than can be filled with the available photosynthetic assimilates, leading to the abortion of a portion of the set fruit early in their development. So reduction of fruit set by water stress may or may not reduce HI, depending on the extent of the reduction and the extent of the excessive fruit setting. *AquaCrop* simulates this also with the Ks approach, to reduce pollination (hence fruit set) each day according to the extent of water depletion. The effect on HI is adjusted for tendency to set excess fruit by providing categories differing in excessiveness.

Another negative impact on HI is the underfilling and abortion of younger fruits resulting from a lack of photosynthetic assimilates. Photosynthesis is tightly correlated with stomatal conductance. Water stress, by reducing stomatal opening, diminishes the amount of assimilates available to fill all developing fruit. The youngest fruit are then the most likely to be aborted and only the older fruit mature, but likely underfilled. This occurs during the grain filling and maturing period, when most of the vegetative growth has already taken place and most of the assimilates go to the grain. *AquaCrop* simulates this in two ways, one is simply by reducing HI with a coefficient that is a function of Ks for stomata. Stomatal closure may often be only the minor cause, however, because water stress at this growth stage commonly accelerates canopy senescence, resulting in an early decline in photosynthetic surface area and shortens the duration of the canopy. As programmed in *AquaCrop*, HI increases continuously up to the time of normal maturity (Figure 6), but only if a portion of the green canopy remains. As CC declines to some low limit value, HI is considered to have reached its final value. With CC reaching this low limit earlier because of stress induced early senescence, HI is automatically reduced. This effect can be dramatic if canopy duration is shortened substantially.

The last of the negative impacts on HI has to do with not having sufficient water stress. This centres on the competition between vegetative and reproductive growth, which also accounts for the positive impact of water stress on HI. As demonstrated for cotton and some other crops, HI can be reduced by overly luxurious vegetative (leaf) growth during the reproductive phase when water is fully available, while restricting vegetative growth by mild water (and nitrogen) stress is known to enhance HI. The cause is apparently the competition for assimilates. Negative effect on HI comes about when high water availability stimulates fast leaf growth, with too many assimilates diverted to the vegetative organs, depriving the younger potential flowers or nascent fruits so they drop off the crop. The end result is that too few fruits mature, reducing HI. On the other hand, mild water stress would reduce leaf growth substantially because it is most sensitive to water stress, while stomata, being substantially less sensitive, would remain open to maintain photosynthesis. Consequently, without the excessive diversion to vegetative organs, an ample amount of assimilates are available to enhance fruit retention and growth, leading to higher HI. *AquaCrop* simulates this behaviour relying on the Ks functions for leaf growth ($Ks_{exp,w}$) and for stomata closure (Ks_{sto}), with HI being enhanced as $Ks_{exp,w}$ declines, and being reduced as Ks_{sto} declines. In the adjustment, HI is first enhanced as stress develops and vegetative growth is inhibited, then is more enhanced as stress intensifies, until stomata begin to close restricting photosynthesis, at which point the HI does not change. At some level of stress severity HI is reduced to the normal value because the positive effect of leaf growth inhibition is counterbalanced by the negative effect of stomata closure. As stress intensifies beyond this level, the overall effects would switch to negative with proper programme setting parameters (Figure 13).

FIGURE 13 Multiplier (f_{HI}) adjusting the reference harvest index (HI_o) for various root zone depletions with indication of the degree (blue shaded area) of the reduction in canopy growth and the closure of stomata when root zone depletion (D_r) increases.



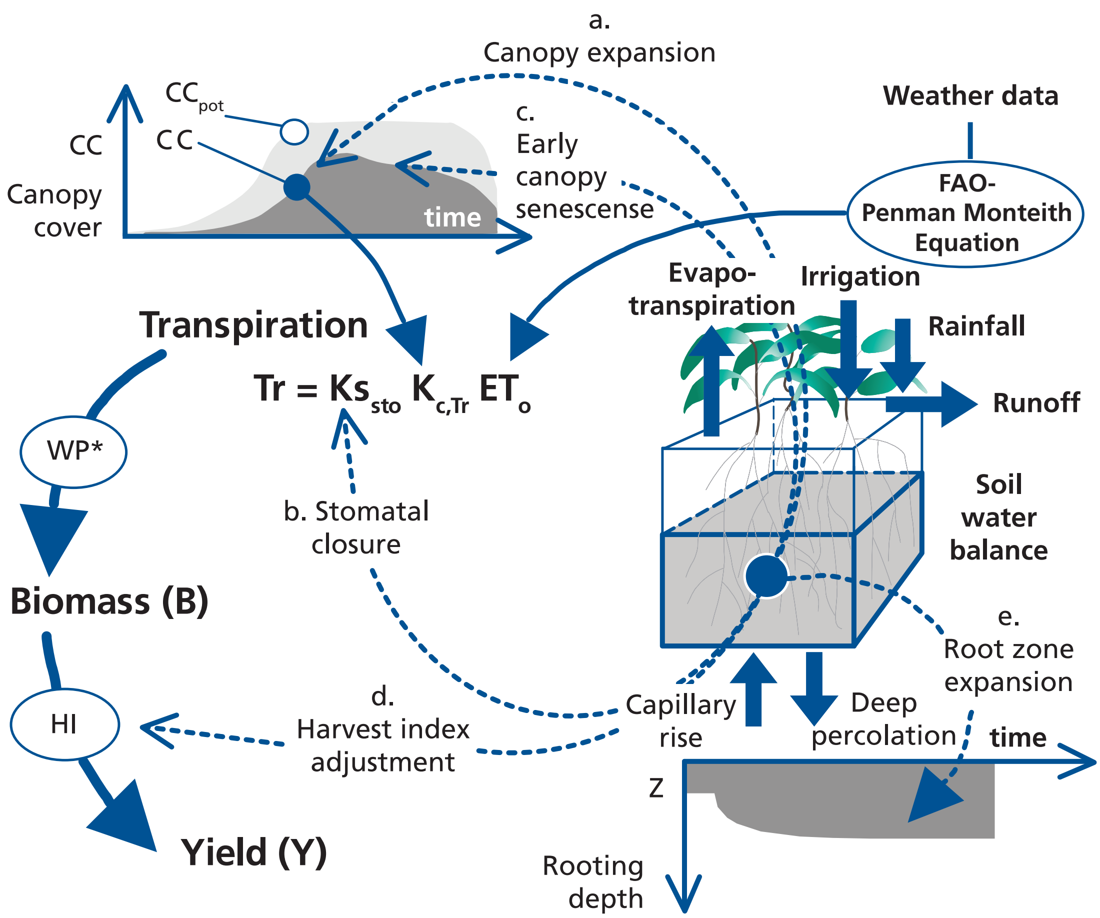
In addition to water stress effects on competition for assimilates during fruit set and grain filling, studies have shown that mild to moderate water stress just before the reproductive phase (pre-anthesis) can enhance HI in some cases. The increase is correlated to the reduction in the accumulation biomass. *AquaCrop* includes an algorithm that operates in some crops to enhance HI based on the stress effect on reduction (relative to the potential) in biomass accumulated up to the start of flowering. The effect is dependent on the extent of reduction and limited to a range with optimal effect before the midpoint of the range.

Overall, in *AquaCrop* the reference HI is adjusted daily for water stress effects based on the inhibition of leaf growth, closure of stomata, reduction in biomass at pre-anthesis, reduction of green canopy duration resulting from accelerated senescence and failure of pollination.

Schematic representation

A schematic representation of the dynamics of the crop response to water stress, as simulated by *AquaCrop*, is given in Figure 14.

FIGURE 14 Schematic representation of the crop response to water stress, as simulated by *AquaCrop*, with indication (dotted arrows) of the processes (a to e) affected by water stress. CC is the simulated canopy cover, CC_{pot} the potential canopy cover, Ks_{sto} the water stress for stomatal closure, $K_{c,Tr}$ the crop transpiration coefficient (determined by CC and $K_{c,Trx}$), ET_o the reference evapotranspiration, WP* the normalized water productivity and HI the harvest index (adjusted from Raes *et al.*, 2009).

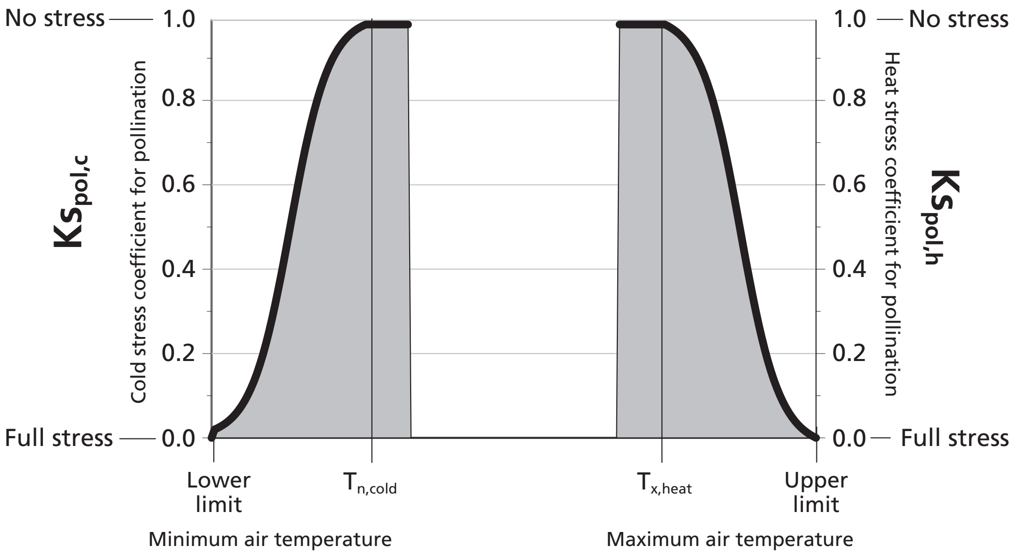


Temperature stress

By using GDD as the thermal clock, much of the temperature effects on crops, such as on phenology and canopy expansion rate, are presumably accounted for. The effect of temperature on transpiration is accounted for separately by ET_o. Damaging effects of extreme or close to extreme temperatures, however, fall into the stress category and require different considerations.

In general *AquaCrop* simulates temperature stress effects with temperature stress coefficients, which vary from zero to 1.0 and are functions of air temperature or GDD. Value of GDD for a given day may be considered as an integrated measure of the daily temperature. Lower and upper thresholds delineate the temperature window wherein the process is affected. Lacking more definitive data currently, the shape of the Ks vs. temperature curve (Figure 15) is taken to be logistic, and may be changed in the future when better data become available.

FIGURE 15 Variation of the temperature stress coefficient (Ks) for cold (left) and heat stresses (right) on pollination.



One important temperature stress effect is on pollination, which is inhibited by temperatures either too high or too low. The left graph in Figure 15 illustrates the $Ks_{pol,c}$ curve for cold stress on pollination, with daily minimum temperature (T_n) as the independent variable and the upper threshold set at a specified threshold temperature ($T_{n,cold}$) and lower threshold at 5 °C below $T_{n,cold}$. The curve for heat stress on pollination is the mirror image of the cold stress (right graph in Figure 15), except the independent variable is maximum temperature (T_x) and the range would be higher and the thresholds also higher. Analogous to the case of water stress, for cold stress pollination begins to be inhibited once the T_n drops below the upper threshold and $Ks_{pol,c}$ drops below 1.0. Pollination decreases further as T_n and $Ks_{pol,c}$ drop further, and is halted ($Ks_{pol,c} = 0$) at the lower T_n threshold or below. For heat stress it is the other way round: below the lower threshold $Ks_{pol,h}$ is 1.0 and pollination is unaffected, and above the upper threshold Ks is zero and pollination is halted (Figure 15). The ultimate effect of temperature stresses on pollination is on HI, in exactly the same way as the effect of water stress.

In addition to effects on pollination, cold temperature may hamper biomass production beyond the restriction accounted for by GDD and irrespective of Tr and ET_o. *AquaCrop* adjusts for this with again the stress coefficient approach. The biomass produced each day is multiplied by the Ks for cold stress ($Ks_{b,c}$) to account for the restriction on production. Since biomass is derived from Tr using WP*, a constant, adjusting biomass this way, in essence, is an adjustment of WP*.

Aeration stress

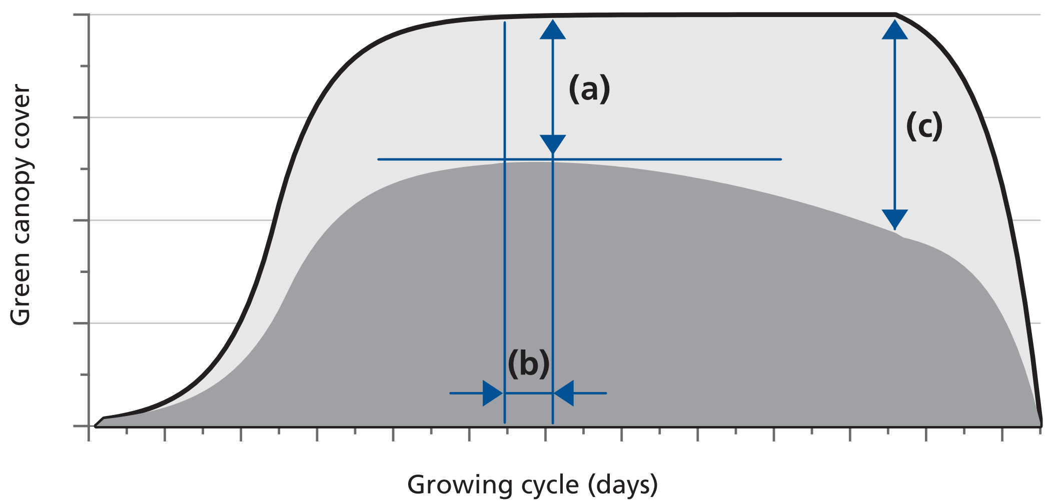
The lack of soil aeration is another abiotic stress considered by *AquaCrop*. The treatment is simple, using the stress coefficient approach to modulate Tr, hence biomass production and ET. The independent variable for the Ks function (Ks_{aer}) is the percentage of soil pore volume occupied by air in the root zone. The function is assumed to be linear with a settable upper threshold and the lower threshold fixed at zero (fully saturated soil). When the percentage air volume drops below the upper threshold, Ks_{aer} starts to decrease below 1.0, causing proportional reduction in Tr.

The sensitivity of the crop to waterlogging is specified by setting the upper threshold, and by indicating the number of days waterlogging must remain before the stress becomes fully effective and Tr is affected. It should be pointed out that so far aeration stress parameters given for the crops already calibrated are all default values, because definitive data for crop under aeration stress are rare.

Low soil fertility (or mineral nutrient stress)

As already mentioned under *Field management*, *AquaCrop* does not simulate nutrient cycles and balances, but provides the means to adjust for fertility effects with a set of soil fertility stress coefficients, to simulate the impact on the growing capacity of the crop in terms of four pivotal components of productivity: canopy growth coefficient (CGC), maximum canopy cover (CC_x), canopy decline, which includes a slow but substantial decline upon reaching CC_x in addition to the senescence near maturity, and WP*. Accounting for the first three of these components, as affected by fertility, results in simulated pattern of CC vs. time very similar to plots based on measured data (Figure 16). The last component, WP*, is also adjusted downward for low fertility. The basis for making these adjustments are the following observations, well established in the literature: plants grown on soil deficient in nutrients (N, P, and/or K) produce leaves more slowly, with lower leaves senescing quite or very early but the upper and youngest leaves remain green until maturity or very near maturity. Photosynthetic capacity of

FIGURE 16 Green canopy cover (CC) for unlimited (light shaded area) and limited (dark shaded area) soil fertility with indication of the processes resulting in (a) a reduced maximum canopy cover, (b) a slower canopy development, as indicated by the reduced slope of CC vs. time in early season, and (c) a continuous and slow decline of CC once the maximum canopy cover is reached.



the deficient leaves is less and their ratio of photosynthesis to transpiration is lower, consistent with the observed changes in WP in field studies.

AquaCrop provides default adjustments of the pivotal components for several categories differing in fertility limitation, ranging from near optimal to poor. To make the adjustments more reliable, biomass production data obtained at different fertility levels at the same location and time should be used to make a local calibration, as provided for in *AquaCrop*.

Soil salinity stress

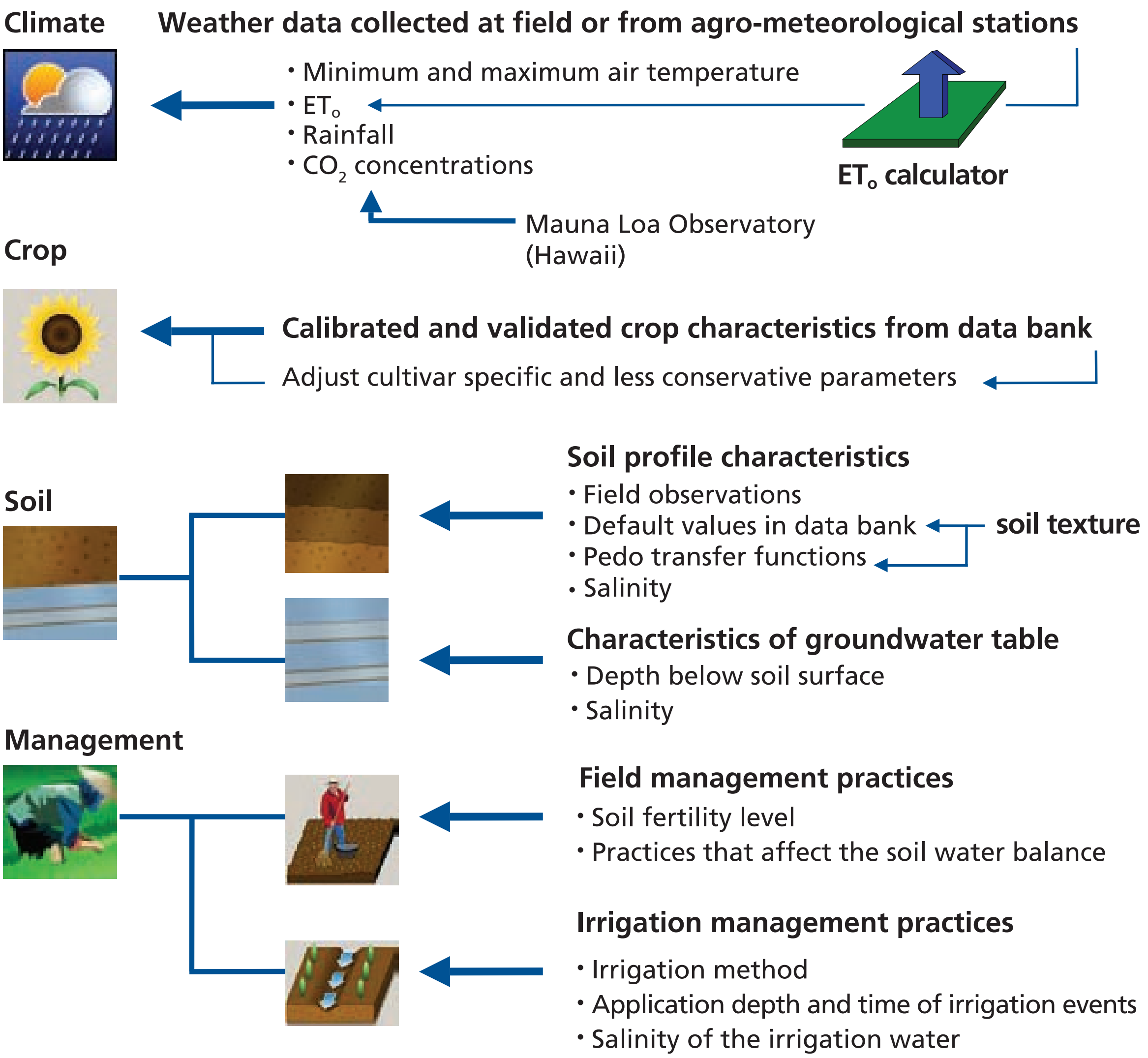
The average electrical conductivity of saturation soil paste extract (ECe) from the root zone is the indicator of soil salinity stress. At the lower threshold of soil salinity (ECe_n), Ks becomes smaller than 1 and the stress starts to affect biomass production. Ks becomes zero at the upper threshold for soil salinity (ECe_x) and the stress becomes so severe that biomass production ceases. Values for ECe_n and ECe_x for many agriculture crops are given by Ayers and Westcot (1985) in the FAO *Irrigation & Drainage Paper No. 29*.

The soil water in the root zone becomes less available for root extraction when salts build up in the soil profile. This affects crop development, crop transpiration and hence biomass production and harvestable yield. *AquaCrop* does not simulate each of these crop responses but simulates only its global effect on biomass production. Given a user calibrated relationship between soil salinity stress and relative biomass production, *AquaCrop* translates the expected reduction in production into a stress resulting in stomata closure (Ks_{sto}) and affecting the canopy development (CGC, CC_x and canopy decline upon reaching CC_x). The simulation is similar as the approach used to simulate the crop response to low soil fertility.

INPUTS

AquaCrop uses a relative small number of parameters and fairly intuitive input variables, either widely used or largely requiring simple methods for their determination. Input consist of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop, and are summarized schematically in Figure 17. The inputs are stored in climate, crop, soil and management files and can be easily retrieved from *AquaCrop*'s database and adjusted with the user interface.

FIGURE 17 Input data defining the environment in which the crop develops.



Climate data

For each day of the simulation period, *AquaCrop* requires minimum (T_n) and maximum (T_x) air temperature, rainfall, and reference evapotranspiration (ET_o) as a measure of the evaporative demand of the atmosphere. Further, the yearly mean atmospheric CO_2 concentration has to be known.

For consistency and as the standard, ET_o is to be calculated using the Penman-Monteith equation (Allen *et al.*, 1998), from full daily weather data sets. The full data set consists of radiation, T_x and T_n, wind run or speed, and humidity, all daily. An ET_o calculator, a free public domain software, is available from the FAO website for the calculation (FAO, 2009). The calculator accepts weather data given in a wide variety of units. In the absence of full daily data set, the calculator can also estimate ET_o from 10-day or monthly mean data, and make approximations when one or several kinds of the required weather data are missing. This makes it possible for a user to run rough simulations even when the weather data are minimal.

Care must be taken, however, to avoid misuse of the calculator's versatility. For validation and parameterization of the model for a particular crop, such approximation should not be relied on. The more the weather elements are missing the rougher the approximation of ET_o, the less reliable would be the simulated results and derived *AquaCrop* parameters.

The daily, 10-day or monthly air temperature, ET_o and rainfall data for each specific environment are stored in their own climate folder in the *AquaCrop* database from where the programme retrieves data at run time. In the absence of daily weather data, because the programme runs in daily steps, it invokes built-in procedures to approximate the required daily data from the 10-day or monthly means. Again, the more approximate, the less reliable is the outcome. This is particularly an acute problem for rainfall data. With its extremely heterogeneous distribution over time, the use of 10-day or monthly rainfall data completely grosses over the dynamic nature of crop response to water stress.

Additionally, *AquaCrop* provides the mean yearly CO_2 concentration required for the simulation, applicable for most locations. These yearly values are measured at the Mauna Loa Observatory in Hawaii and encompass the period from 1902 to the most recent available data. Several projected values can be retrieved from the *AquaCrop* database or entered by the user, following the climate change scenario to be investigated.

Crop parameters

Although grounded on basic and complex biophysical processes, *AquaCrop* uses a relative small number of crop parameters to characterize the crop. FAO has calibrated crop parameters for several crops (Section 3.4), and provides them as default values in the crop files stored in *AquaCrop* database. The parameters fall into two categories, distinguished as *conservative* or *cultivar* and *conditions dependent* (see also Section 3.3).

- The *conservative* crop parameters do not change with time, management practices, climate, or geographical location. Regarding cultivar differences, so far tests show the same value of a conservative parameter is applicable to many cultivars, although some deviation may be expected for cultivars of extreme characteristics. The decision to assign a particular parameter to the conservative category is based on conceptual and theoretical analysis, and on extensive empirical data demonstrating near constancy. Depending on extensiveness of the data sets used for the calibration, the calibrated value for a conservative parameter may require some small adjustment. This should be done, however, only if the adjustment is based on high quality experimental data. Generally and in principle, the conservative parameters require no adjustment to the local conditions or for the common cultivars, and can be used as such in simulations. The conservative crop parameters are listed in Table 1.

- The *cultivar* and *condition dependent* crop parameters are generally known to vary with cultivars and situations. Outstanding examples are life-cycle length and phenology of cultivars. In Table 2, an overview is given of crop parameters that are likely to require an adjustment to account for the local cultivar and or local environmental and management conditions. Reference HI (HI_o) is usually conservative for well developed high yielding cultivars, and therefore is not included in Table 2 as a cultivar specific parameter. It is known, however, that some special cultivar may have HI consistently either slightly higher or lower than the common cultivars. Adjustment in HI_o would be justified in such cases.

TABLE 1 Conservative crop parameters.

Crop growth and development
• Base temperature and upper temperature for growing degree days • Canopy size of the average seedling at 90 percent emergence (cc_o) • Canopy growth coefficient (CGC); Canopy decline coefficient (CDC) • Crop determinacy linked/unlinked with flowering; Excess of potential fruit (%)
Crop transpiration
• Decline of crop coefficient as a result of ageing
Biomass production and yield formation
• Water productivity normalized for ET_o and CO_2 (WP*) • Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity • Reference harvest index (HI_o)
Stresses
Water stresses • Upper and lower thresholds of soil-water depletion for canopy expansion and shape of the stress curve • Upper threshold of soil-water depletion for stomatal closure and shape of the stress curve • Upper threshold of soil-water depletion for early senescence and shape of the stress curve • Upper threshold of soil-water depletion for failure of pollination and shape of the stress curve • Possible increase of HI resulting from water stress before flowering • Coefficient describing positive impact of restricted vegetative growth during yield formation on HI • Coefficient describing negative impact of stomatal closure during yield formation on HI • Allowable maximum increase of specified HI • Anaerobiotic point (for effect of waterlogging on Tr)
Temperature stress • Minimum and maximum air temperature below which pollination starts to fail • Minimum growing degrees required for full biomass production

TABLE 2 List of crop parameters likely to require adjustments to account for the characteristics of the cultivar and local environment and management.

Phenology (cultivar specific)
• Time to flowering or the start of yield formation • Length of the flowering stage • Time to start of canopy senescence • Time to maturity (i.e. the length of crop cycle)
Management dependent
• Plant density • Time to 90 percent emergence • Maximum canopy cover (depends on plant density and cultivar, see Section 3.3)
Soil dependent
• Maximum rooting depth • Time to reach maximum rooting depth
Soil and management dependent
• Response to soil fertility • Soil salinity stress

It should be emphasized that for temperature dependent processes, such as canopy expansion with its conservative parameter CGC, the constancy of their parameters is entirely based on operating the model in the GDD mode. It is obvious, that for simulation of production and water use under different yearly climate or different times of the season, *AquaCrop* must be run in the GDD mode, otherwise temperature effects on key crop processes would be completely ignored by the model.

Another important consideration is the thoroughness of the calibration and the extensiveness of the data set on which the calibration is based. Diverse data sets are necessary to cover a wide-range of climate and soil conditions, and more cultivars. Particularly crucial are data sets for water-deficient conditions, on which the calibration of the water-stress parameters depend, and are often not readily available.

Of the number of crops calibrated by FAO, the thoroughness ranges from very good to fair and limited. Users need to consult the rating, available on the *AquaCrop* website, to determine the firmness of the conservative parameters. With time, calibration of the various crops will be improved based on additional data sets, and more crop species will be calibrated.

The reader is referred to Section 3.3 of this Chapter and the *AquaCrop Reference Manual* (Raes *et al.*, 2011) for procedures on how to calibrate a crop for local conditions and how to modify the crop parameters in the data files.

Soil data

Needed parameters are: volumetric water content at field capacity (FC), permanent wilting point (PWP), and saturation, and the saturated hydraulic conductivity (K_{sat}), for each differentiated soil layers encompassing the root zone. From these characteristics *AquaCrop* derives other parameters governing soil evaporation, internal drainage and deep percolation, surface runoff and capillary rise (Raes *et al.*, 2011). The default values for these parameters can be adjusted if the user has access to more precise information. In case some of the first four parameters values are missing, the user can make use of the indicative values provided by *AquaCrop* for various soil texture classes, or import locally-determined or derived data from soil texture with the help of pedo-transfer functions (see for example The Hydraulic Properties Calculator on the web: http://hydrolab.arsusda.gov/soilwater/Index.htm). These functions are based on primary particle size distribution of the different soil textures. Since these functions depend on texture class only, they do not account for differences in soil aggregation and should be taken as rough approximations. Users should adjust their estimates based on their own data and experience.

If a layer exists in the soil to stop root deepening, its depth has to be specified as well. In addition, the water content of the soil profile layers at the start of the simulation period need to be specified if it is not at field capacity.

Management data

Management practices are divided into irrigation management and field management. Under field management practices are choices of soil fertility levels, level of weed infestation, and practices that affect the soil-water balance such as mulching to reduce soil evaporation, soil bunds to store water on the field, and the elimination of runoff by conservation practices.

The fertility levels range from non-limiting to poor, with effects on WP, on the rate of canopy growth, on the maximum canopy cover and on senescence.

Under irrigation management the user chooses whether the crop is rainfed or irrigated. If irrigated, the user specifies the application method (sprinkler, drip or surface), the fraction of surface wetted, and for each irrigation event, the irrigation water quality, the timing and the applied irrigation amount.

There are also options to asses the net irrigation requirement and to generate irrigation schedules based on specified time and depth criteria. Since the criteria can be changed during the season, the programme provides the means to test deficit irrigation strategies by applying chosen amounts of water at various stages of crop development.

THE USER INTERFACE AND OUTPUT

AquaCrop has a menu-driven software programme with a well-developed user interface. Multiple graphs and schematic displays in the menus help the user to discern the consequences of input changes and to analyse the simulation results.

The main menu

The *Main Menu* of *AquaCrop* provides three panels (Figure 18): *Environment and Crop*, *Simulation* and *Project*.

On the *Environment* and *Crop* panel of the *Main menu*, users have access to a whole set of menus of the four structural components of *AquaCrop* (climate, crop, management, soil), where files are selected, input data are displayed or updated and the planting date is specified. Data can be retrieved from input files stored in the database. In the absence of input files, default settings are provided.

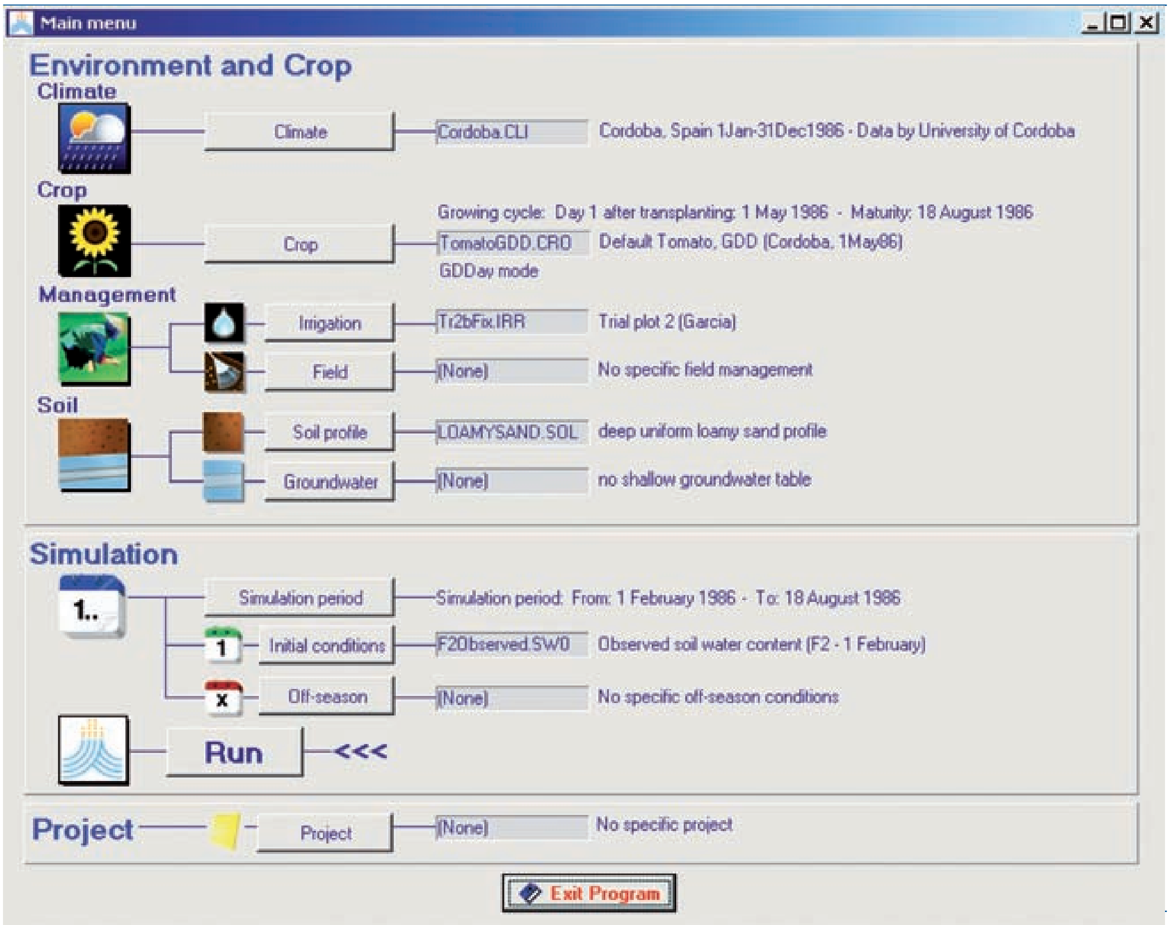
On the *Simulation* panel, a simulation period different from life-cycle of the crop, and conditions of the soil water and salt content in the soil profile at the start of the simulation can be specified. Also, off-season (outside the growing period) practices (mulching or irrigation) can be specified. These features make it possible to simulate effects of fallow and pre-season irrigation.

On the *Project* panel, users can define projects to simulate multi-year cropping, either of the same crop or crop rotations. Note that the climate file needs to span the total simulation years. Under *Project*, users can also specify all the input files for any simulation trial for a single year or season, to avoid having to choose again each file individually when resuming the trial after exiting *AquaCrop*.

Display of simulation results

When running a *Simulation*, the user can track changes in soil-water and salt content, components of soil water balance, canopy development, transpiration, biomass accumulation, and yield and water productivity. The key simulation results are displayed in a number of graphs, updated at the end of each daily time step. From these graphs and associated displays the user can follow the dynamic effects of water, temperature, fertility and salinity stress on crop development and production and water use. By switching among different output

FIGURE 18 The Main *AquaCrop* menu.

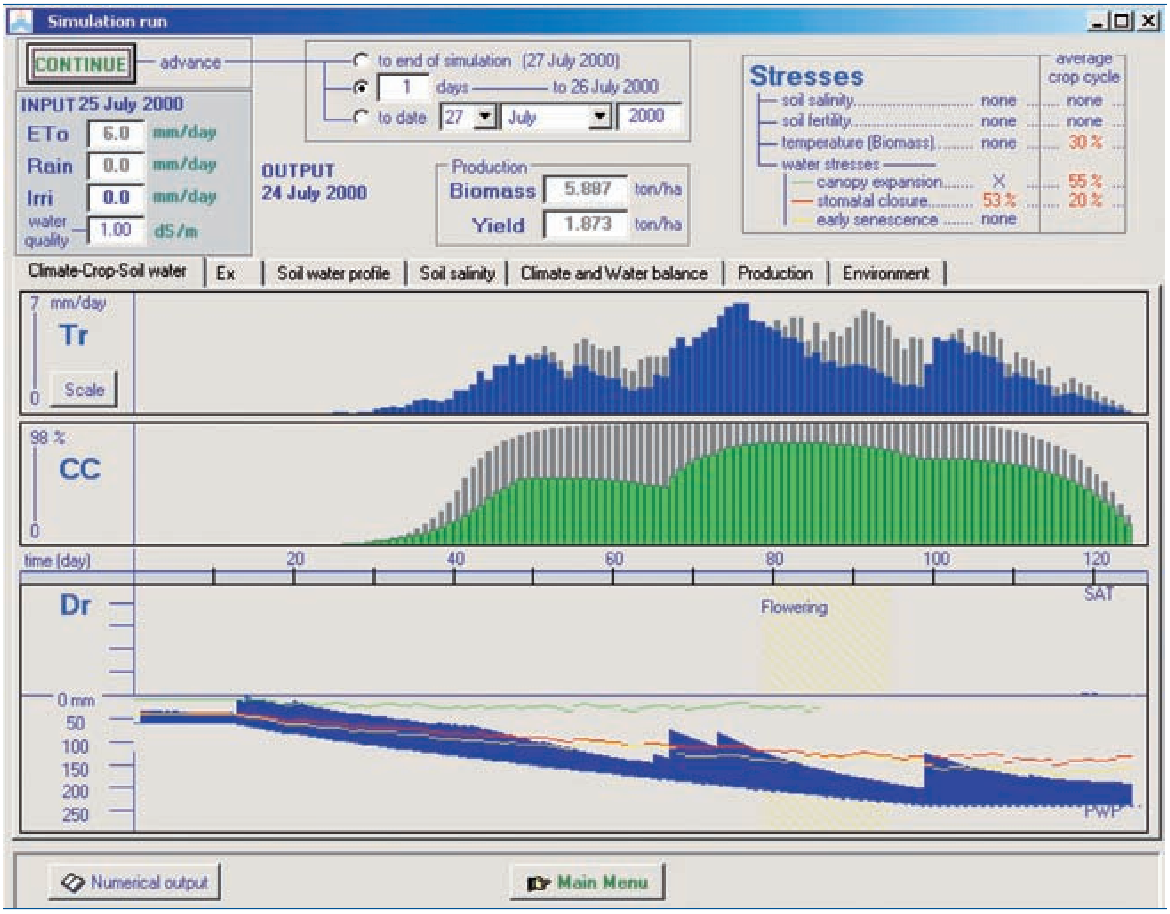


displays on *tab* sheets for different aspect of crop, soil water and salt balance, the user can observe and analyse a particular event on a specific parameter.

Climate-Crop-Soil water is the most useful of the *tab* sheets (Figure 19). It displays three graphs plotted as a function of time: (i) depletion of root zone soil water (D_r), with the three water stress thresholds represents by lines of different colours; (ii) the corresponding progression of green canopy cover (CC), with the potential CC (no stresses) shaded gray; and (iii) the transpiration (Tr) of the canopy (for the simulated CC size), with potential Tr shaded gray. On top of the menu the biomass and yield are displayed along with the status of the water, temperature, soil fertility and salinity stresses. The graphs vividly show how canopy expansion and transpiration are affected when the absence of rain and irrigation led to drops in root zone water content below the threshold (green line, bottom graph) affecting canopy expansion, below the threshold for stomata (red line) affecting Tr, and below the threshold (yellow line) triggering canopy senescence. The reversal effects of water supply or irrigation are also obvious in the graphs.

One feature of the *Simulation run* menu is particularly helpful to users seeking to develop a regulated deficit irrigation schedule to optimize water use. By selecting short simulation time steps (1 to 3 days), a chosen amount of irrigation can be specified on the upper left panel at any time step (and date) during a simulation run, allowing quick and close scrutiny of the resultant benefits in the context of irrigation time, frequency, and amount. For more details, see Section 3.3 and the *AquaCrop Reference Manual* (Raes *et al.*, 2011).

FIGURE 19 Graphical displays of Climate-Crop-Soil water output in the *Simulation run* menu.



Output

On exiting the *Simulation run* menu, the user is asked whether to save the output, and can choose one or more of the categories of output: daily (Table 3) and/or seasonal. The files are automatically assigned the file extension OUT, with the name of the category of file contents forming the last part of the default file name as shown in Table 3.

TABLE 3 Default file name and content of the seven output files with daily simulation results.

Default file name	Nature and number (in parenthesis) of output variables in the file
ProjectCrop.OUT	crop processes, production, & related data (18)
ProjectWabal.OUT	soil water balance and related data (16)
ProjectProf.OUT	water content of root zone profile (10)
ProjectSalt.OUT	soil salinity of root zone profile (8)
ProjectCompWC.OUT	soil water content of model compartments (12)
ProjectCompEC.OUT	soil salinity of model compartments (12)
ProjectInet.OUT	net irrigation requirement (if simulated) (5)

Users should change the first part (Project) of file name to identify the particular simulation, otherwise the next simulation would be automatically assigned the same default file name and overwrite the files resulting from the preceding simulation. Daily simulation results are also summarized as seasonal totals. The files are stored by default in the OUTP directory of *AquaCrop*. The data in the files can be retrieved in spreadsheet programmes for further processing and analysis.

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3.2 *AquaCrop* applications

INTRODUCTION

Agricultural production takes place in an environment characterized by risk and uncertainty. This is particularly so in arid and semi-arid zones where water supply to crops from rainfall is variable and erratic. Even in areas under irrigation, water scarcity is not uncommon and yields are often affected, therefore procedures and tools are needed to predict the crop response to a given supply of water, so as to reduce uncertainty and to manage risk. For a long time, FAO has worked on providing methods to assist a diverse range of users in determining the yield response to water. Recently, the development of *AquaCrop* by FAO provides an improved and powerful approach for the assessment of the attainable yield of the major herbaceous crops as a function of water supply.

The main outputs of *AquaCrop* are the yield and water use (E and Tr) of a crop grown at a specific location, with that climate, soil, and with a certain water supply (Steduto *et al.*, 2009). When the input information is precise, its performance is accurate, as shown in the validation tests conducted in many locations (e.g. Mainuddin *et al.*, 2010; Todorovic *et al.*, 2009; Heng *et al.*, 2009; Farahani *et al.*, 2009). The information provided by crop simulation models such as *AquaCrop* may be used in a myriad of ways and by many different types of users. Yield predictions may be useful for farmers, extension specialists, field consultants, engineers, water planners, economists, policy analysts, and scientists. *AquaCrop* simulation results may also be inputs to other types of tools and models.

The type of application depends on the type of user, on the objective the user wants to achieve, and on the temporal scale of the analysis. At the farmers and agricultural technician level, the simulation of yield provides the information needed to explore the outcomes of decisions that can be made at three temporal levels:

- **Days to weeks**: Decisions made at the **operational level** refer to those taken within a growing season, on a scale of days to few weeks, such as determining the date and amount of next irrigation or of a fertilizer topdressing application.
- **Weeks to months**: Tactical farming decisions have a time frame of weeks to months and are typically made at the start or different times during

the growing season. An example would be the determination of the seasonal irrigation scheduling programme, or a decision concerning the best planting density.

- **Years**: Strategic decisions are long-term, when a series of years are considered in the analysis. Strategic decisions may be made with the aid of *AquaCrop*, for example in evaluating when the optimal planting date would be to exploit the stored soil water, based on the anticipated long-term rainfall, by running the model with different planting dates over a series of years.

There are many different farm management decisions at the three levels described, and the use of *AquaCrop* simulations can help in making better informed decisions.

Engineers involved in irrigation management over large areas, at scales above that of an individual farm, need to assess the impact of a number of decisions dealing with irrigation water allocation that scales up from a single farm to groups of farms, single or various irrigation districts, up to the river basin or catchment level. Water is typically allocated according to historical customs, or legal, institutional, political, or social criteria. In situations of water scarcity, economic considerations take a higher priority, and the focus must be placed on achieving efficient and equitable use of the limited resources; this is often accomplished by managing water more as an economic factor.

The economics and management of agricultural water demand and use require information on crop productivity as affected by water supply. This information has been typically obtained by engineers, water planners, and economists from empirical crop-water production functions that use a simple equation to relate yield to the amount of water consumed. *AquaCrop*, however, by dynamically simulating the yield response to different amounts of applied water under a specific set of agronomic conditions, provides a more powerful and flexible alternative and a more realistic range of results as compared to the traditional water production functions.

There could be many applications of *AquaCrop* at different scales, from the plot to the watershed. It can assist in benchmarking irrigation performance or the yield gap, and in making informed decisions from operational up to strategic water-related management decisions. It can be used to test the role of different soils-climate systems on water-limited crop production, and, can also be very useful for the analysis of different scenarios, including variations in climate (present and future), water supply, crop type, field management, etc.

It would be nearly impossible to describe all possible applications of *AquaCrop*. Therefore, what follows is a range of examples and case studies that illustrate some of the applications for different purposes. Users may find the model useful to resolve some of the questions that they face related to different aspects of the prediction of water-limited crop production. The applications described include the range of applicable scales: field to farm to irrigation district and regional scales. Other applications illustrate the usefulness for benchmarking, irrigation scheduling, variations in soils, agronomy and crop management practices as well as effects of variation in climate.

To fully appreciate the applications reported hereafter, the user must be already familiar with *AquaCrop* and with the overall data required to run the model adequately.

APPLICATIONS TO IRRIGATION MANAGEMENT AT THE FIELD AND FARM SCALES

Two types of applications are described. The first describes applications when the water supply is adequate, while the second type refers to examples of how to use *AquaCrop* to assist in coping with irrigation management under water scarcity.

CASE 1 - Developing a seasonal irrigation schedule for a specific crop and field

Specific data requirements:

- long-term climatic data (Rain and ET_o) statistically processed to determine typical climatic conditions of dry, wet, or average years. Note that average ET_o is much less variable than average rainfall; thus, the user could combine average ET_o information with seasonal daily rainfall from different years, representing dry, wet, and average years, if long-term ET_o data is not available;
- soil profile characteristics of the field as needed to run *AquaCrop*; and
- crop characteristics as needed to run *AquaCrop*.

Approach:

The model is run for the season of typical year (dry, wet, average year) using the feature 'Generation of Irrigation Schedule' where the timing and depth of irrigation are determined by selected criteria. The selected time criterion depends on the objectives of the manager; for instance, the user can choose to irrigate every time the root zone water content is depleted down to 50 percent of its total available water or can choose to irrigate every time a certain depth of water has been depleted, such as 25 or 40 mm or even at a fixed time interval as used on many irrigation schemes. A 'fixed application depth' is typically selected as depth criterion. The selection of the fixed amount of water to apply depends on many factors such as farmers' practices, the irrigation method, the irrigation interval, the rooting depth and soil type.

Output:

An indicative irrigation schedule for the crop-climate-soil combination is produced based on the criteria selected by the manager. This simulated schedule may be used for benchmarking the actual irrigation performance of a specific farmer against the ideal for that particular year or different schedules according to different irrigation criteria could be presented to the farmers for discussion.

CASE 2 - Determining the date of next irrigation with AquaCrop

Specific data requirements:

- real-time weather data are used to run *AquaCrop*. Current season daily weather data are used to compute actual ET_o and the soil-water balance from planting until the last day of available weather data, before the simulation of next irrigation date;
- soil profile characteristics as needed to run *AquaCrop*; and
- crop characteristics as needed to run *AquaCrop.*

Approach:

The model is run for the current season, using actual ET_o data from planting until the last day for which actual weather data and thus ET_o is available. From then on, the model is run for daily time steps using the average, long-term ET_o information or weather forecast information, and the projected soil water depletion is simulated day by day.

Outputs:

By considering the current status of the soil-water balance and the depletion of soil water relative to thresholds for restricting canopy growth, transpiration and enhancing of senescence, the user can select the date of next irrigation based on his management goals or availability of water. Such a projection may be adjusted daily by entering new actual weather data to modify the long-term average ET_o used in the projection.

CASE 3 - Determining the seasonal water requirements and its components for various crops on a farm

Specific data requirements

- average or historical climatic data;
- soil profile characteristics as needed to run *AquaCrop*; and
- crop characteristics as needed to run *AquaCrop* for the various crops considered in the case study.

Approach:

AquaCrop is run for the selected crops on the corresponding soils, as selected by the user. For each crop-soil combination, the mode 'Determination of Net Irrigation Water Requirement' is used to determine irrigation needs. Then together with the output from 'Generation of an irrigation schedule', one can plan the timing and depth of irrigation scheduling across all the crops. The manager may vary the selected criteria for the different crops, depending on several factors such as their sensitivity to water deficits or according to total water available. This will enable him/her to learn how the crop will respond to different water regimes and to balance the requirements of different fields or crops according to water supply, thus providing a farm level management plan.

Outputs:

The seasonal water-balance components, and ET_c and its components, E and Tr, will be extracted from the *AquaCrop* simulations, together with the net irrigation requirements for each crop. A comparison of the ET_c of different crops and their irrigation needs, as affected by time of the year (winter vs. summer crops) and by season length and other crop characteristics can be performed by the user in different 'run's of the model and 'saved to disk'. For instance, a farm in a Mediterranean, semi-arid climate with 450 mm/year of annual rainfall, had simulated ET_c values for wheat, maize and potatoes of 425, 650 and 500 mm, respectively, while the corresponding net irrigation requirements were 105, 540, and 415 mm. This is because of the differences in the contribution of seasonal rainfall between a winter crop, wheat, where rainfall is a major contributor and ET_o is low, and a summer crop, maize, grown in the rainless, warm summer. The differences between the two summer crops, were due to potato having a shorter growing season than maize. This information can then help the manager to make appropriate decisions regarding the distribution of the available irrigation water between crops.

CASE 4 - Benchmarking current irrigation practices

Specific data requirements

- actual weather data for the irrigation season;
- soil profile characteristics representative for actual farm conditions, as needed to run *AquaCrop;*
- crop specific characteristics as required to run *AquaCrop*; and
- irrigation practice details in terms of timing and amount of each application.

Approach

With the actual field data, a simulation run is carried out with the exact planting dates and plant population, and the model outputs (yield, irrigation, drainage and rainfall amounts from both 'Production' and ''Climate and Soil Water Balance' tab sheets) are then compared against the actual field data. By evaluating the model output in this way, it would be possible to decide if the current schedule could be improved by reducing drainage or runoff losses and/or avoiding water deficits that may be less detrimental at other times of the season. By alternative trials in reiterative model runs, the user can improve the current irrigation schedule and propose an alternative schedule using the same amount of seasonal irrigation but that maximizes yield, i.e. an optimal schedule.

Outputs

The water balance components of the current schedule, the simulated yield and the yield water productivity are compared to information obtained from the field. Actual vs. simulated yields, corresponding to the current and optimal schedules, should be compared. Large differences between actual and simulated yield would be an indication that either there may be factors other than water (soil fertility, pests, etc...) that are affecting actual yields or that inadequate assumptions or incorrect inputs were made when running the model. If the yield difference is reasonable (i.e. < 15-20 percent), the improvements in the current schedule as predicted by the simulated optimal schedule are probably realistic and should be recommended for field testing.

CASE 5 - How to make best use of stored soil water when irrigation supply is limited

Specific data requirements

- average climate, or real-time weather data;
- soil profile characteristics, typical of the farm, as needed to run *AquaCrop*; and
- crop specific characteristics as required to run *AquaCrop.*

Approach

The objective is to end the season with the soil-water content within the crop root zone fully depleted. For that purpose, the mode 'Generation of Irrigation Schedule' is run with two settings in the 'Time' and 'Depth' criteria so as to change them towards the end of the season. In the first setting an irrigation schedule is generated in which timing and application does not result in water stress. By selecting towards the end of the season a second time criterion (such as an interval longer than the remaining time to reach maturity, or an allowable depletion corresponding with wilting point) further irrigations are no longer generated and the end of the season will be reached with the root zone completely depleted.

Output

An irrigation schedule that leaves the profile completely dry at the end of the season is generated, thus maximizing the use of the water stored in the profile from rainfall and irrigation. A comparison between this schedule, that does not allow significant crop water deficits, and the standard schedule that it generates using the standard 'Time' and 'Depth' criteria should show the potential irrigation water savings by fully utilising the stored soil water. However, the practical details in terms of the amount of irrigation water applied, number of irrigations, and other parameters of the water balance need to be carefully considered.

CASE 6 - Developing deficit and supplemental irrigation programmes at a field scale

a) Deficit irrigation programme under a moderate (25-35 percent) reduction of normal water supply.

Specific data requirements

- standard climate, soil, and crop data needed to run *AquaCrop*; and
- the level of irrigation supply for the season relative to an adequate supply (obtained by running option 'Net Irrigation Requirement' in *AquaCrop*) or usual irrigation water (IW) supply must be known.

Approach

The approach to be followed depends on the crop specific sensitivity to water deficits (Fereres and Soriano, 2007). An example for cotton using this model has been published (García-Vila *et al.*, 2009). A standard schedule must first be developed with *AquaCrop*, as shown in CASE 2 using the normal IW supply for cotton under local conditions. Then, the amount of IW will be reduced by 30 percent, and there are many different choices to generate a deficit irrigation (DI) programme – two approaches may be followed:

- plan the last application to end the season with the soil profile completely dry. This would be general methodology for most DI programmes (see Case 5); then, apply the same number of irrigations but reduce each of their depths by 30 percent in order to apply continuous or sustained DI; or
- using knowledge of the differential sensitivity of cotton to water stress (see Cotton Section under 3.4) plan the crop water deficits that have the least impact on yield, using a so-called regulated DI (RDI). For instance, delay the timing of the first irrigation, then concentrate the water applications around flowering and early fruit set and finally impose more severe deficits as the season progresses after boll set. Two or three options of RDI should be simulated with the same amount of IW. Then the simulated yield values can be compared and the RDI programme that produces the highest yield for the same level of IW will be selected (García-Vila *et al.*, 2009).

b) Deficit irrigation programme with a severe (50-60 percent) reduction in normal supply.

The approach should be the same as above. However, in this case, the number of irrigations must also be reduced during the beginning of the season and concentrated from early flowering to early fruit set, leading to an early senescence and a shorter growing season. This should have some yield penalty relative to full irrigation supply. Several simulations should be conducted (and saved to disk) to reach the best solution in terms of maximum harvest index which would lead to the maximum yield for the given IW.

c) Supplemental irrigation programme to determine the best timing for a single irrigation application

Specific data requirements

- In addition to the standard data requirements of it, it is useful to have rainfall probability information to optimize the timing of a single application.

Approach:

In the real world, the availability of water determines the timing of application. In collective networks, the timing is imposed by the delivery schedule. If farmers have on-farm storage or access to groundwater, then there is flexibility in the timing of applications. The *AquaCrop* simulations will differ in each of these cases. It is also possible to use *AquaCrop* to simulate DI programmes in near real-time, i.e. for the current year, by running the model up-to-date, and then use rainfall probabilities for the coming weeks (available from weather services), and simulate the subsequent week (with long-term mean ET_o and expected rainfall in the climate file). It is then possible to assess the impact on yield of applying the single irrigation in the following week, relative to postponing it. It is also possible to quantify the E vs. Tr effects of the single irrigation; if canopy cover is still developing, the E component will be more important than if the irrigation is applied when maximum cover is reached. On the other hand, early irrigation would enhance canopy cover leading to more intercepted radiation (and relatively lower E) and consequently more biomass production. But the crop-water requirement of a well-developed crop early in the season might largely exceeds the limited amount of water available in the root zone, triggering an early senescence of the canopy. The user is encouraged to evaluate these trade-offs in each specific case and compare the final yields.

Output:

In an example run of *AquaCrop* for wheat in a semi-arid climate, on a soil of medium water storage capacity (110 mm of TAW) with an increasing drought probability as the season progresses, the best timing for a single irrigation is around early grain filling. *AquaCrop* simulated yields with a single 60 mm irrigation just after end of flowering were 4.1 tonne/ha, relative to a yield of 2.4 tonne/ha under rainfed, and 3.5 tonne/ha if the irrigation is delayed 10 days. In another example, when only two irrigations 10 days apart were applied on a very deep soil, maize yielded either 6 tonne/ha or 9 tonne/ha when irrigation started on day 30 and on day 80 after planting, respectively. In this example, early applications were more detrimental to yield as the crop ran out of water too early in the season before its normal senescence date.

One example of the effects on E and Tr of a single irrigation on cotton, when applied during canopy development (at 30-40 percent of maximum), had 7 percent more E than when the single 60 mm irrigation was applied after attaining full canopy. The lower E (and higher Tr) in the second case, together with the beneficial effects of the stress pattern (better water status during reproductive development), led to higher water productivity, with more than 10 percent increase in yield with the same amount of irrigation water (2.7 vs. 2.4 tonne/ha).

A specific case study of simulation of deficit irrigation of cotton is presented in Box 1.

Box 1 Simulating deficit irrigation in cotton production

Background

Cotton is grown in many water limited regions where deficit irrigation may be practised either as a necessity driven by lack of water or for economic reasons (costs of water and/or energy for pumping). The United States southern high plains region is exemplary of both limited water and high pumping costs. *AquaCrop* simulations were carried out for a Texas location at 35°11′ N, 102°6′ W, 1170 m elevation above sea level. The slowly permeable soil is a Pullman silty clay loam with a strong argillic horizon containing approximately 50 percent clay above a wavy boundary of a calcic horizon at 0.1 to 0.14 m depth. The soil water-holding capacity is about 200 mm to 1.5-m depth (Tolk and Howell 2001). Mean annual precipitation is 490 mm, 65 percent of which falls during the growing season (May-August). ET_o greatly exceeds precipitation in all months.

AquaCrop simulation

Simulations were performed for cotton sown in rows on raised beds and with the furrows diked to store irrigation and precipitation. Irrigation was either Full (FI), indicating that soil water was replenished to replace that lost to ET, or one half of that (Deficit, DI). Irrigation scheduling was performed assuming a lateral-move sprinkler irrigation system that applies ~25 mm per irrigation. The sowing rate was at 21 seeds/m^2. Late in the season, FI was reduced relative to the crop-water requirement (ET_c demand), so as to enhance crop maturation.

Reference evapotranspiration for input into *AquaCrop* was calculated using the FAO ET_oCalc computer programme (*FAO, 2009*) and weather data measured at a weather station close to the cotton field. *AquaCrop* field management parameters were set so that no runoff occurred (due to the furrow dikes), and soil fertility was non-limiting. Five soil depths were considered, with initial water contents of 23, 33, 34, 30, and 27 vol percent at depths of 0.10, 0.29, 0.45, 0.66, and 1.00 m, respectively, as measured in the field. The crop calendar was set as 10 days from sowing to emergence, 94 days from sowing to maximum root depth, 121 days from sowing to start of senescence, 140 days from sowing to maturity, 60 days from sowing to flowering, and 71 days the duration of flowering.

Results

Simulated yields were in the range of 3.3 to 3.6 tonne/ha, (equivalent to 1.3 to 1.4 tonne/ha of lint) and were comparable to values reported in the region. Deficit irrigation (DI) seed-lint yields were ~95 percent of full irrigation (FI) yields. The water productivity of DI cotton was ~10 percent greater than that of FI (both in the range of 0.49 to 0.54 kg/m^3(seed plus lint), or 0.19 to 0.21 kg lint/m^3). Crop ET was about 15 percent greater for FI than for DI, both in the range of 625 to 720 mm, which matches well observed values in several regions. However, DI received 240 mm of irrigation, only 43 percent of the FI amount.

Conclusions and recommendations

Farmers in the region pump from a water table about 90 m below ground and, given rising fuel costs, the energy savings of DI were more than US$250/ha. At cotton prices ranging from US$0.4 to 0.8/kg, the loss in production associated with DI represents only US$100 to 200/ha, giving the economic edge to deficit irrigation.

APPLICATIONS RELATED TO THE INFLUENCE OF FIELD MANAGEMENT AND SOIL PROPERTIES ON YIELD AND WATER USE

CASE 7 - Inf uence of field management on rainfed agriculture

Specific data requirements

- typical climate and soil characteristics as needed to run *AquaCrop*;
- crop specific characteristics as required to run *AquaCrop*; and
- current field management practiced by farmer (e.g. mulch or soil bunds under 'Management').

Approach

The simulation run with input data will generate a seasonal soil-water balance and yield. The field management practices that can be modified in *AquaCrop* should be tested, such as applying mulches and/or soil bunds. Also, using data for years of different rainfall amounts/ patterns, *AquaCrop* simulations can help assess the role of different field management on soil E and water supply to the crop and consequently, on yield under different rainfall in different years. The importance of runoff may be assessed by switching off the runoff calculations (under *Field Management*) or by changing the curve number (CN) or the amount of readily evaporable water (REW) for soil evaporation (under *Soil Characteristics*).

Output

The role of variations in field surface management on water-limited production may be assessed in order to derive recommendations from the simulations. In one example, run in a semi-arid area with irrigated maize to obtain an estimate of the role of mulches in the reduction of evaporation from soil, the E component under bare soil was 133 mm, and it was reduced to 90 mm when the soil surface was 100 percent covered with an organic mulch.

CASE 8 - Impact of variations in soil water properties and soil fertility levels

Specific data requirements

- average or typical climate and soil characteristics as needed to run *AquaCrop*;
- crop specific characteristics as required to run *AquaCrop*; and
- various soil water properties and soil fertility levels.

Approach

If the user is uncertain about the values of soil-water parameters and/or about the level of soil fertility and actual yield measurements for benchmarking, *AquaCrop* may be run varying the soil-water properties quite drastically (for instance, by selecting various soil types with different soil-water holding capacities) and then comparing the *AquaCrop* output yield across these simulations. If the user suspects that the level of fertility is not at its optimum, the option *Fertility stress*, under *Field management*, provides mild, moderate, and severe fertility stress levels that the user can utilize to simulate possible effects of limited nutrient supply on biomass production.

APPLICATIONS RELATED TO AGRONOMY AND CROP MANAGEMENT AT FIELD AND FARM SCALES.

CASE 9 - Benchmarking yield gaps in rainfed and irrigated agriculture and assessment of long-term productivity

Specific data requirements

- climate (long-term data set) and soil profile characteristics as needed to run *AquaCrop*;
- crop specific characteristics as required to run *AquaCrop*; and
- current practices related to irrigation management, fertilization, level of crop protection and other agronomic practices relevant to actual yields.

Approach

It is important to determine the differences between potential, attainable and actual yields (Loomis and Connor, 1992) at various scales, from a field to a region. If all information is available, the model should be run to determine the attainable yield for each year. Several years of data (standard is 30 years) would be desirable for the comparison of the long-term productivity under various production systems, using the cumulative distribution functions to show the relative risk levels.

Output

Given the actual yield information and the simulated yield, the capacity of rainfed environments and the yield gap (simulated minus actual yield) can be determined. Results from different years will give some clues as to the possible reasons for the yield gap (i.e. low soil fertility, pest, disease, and weed limitations, socio-economic constraints, or low-yielding crop varieties, etc.). A specific application of this approach for assessing wheat yield constraints in a region may be found in Calviño and Sadras (2002). Additional simulations with *AquaCrop* varying the scenarios, with possible remedial actions, would also help in identifying the possible underlying causes of the yield gap and identify regions and crops where substantial improvements in production and productivity may be possible. If combined with geographical information systems (GIS), yield gap maps for regions could be developed.

CASE 10 - Determining the optimal planting date based on probability analysis

Specific data requirements

- at least 20 years of ET_o and rainfall data are needed for the area; and
- crop and soil characteristics as required to run *AquaCrop* and representative of the area.

Approach:

Early, middle, and late planting dates are used to simulate 20 or more seasons with *AquaCrop*. For this application, *AquaCrop* should be run in the multiple project mode, as a minimum of 60 simulations need to be done. If a much larger number of runs are required, the plug-in version of the model should be used (downloadable at www.fao.org/nr/water/aquacrop).

Output

Once the yields for every year and for the different planting dates (keeping all other parameters the same) have been simulated, the values are organized from lowest to highest, for each planting date. If there are 20 years of simulations, each value represents a 5 percent probability. Then, the yield can be plotted against the cumulative probability graphically, and it is possible to choose the most favourable option with least risk from the graph or compare different options for years with differing conditions, say amounts of rainfall or El Niño phases.

A specific example of an *AquaCrop* application to determine the optimal sowing date for wheat as a function of the initial soil moisture conditions is reported in Box 2.

Box 2 Determining the optimal sowing date for wheat

Background

The *AquaCrop* model was used to analyse the optimum sowing date at three different initial soil water conditions under rainfed Mediterranean conditions. The importance of early sowing has been emphasized by many authors (Photiades and Hadjichristodoulou, 1984; Anderson and Smith, 1990 and Connor *et al.*, 1992), who reported a decline in yield when sowing is delayed after the first sowing opportunity (initial rainfall in autumn) within an optimum sowing window. Wheat yields are estimated to be reduced by 4.2 percent (Stapper and Harris, 1989) to 10 percent (Asseng *et al.,* 2008) for each week of any delay in sowing in autumn in Mediterranean environment. On the other hand, soil water conditions at sowing can also be important for wheat production, particularly in low rainfall regions (Rinaldi, 2004; Heng *et al.*, 2007; Asseng *et al.,* 2008).

Initial soil water from summer rainfall or left over from the previous year can influence early establishment of the crop and can contribute to water use and yield later in the season, in particularly in low rainfall seasons. Therefore, simulations were carried out with *AquaCrop* to determine the optimal sowing date in relation to initial soil water to maximize wheat grain yields.

Location and simulation experiments

The site of the simulation experiments was selected within the northern part of the Western Australia wheat-belt, at Buntine (29.51°S, 116.34°E, 365 m elevation) one of the main wheat-growing regions of Australia, where wheat is grown under rainfed conditions. The location is a relative low-yielding environment with a typical Mediterranean-type climate. Rainfall mainly falls in winter, but varies from season-to-season in terms of seasonal distribution and amount. Rainfall quickly declines in spring during grain filling. Average long-term annual rainfall is 329 mm. Average seasonal (May to October is the main growing season in the Southern Hemisphere) rainfall was 243 mm over the last 30 years period (1979-2008), varying between 125 and 417 mm. In such an environment, a mild winter is followed by increasing temperatures in spring.

Box 2 (CONTINUED)

A common soil for the study region was used in the simulation experiment, a loamy sandy soil with 101 mm of plant available soil water to the maximum rooting depth of 1.7 m.

Simulations were carried out using measured daily weather records from 1999 to 2008. Crops were sown when rainfall was at least 20 mm during the previous 10 days during a sowing window of May to July and again at 30 days after the first sowing opportunity as a delayed sowing practice (e.g. to manage weeds or due to technical limits of sowing all crops early on a farm).

Each sowing date treatment was simulated with an initial soil water of 0, 30 and 60 mm plant available soil water stored below 20 cm depth. The earliest sowing date possible was 1 May, the date at which the initial soil water conditions were set every year. Nitrogen was assumed to be not limiting for crop growth.

A bread-wheat spring cultivar was used in the experiments, cv. Wyalkatchem, a standard early-medium flowering cultivar for this region. Conservative parameters based on typical growth and development in the considered environment were used as inputs (See wheat Section in Chapter 4).

Results

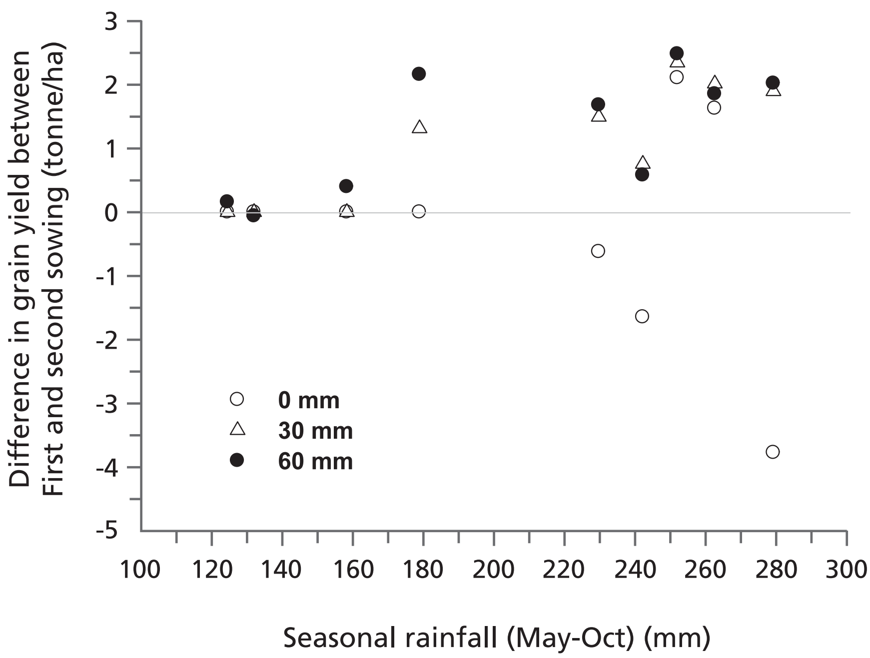
The simulated differences in grain yields between the first and the second sowing dates as a function of the seasonal rainfall for different initial soil-water contents are shown in Figure 1. Simulated differences in grain yield became negative at zero mm of initial soil water, but were positive at 30 and 60 mm initial soil water. When the soil profile was dry, 70 percent of the crops sown with an early sowing opportunity failed, while this percentage decreased to 40 percent with the second sowing date. But, crops which were sown early in to dry subsoil with the first rainfall in autumn which did not fail yielded on average 30 percent more than the second sowing date. On average, the first sowing yielded 35 percent more than the second sowing with 30 and 60 mm of initial water, but 13 percent less with zero mm of initial soil water.

Conclusions and recommendations

The results of the simulation experiments indicate that in a Mediterranean environment, sowing a wheat crop early with the first rainfall events in autumn can give higher yields, consistent with other simulation and field experimental studies. However, early sowing can increase the risk of crop failure if the subsoil profile is dry at sowing. Therefore, early sowing is only warranted if there is some initial soil water in the soil profile from summer rainfall or left over from the previous year. If the soil profile is dry at the beginning of the season, delaying sowing, despite some loss of yield potential, reduces the risk of crop failure in such an environment.

Box 2 (CONTINUED)

FIGURE 1 Differences in simulated grain yields between the first and the second sowing opportunity as a function of the seasonal rainfall at different initial soil water (0, 30 and 60 mm) for the period between 1999 and 2008 at Buntine, Western Australia.



In similar regions, but with water resources available for irrigation, applying a small amount of water (about 30 mm) before sowing will significantly reduce the risk of crop failure with an early sowing opportunities and would allow to maximize yield potential in such an environment.

CASE 11 - Developing water production functions with *AquaCrop* and using them in Decision Support Systems

Specific data requirements

- average or historical series of preferably 20-30 year, or at least 10 years, of data on ET_o and daily rainfall; and
- crop and soil characteristics necessary to run *AquaCrop*.

Approach

Two approaches may be used: (i) with the average climatic records, the user will simulate the yield response to different amounts of applied irrigation (IW) changing the level of application in 30-50 mm step intervals ('Irrigation Events' tab sheet in 'Irrigation Management'); (ii) if a climate dataset is available as historical series, simulate the yield response to different amounts of IW using each year of the available climate records. This will yield a family of curves from which a mean curve and probabilities of exceeding a certain yield value could be derived (see Case 10).

Output

An example is shown in Figure 2 of the results of simulating potato production with *AquaCrop* over 25 years of climate with varying irrigation levels (García-Vila and Fereres, 2012). The resulting curves could serve as inputs in economic models to build decision support systems that would aid farmers to determine the optimum irrigation level to maximize economic profits under specific sets of conditions. Another example is shown in Figure 3 for the quinoa crop (Geerts *et al.*, 2009). This crop has a unique response in that the yield-ET relationship is not linear but curvilinear (Figure 3a). The simulated yield data points for different levels of ET vary because of differences in irrigation timing. The envelope curve of the data points giving the highest yield values represents optimal DI regimes for the different ET levels. In Figure 3b, the region with the highest yield water productivity is indicated, and from the graph, the optimal level of ET may be defined (Geerts *et al.*, 2009).

FIGURE 2 Simulation of potato yields as a function of applied irrigation water with *AquaCrop* for 25 years of data at Cordoba, Spain. The three yield-response curves represent the average response and the expected response on a good (wet and relatively warm) and bad (dry and cold) climatic year (García-Vila and Fereres, 2012).

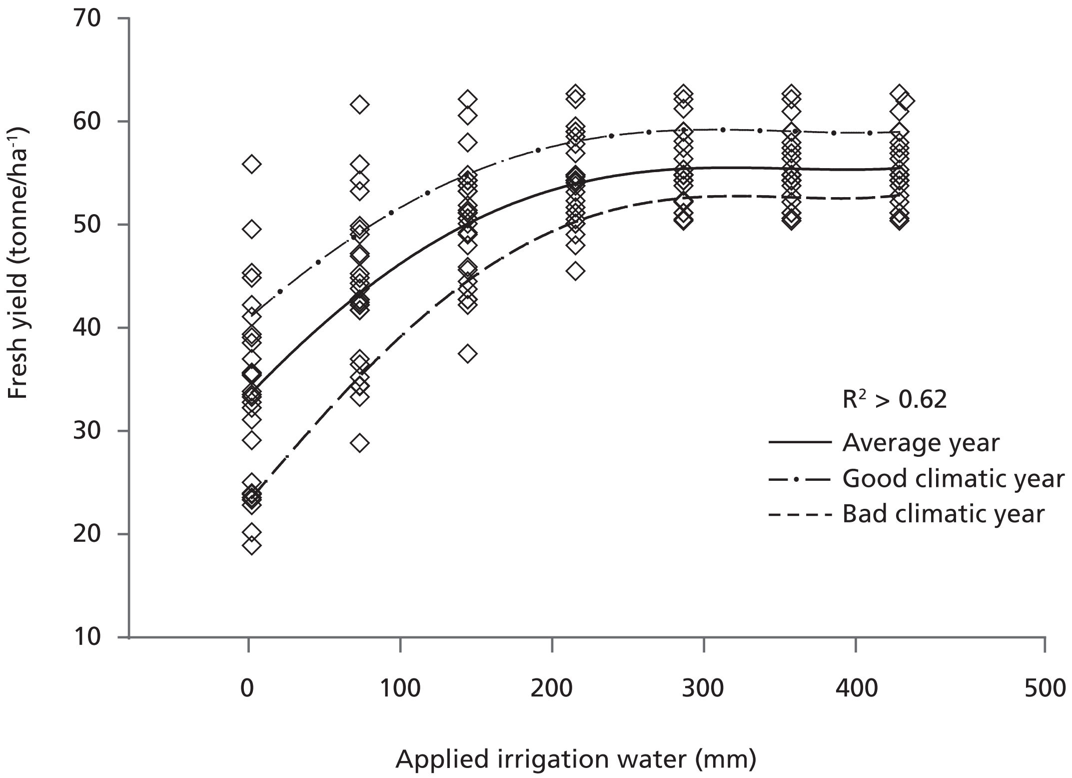
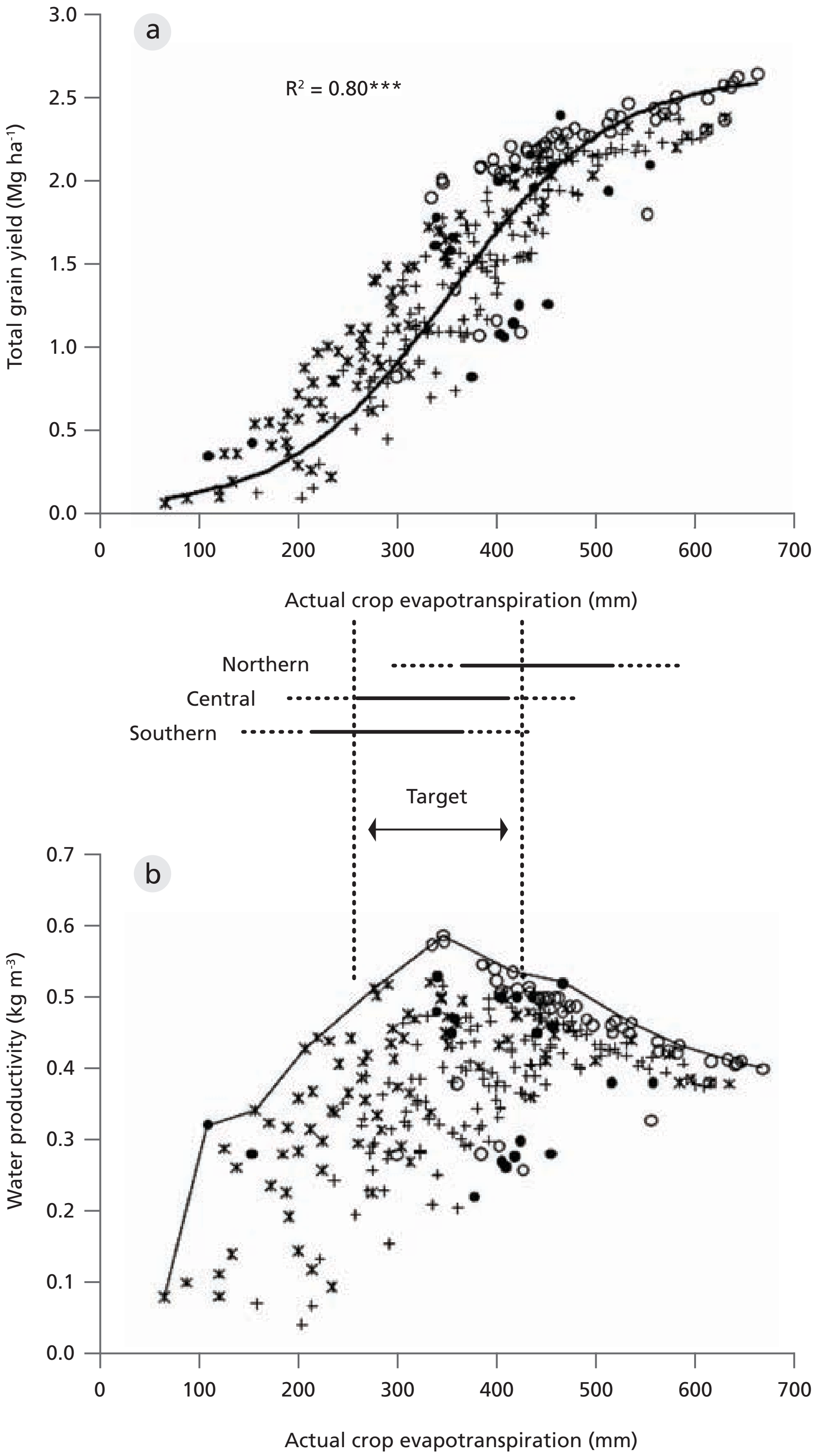


FIGURE 3 (a) Simulated yields of quinoa with *AquaCrop* as a function of ET, from rainfed to full irrigation, and for different deficit irrigation regimes; (b) Water productivity as a function of ET, showing the optimal levels for intermediate levels of ET induced by optimal DI regimes (Geerts *et al.*, 2009).



CASE 12 - Assessing the effects of plant density on yield

Specific data requirements

- average climate data representing a typical year; and
- crop and soil data needed to run *AquaCrop* for average or most probable field conditions.

Approach

Plant densities have been optimized in commercial plantings of most crops; however, there are situations where it is necessary to assess the role of plant density on water use and yield. To judge the impact of drastic changes in plant population on yield, the user should try a range of quite diverse values of plant density (which can be specified in the *Development* tab sheet under *Crop Characteristics*) and change accordingly the maximum canopy cover that can be reached (CC_x). The resulting changes to the parameters CC_o and CC_x would allow the evaluation of the role of these two features in canopy development, and hence on yield.

Output

In one example, contrasting densities (30 000 vs. 75 000 plants per ha) for rainfed maize grown in California on a very deep, fertile soil with the profile nearly fully charged at the time of planting were compared. Yield was 4.7 tonne/ha for the low density, and 4.2 tonne/ha for the high density. The main reason for the difference in yield is due to a slightly higher HI for the low density (0.31 vs. 0.28) because less water is transpired early in the season as a result of a smaller canopy, leaving a little more water to allow the canopy to stay green longer, with the corresponding longer build-up of HI.

BEYOND THE LEVEL OF FIELD AND FARM: APPLICATIONS RELATED TO THE EFFECTS OF WEATHER AND CLIMATE ON CROP PRODUCTION AND WATER USE

CASE 13. Assessing the impact of rainfall variability on water-limited yields

Specific data requirements

- a long-term series of daily rainfall and ET_o, for at least 20 to 30 years;
- typical rainfed crop of the area; and
- representative soil and management conditions, as needed to run *AquaCrop*.

Approach

AquaCrop will be run with a selected crop, preferably one grown in the rainy season, for every year where data is available. The climate dataset will include years with a range of annual rainfall, and also some years having the same annual rainfall but with different distribution through the season.

Output

Yields and other parameters will be obtained for all the simulations performed. If the runs cover a sufficiently large number of years, yield probability curves as a function of annual rainfall could be generated (see explanation in Case 9; or example output in Geerts *et al.*, 2009).

CASE 14 - Mapping water-limited yield potential of a region

Specific data requirements

- average or historical climate data (rainfall and ET_o) processed in GIS mapping data-set; and
- typical rainfed crop with representative soil and management conditions, as needed to run *AquaCrop.*

Approach

This application would require the use of the *AquaCrop* model with a GIS that would allow the spatial simulation of yield, based on maps of ET_o, rainfall, soil profile characteristics, as well as the crop features required to run the model. An example is the FAO-MOSAICC project that being developed in the framework of the EC/FAO Programme on *Linking information and decision-making to improve food security*, Theme 3 *Climate change and food security* (http://www.fao.org/climatechange/mosaicc/en/).

CASE 15 - Climate Change effects on crop production and water use

Specific data requirements

- climate data processed to simulate future climate change conditions; and
- typical crops with representative soil and management conditions, as needed to run *AquaCrop.*

Approach

a) Global warming effects on simulated yields and water use

The effects of the increased temperatures on ET_o and crop development (predicted with climate change) can be simulated with *AquaCrop*. If there are regional predictions that permit the generation of future daily weather data, such data would be the input of *AquaCrop* simulations, thus providing prediction of changes in yield and water requirements. The model can also be used to quantify the climatic risk associated with various management options (e.g. changing varieties, short vs. long season cultivars, irrigation input and low dosage of fertilizer) to help farmers choose low-risk management options to suit household resource constraints. Dimes *et al.*, (2009) have assessed the climate change effects in some areas of Southern Africa using the simulation model APSIM.

b) Integration of global warming and of increase in greenhouse gas concentration

Aquacrop simulations respond to changes in CO_2 concentration, thus it is possible to evaluate the interactive effects of the increase in temperatures, the more scattered rainfall and of the increase in CO_2 in the atmosphere in future climates. Different scenarios may be introduced, including a variable sink capacity (Vanuytrecht *et al.*, 2011) as provided in *AquaCrop*, following predictions of the regional climate change models.

CASE 16 - Using *AquaCrop* for water allocation decisions at basin or regional levels

Specific data requirements

- climate data processed to represent average, adverse or favourable climate conditions; and

- typical crops with representative soil and irrigation management conditions, as needed to run *AquaCrop.*

Approach

AquaCrop outputs may be the input of water allocation optimization models that have strong economic and institutional components. Such models are needed to assist in the management of water by institutions in charge of water governance. *AquaCrop* inputs would be particularly valuable in the event of a drought, where different scenarios are considered and yield/income predictions for the area are essential to make informed decisions when allocating limited supplies. One example of an application at the farm scale is given in García-Vila and Fereres (2012).

Conclusion

These case studies are a small sample of the applications that may be possible to tackle with the assistance of *AquaCrop* and illustrate the use of the simulation model. The examples have also illustrated the possibilities that *AquaCrop* offers for various types of users – namely irrigation specialists, agricultural engineers and agronomists, agricultural extension personnel. Additional users include water engineers, hydrologists, and economists working at catchment scale and climate scientists wanting to investigate the effect of different climate change scenarios on the water-use of various crops. There are many more applications of *AquaCrop* that may be used in practical ways and which will be revealed as users around the world incorporate this simulation model in their assessments of crop yield response to water.

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3.3 *AquaCrop* parameterization, calibration, and validation guide

This guide is mainly for *AquaCrop* users with an agronomic background and some experience of crop modelling, and for those needing to: simulate the productivity of a crop already parameterized, but not yet validated for their specific conditions; calibrate the model for a crop not yet parameterized; or to improve the parameters already worked out by others and to validate them for the same crop. These users should be acquainted with all Chapter 3 of this publication and the Reference Manual which can be downloaded from the FAO *AquaCrop* website (www.fao.org/nr/water/aquacrop). Users with less experience and background, who need more detailed instructions to run simulations with *AquaCrop* already calibrated for a particular crop, should download the instructions for *Group 1 Users* from the same website.

IMPORTANT DISTINCTIONS OF MODEL PARAMETERS

Conservative vs. user-specific parameters

AquaCrop is designed to be widely applicable under different climate and soil conditions, without the need for local calibration, once it has been properly parameterized for a particular crop species. To this end the model is constructed with parameters falling into two groups. One group is considered conservative, in that the parameters should remain basically constant under different growing conditions and water regimes. The other group encompasses parameters that are dependent on location, crop cultivar, and management practices, and must be specified by the user. A critical stipulation for many of the conservative parameters is that their values are based on data obtained from modern high-yielding cultivars grown with optimal soil fertility without limitation by any mineral nutrient, particularly nitrogen. With some notable exceptions, it is also stipulated that values are based on data obtained when water is not limiting. It follows that, if the conservative parameters already calibrated for a given crop do not provide simulated results, matching measured data for a crop in a particular case, the first thing to check is that mineral nutrients are not limiting the growth of the crop. To keep the model relatively simple, *AquaCrop* does not simulate nutrient cycles and nutritional effects on the crop directly. Instead, a way is provided in the 'Biomass' *tab sheet* to account for nutritional effects after performing a calibration based on the reduction of biomass produced by a nutrient-deficient treatment.

Cultivar classes

For simplicity, the parameters are grouped into two categories, as described above, in reality some of the parameters assigned to the conservative group may vary within small limits for different cultivars of the crop species. This brings up the need for a new term, ‘cultivar class’, to designate cultivars of a crop with very similar values of conservative parameters, to distinguish them from cultivars of the same species but differing by a limited amount in one or more conservative parameters. Take maize cultivars as an example. The reference HI for a number of maize cultivars has been parameterized at 48 percent (*Hsiao et al., 2009*), and together they comprise one cultivar class. If two or three other cultivars are found to have a higher reference harvest index (e.g., HI=51 percent), they would constitute another cultivar class. It is anticipated that over the long term, plant breeding and biotechnology will alter a number of the conservative parameters, increasing the number of cultivar classes.

INPUT INFORMATION AND DATA FOR VALIDATION AND PARAMETERIZATION

Table 1 lists the required information for using the model to simulate production and water use. The first column lists the absolutely required minimum. If this is the only available information, the simulated results would at best be first order approximations. The second column of the table lists additional information needed to make the simulation more reliable. In this case, agreement between the simulated and observed biomass production and yield should not be considered as validation of the model, unless the agreement is observed for several water regimes and for more than one climate. Essentially, the more exact and detailed information, the more close to reality would be the simulated results.

To validate the model and to parameterize the model, more detailed and exact data are needed, as listed in Table 2. The first column lists the minimum information needed in addition to that in Table 1 for a reasonable validation of the model or initial calibration of the conservative parameters. The second column lists the additional information needed to validate the model for general use, and calibrate the conservative parameters for a wide-range of climate, soil, and water regimes. In the validation and parameterization process, attention must be paid equally to how well the simulated results (canopy cover, biomass, and consumptive water use) agree with the measured values as time progresses through the season, as well as the total biomass, yield and total ET at crop maturity.

ITERATION, ASSESSMENT OF SIMULATION RESULTS, AND REFINING OF PARAMETERS

The common practice is to run simulations with the model starting with estimated or guessed parameter values and than compare the output with the measured experimental data, then adjust the parameters and run the simulation and compare again. This is done repeatedly until the simulated results closely agree with the experimental data. Trial-and-error iterations being the heart of the process, how can the process be streamlined to minimize the time and effort required? Some general rules may be helpful.

Rule 1: The better one understands the principles underlying the model, its flow diagram, and the flow of calculation steps, the more capable one would be in identifying the likely input or

TABLE 1 Information and data needed for simulation of crop growth, yield and water productivity with *AquaCrop*.

	1. Absolute minimum	2. Additional for reliable simulation
Crop	Grain yield, and indication of the proportion of grain dry weight to above-ground biomass, i.e. rough idea of harvest index (HI) Planting and harvesting dates (can be approximate), and estimated crop life-cycle length Seeding rate and germination percentage	Above-ground biomass at harvest Date of emergence (either the start of or nearly full emergence) and date of grain maturity Plant density; estimated maximum rooting depth Maximum green leaf area index (LAI) or indication of the extent of maximum canopy cover or canopy cover at a given time
Climate and ET	Ten-day or monthly mean values of: minimum and maximum temperature, and indication of fraction of sunny days, and wind and humidity regimes. Latitude and elevation Alternatively, pan evaporation data with information on the type of pan and whether the pan is set in a dry or green surrounding, to estimate reference evapotranspiration (ET_o) Daily rainfall data (10-day or monthly mean not recommended although better than none)	Weekly or 10-day mean values of: daily solar (global) radiation or sunshine hours, minimum and maximum temperature, minimum and maximum relative humidity, and wind run Daily rainfall Evapotranspiration (ET) estimated by long-term water balance
Soil and fertility	Textural class of the soil and indication of variation with depth Indication of land slope and soil-water holding capacity Indication of native fertility of the soil General fertilization practice	Texture of the various layers (or horizons) of the soil, and any layer restrictive to root growth and its depth Kind, rate and time of fertilization
Irrigation and water in soil	Water application method and approximate irrigation schedule Rough idea of soil-water content at planting based on rainfall of past months and the crop grown before the current one	Actual irrigation dates and rough amounts Estimate of soil-water content at planting based on some measurement or close observation

parameter to adjust, and in what direction. To this end, any time taken to read the three initial publications on *AquaCrop* (Steduto *et al.;* Raes *et al.;* Hsiao *et al.,* all 2009) is worthwhile.

Rule 2: Always pay attention to the graphic display of the *Climate-Crop-Soil water tab sheet* on the simulation run page, as well as the output numbers of the *Production* and the *Climate and water balance tab sheets*. By switching the simulation run to advance in time steps, one can see how the crop and soil water change step-by-step. The graphic display is particularly useful for water limited conditions to see whether the crop canopy cover (CC), transpiration relative to potential transpiration, and acceleration of canopy senescence are reasonable or need adjustment.

TABLE 2 Additional information and data needed for parameterization and validation of *AquaCrop*. The required data include those not mentioned here but listed in Column 2 of Table 1.

	1. Minimal additional beyond Column 2 of Table 1	2. Additional for reliable parameterization
Crop	Periodic measurements of leaf area index (LAI) or canopy cover over the season Periodic measurements of above-ground biomass over the season Date when foliage canopy begins to turn visibly yellow Measured rooting depth Signs of water stress and dates	Data as in Column 1 but obtained at several locations and climates on different soil types
Climate and ET	Daily maximum and minimum temperature and humidity Daily solar radiation and wind run ET by soil water balance (optional)	Data as in Column 1 but obtained at several locations and climates for different soil types Measured daily ET
Soil and fertility	Must have one treatment with optimal soil fertility Field capacity and permanent wilting point of soil horizons Infiltration rate or saturated hydraulic conductivity of the soil	Data as in Column 1 but obtained at several locations and climates for different soil types
Irrigation and water in soil	Must include a well-watered (full irrigation) treatment and water-stress treatments Amount of water applied at each of the irrigations Measured or good estimate of soil-water content for different soil depths at planting Periodic measurements of soil-water contents at various depths of the root zone (optional alternative to soil-water balance)	Data as in Column 1 but obtained at several locations and climates for different soil types Must include treatments with water stress at different times and different severities

Rule 3: Differentiate the input information and measured or observed data according to their reliability and exactness, and make rational adjustment to the vague or rough estimates of input first to see if the simulated results better match the measured results, before changing the model parameters. In later Sections, many of the uncertainties of the input information or data, and the measurements taken on crops, are mentioned and discussed to decide which inputs can be altered based on a rational evaluation of its likely range of uncertainty.

Rule 4: When simulated results and measured data do not agree, the problem could also be in the measured data. If simulated results coincide with measured data obtained in several different studies, but not with that of another study, the data in the other study are more suspect and additional data sets should be sought to complete the validation or parameterization.

LOCATION AND USER SPECIFIC PARAMETERS AND INPUT

Climate and soil are location specific, and crop cultivar, timing of crop cycle, water management and agronomic practices are user specific.

Climate data and reference evapotranspiration (ET_o)

AquaCrop simulates in daily time steps because plant responses to water status are highly dynamic and cannot be easily represented as weekly or 10-day means. The model runs with 10-day or monthly mean temperature and ET_o files, through interpolations. The results are, however, obviously approximations, and should not be used to calibrate or validate the model except as the last resort. ET_o is a key input for *AquaCrop* as the model calculates daily crop transpiration (Tr) and soil evaporation (E) using daily ET_o values.

ET_o is to be calculated using the FAO Penman-Monteith equation from full daily weather data sets, as described by Allen *et al.* (1998). A programme to do this calculation, named ET_o Calculator (FAO, 2009) is available on the FAO website. The ET_o Calculator has the advantage of allowing approximations when one or several kinds of the required weather data are missing, also following the approximation procedure of Allen *et al.* (1998). This makes it possible for a user to run rough simulations, even when the weather data are minimal, but can be easily misused. For validation and parameterization, such approximation should not be relied upon. The rougher the approximation of ET_o, the less reliable would be the simulated results and derived *AquaCrop* parameters. For example, ET_o Calculator can use daily maximum and minimum temperature, relative humidity, wind run, and sunshine hours in place of radiation, to calculate ET_o, and also can calculate ET_o simply from daily minimum and maximum temperature data and general information on site location such as whether it is arid or humid and windy or calm. Obviously, the ET_o calculated from the sunshine hours would be somewhat less reliable than that calculated with daily radiation, and the ET_o simply estimated with the daily minimum and maximum air temperature would be essentially worthless for the purpose of model validation and parameterization. Thus, it must be understood that reliable climatic data are critical in *AquaCrop*.

Growing degree day (GDD)

AquaCrop is designed for use under different climatic conditions and hence should be parameterized in the growing degree day (GDD) mode to account for different temperature regimes. This may be difficult, however, because many users may only have data for their specific locations with their limited temperature range. In this case, it is best to select data obtained when cold temperature is not a limiting factor and run the model first in the calendar time mode for parameterization. After arriving at reasonably acceptable parameter values, by switching the model to the GDD mode, the parameters are automatically converted to units in terms of GDD. The challenge is then to define: (1) the base temperature and upper temperature to calculate the GDD, and (2) the temperature thresholds for biomass accumulation and for pollination and fruit set of the specific crop. These are to be discussed later.

Soil water characteristics

In *AquaCrop*, the extent of water limitation is expressed as a fraction of the total available water (TAW) in the root zone, with TAW defined as the water held in the soil between its field capacity (FC) and permanent wilting point (PWP). In the case that the soil has layers differing in FC and PWP, the different values for the layers encompassing the maximum rooting depth need to be entered into the model.

Accurate FC and PWP are only important to specify the local conditions if water is a significant limiting factor. If the simulation is for conditions where water is either not limiting or only minimally limiting, approximate FC and PWP would do, but the water-stress functions (threshold and curve shape) derived cannot be relied on for conditions limited more by water deficits. Approximate FC and PWP may be estimated simply from the textural class of the soil. In *AquaCrop* there are default soil files for a number of textural classes. In each file the relevant water parameters are given in the 'Characteristics of soil horizons' *tab sheet*. More accuracy is required to calibrate the model for the various water-stress functions using data obtained when water is limiting.

Spatial heterogeneity of the soil can be a problem for accurate simulation for a given water limiting location, because FC and PWP, and hence TAW, can vary sufficiently from area-to-area in a field, reducing the accuracy of the simulated results for the field. If data are available for different parts of a field, simulation should be run for each part of the field that differs in soil water characteristics.

Saturated hydraulic conductivity (K_{sat}) of the top soil determines the internal drainage in the soil profile, losses from deep percolation and the amount of water infiltrated in the root zone and the surface runoff after an irrigation or rainfall. Surface runoff is only important if the amount of water applied per irrigation is excessive or the rainfall is intense and heavy. In such situations, the measured K_{sat} should be used for simulation. If measured value is unavailable, the default value provided by *AquaCrop* for the given soil textural class (based on the difference in soil-water content (θ) between saturated soil and FC) should be adjusted according to general knowledge of the local condition.

Initial soil water content

Another local specific factor is the initial water content of the soil for the maximum rooting depth at start of the simulation run. If the values are not measured, estimates may be made based on knowledge of the local climate, particularly rainfall, and the preceding crop or weed history. For example, for a climate with winter rainfall, sufficient to completely charge the soil profile, and dry summer, and the field is kept fallow and weed free, one may assume the deeper layers of the soil to be at FC but reduce soil-water content of the upper layer of the soil by estimating the extent of soil evaporation taking place before the simulation starting time. If weather data before the starting time of simulation are available, *AquaCrop* can be used to make that estimate by setting the start time as the end of the last significant rain. If weeds are present, however, some estimates would have to be made on canopy cover (CC) of the weed in order for *AquaCrop* to simulate a reasonable profile of initial soil-water content.

Crop phenology

Many of the differences among crop cultivars are related to the timing of developmental stages. The timing to reach a particular stage, or its duration for the local cultivar, needs to be specified by the user. These stages are: time to 90 percent seedling emergence, to the beginning of flowering, to the beginning of canopy senescence, and to physiological maturity, and the duration of flowering.

Time to 90 percent emergence

The particular choice of time to 90 percent emergence is explained later, under **Initial canopy size per seedling**. In nearly all the cases, this time is likely to be estimated and not determined by actual counting of the seedlings. It should be adjusted to have a good match between the simulated and measured canopy cover (CC) at the seedling stage and in early season. The adjustment, however, should be taken only after the relevant conservative parameters (initial canopy size per seedling and canopy growth coefficient) are well parameterized and the plant density is ascertained.

Time to start of f owering and duration of f owering

For determinate crops with their short flowering duration (e.g. 15 days), it is important to have an accurate time for start of flowering. For indeterminate crops with their long flowering duration, the timing can be more approximate. In cases where there is no significant water stress, the model is constructed in such a way that timing of flowering does not matter.

Time to maximum canopy cover

This parameter is provided in *AquaCrop* to allow simulation runs when the conservative parameter, canopy growth coefficient (CGC) of the crop, is not known, and should be used only as a last resort. See the later section **Canopy growth coefficient** for more explanation.

Time to canopy senescence

In *AquaCrop*, the timing to the start of canopy senescence is defined as the time when green leaf area falls to or below LAI = 4 as a result of yellowing of leaves, under optimal conditions with no water stress. By this definition, if the plant density is low and the maximum LAI is less than 4.0, canopy senescence starts once there is significant senescence of lower leaves. But if the maximum LAI is considerably higher than 4.0, enough of the lower leaves must senesce to reduce LAI to 4.0 before the canopy is considered to be at the beginning of senescence.

Time to physiological maturity

Different crop species may each have its own specific definition of physiological maturity (e.g. black layer formation in maize grains). To be general, however, *AquaCrop* uses as default the time when canopy cover is reduced to 5 percent of the achieved maximum canopy cover as the time of maturity. Users can change the maturity time according to their own data on the Canopy development *tab sheet*. Clearly, maturity is closely linked to the time of canopy senescence, and this may be one practical way to estimate maturity time if no detailed determination of maturity is made. Seed companies usually supply information on the life-cycle duration of their cultivars. This, however, can be very general, in terms of short, medium, or long season. The information can also be given in degree days, but unfortunately defined in ways different from that used in *AquaCrop*. For accuracy, experimental observations or data are necessary to determine the time to maturity. It would be justified to take the time when only a little green leaf area remains in the canopy as the time of maturity.

Rooting depth and deepening rate

Root development is highly site specific because of differences in soil physical (temperature, mechanical impedance, and aeration) and chemical (pH, salinity, and high levels of aluminum or manganese) characteristics, which strongly affect root growth. When soil conditions are all highly favourable, the root-deepening rate is likely to be in the range of 20 to 25 mm per day for many crops. The probable exceptions are crop species known for their shallow roots.

On deep soils with no layers restricting root growth, as default *AquaCrop* stops root deepening once the time for canopy senescence is reached (for no stress conditions). There is a notion in the literature that roots do not grow or deepen beyond the pollination stage of a crop. Good data on various crops show, however, that roots deepen after pollination, albeit at a slower rate. For soils of limited depth, but also with no growth-restricting layer in between, roots deepen at the normal rate in *AquaCrop* but stop abruptly when the bottom of the soil is reached.

In cases where the observed rooting is too shallow; although the soil is deep, some characteristic of the soil or soil layer may be inhibiting root growth. To approximate the situation with *AquaCrop* there are two possible means. One is simply to reduce the average deepening rate throughout the soil profile, by setting the maximum root depth at the beginning of canopy senescence at a point so that the root depth observed at a particular time matches that displayed by *AquaCrop*. The other approximation is only applicable to situations where root growth is inhibited more as the soil depth increases. By raising the shape factor of the root depth vs. time curve to the 2.5 to 3.0 range in the *Root deepening tab* under *Development* of the Crop file, the deepening rate would start high and slows with time as the roots go deeper. *AquaCrop* also offers the possibility of specifing the soil depth of a restrictive layer blocking root zone expansion as a soil characteristic in the *Restrictive soil layer* tab sheet.

CONSERVATIVE PARAMETERS

Temperature effects

Most temperature effects on crops are accounted for by using the GDD in place of calendar time as the driver, for which the setting of base and upper (cutoff) temperature are critical, and also by the use of ET_o. In addition, three temperature effects should be accounted for by other means. These are inhibitory effects, of low temperature on the conversion of transpiration to biomass production and on pollination, and of high temperature on pollination.

Base and upper temperature

The base temperature may be thought of as the lower threshold for crop growth and development. The upper temperature is the limit above which further increase in temperature has no effect on the rate of progression. The GDD calculation in *AquaCrop* is according to 'Method 2' as described by McMaster and Wilhelm *(*1997*)*, but with an important modification, that no adjustment is made of the minimum temperature when it drops below the base temperature. The base and upper temperature are usually selected in modelling work by trial and error by running simulation models for data collected in different temperature regimes. In terms of guiding principles, C_4 species are generally more cold sensitive than C_3 species, winter crops are obviously more cold tolerant than spring and summer crops, and crops with higher base temperature would benefit from warmer temperature (higher upper temperature). Base temperature for crops, such as barley and wheat, are generally taken to be 0 °C in most crop models, whereas for C_4 summer crops such as maize it is 8 or 10 °C. Upper temperature has been set at 30 °C for maize and 32 °C for cotton, but at 26 °C for wheat in *AquaCrop*.

If the experimental data used to test *AquaCrop* were obtained in a climate where the temperature does not often fall around the base temperature or above the upper temperature, the exact value of these two thresholds, as long as they are reasonable, would not likely make much difference in the simulated results. On the other hand, the difference may be large if the temperature often hovers around the base temperature or rises substantially above the upper temperature. In this case, it is necessary to refine the threshold values, best by securing data sets of the crop grown in other temperature regimes and by trial-and-error to arrive at the most reasonable temperature thresholds.

Low temperature effect on converting transpiration to biomass production

When simulating periods around the base temperature using *AquaCrop*, it was found that the model overpredicted production, probably because transpiration, mostly a physical process, is less inhibited by cold than photosynthesis, a complex metabolic process. It was then decided to apply a logistic function to arbitrarily reduce the amount of biomass produced per unit of normalized transpiration according to the magnitude of GDD each day, with an upper threshold GDD where the reduction begins, and a lower GDD fixed at GDD = 0, where conversion is reduced to zero. Generally, the upper threshold should probably be set in the range of 6 to 10 GDD.

Low and high temperature effects on pollination

These effects are also dealt with by arbitrary reductions using logistic functions, with temperature as the independent variable. The reduction starts at the upper threshold temperature for the cold effect, and the lower threshold for the high temperature effect. Pollination is completely inhibited when the temperature drops to 5 ^{o}C below the upper threshold for the cold effect, and when the temperature rises 5 ^{o}C above the lower threshold for the high temperature effect. Generally these inhibiting temperatures fall outside the temperature regimes favouring the growth and production of a given crop class.

Canopy cover and related parameters

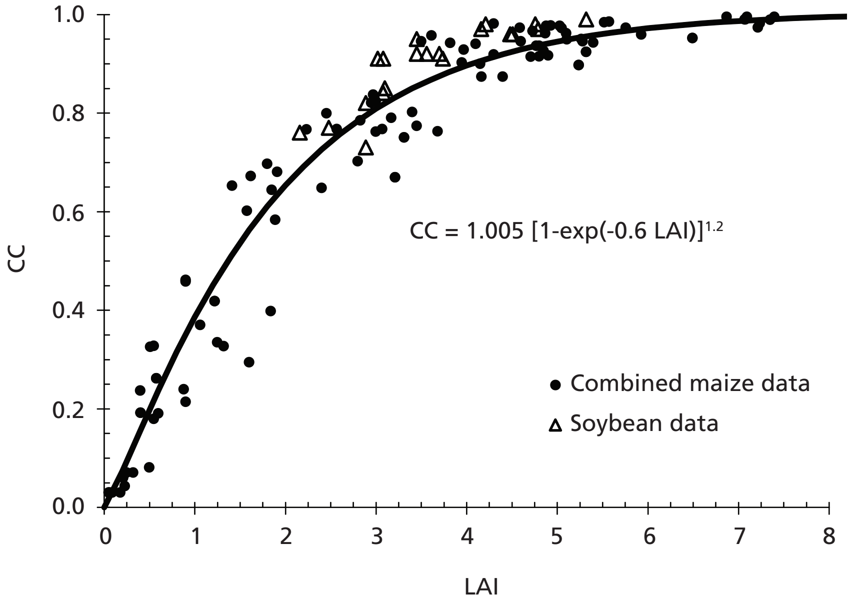
Converting leaf area index (LAI) data to canopy cover (CC)

AquaCrop simulates transpiration in terms of canopy cover (CC) of the crop, but often experimental studies measure LAI but not canopy cover, especially in earlier studies. During the parameterization of *AquaCrop* for maize (Hsiao *et al.,* 2009), a conversion equation, $CC = 1.005\ [1 - \exp(-0.6\ LAI)]^{1.2}$ was arrived at and used to analyse the literature of maize and soybean data (Figure 1).

Crops differing substantially in canopy architecture would have CC-LAI relationships different than that of Figure 1. Several recent reports on such relationships may be found in the scientific literature.

It should be noted that, during the canopy senescence phase, there is no simple way to measure CC, which refers to only green cover, because green and yellow leaves intermingle and some leaves are partly green and partly yellow. Hence, converting measured LAI to CC is the only way to obtain CC values during this crop phase.

FIGURE 1 Canopy cover (CC) in relation to leaf area index (LAI), based on data obtained for maize (combined data of several treatments and years) and soybean. The curve, described by the equation (*Hsiao et al., 2009*), represents the regression line revised slightly at the extreme low and high ends of LAI according to theoretical expectations.



Initial canopy size per seedling (cc_o)

Initial canopy cover per unit land area (CC_o) is computed from the mean initial canopy size per seedling (cc_o) and the plant density, that is, $CC_o = cc_o$ x plant density. CC_o is taken to be the canopy cover on the day of 90 percent emergence. At this stage, the average seedling is likely to be at the start of autotrophy and its growth begins to obey the equation for the first half of the canopy expansion (Equation 3 of Section 3.1).

Ideally, cc_o should be measured on seedlings of the chosen species, about 3 to 4 days after emergence, when the leaf or leaves turn fully green. At this stage, instead of measuring CC, the green leaf area of a seedling can be measured and used to approximate cc_o with a small downward adjustment (e.g. cc_o being 10 percent or 15 percent less than leaf area per seedling). The alternative is to derive cc_o indirectly, from data of CC taken at different times and plant density using the CC growth equations of *AquaCrop*. This approach is described fully later, when the parameterization of CGC is discussed. Regarding cc_o, one guiding principle is that for the variety of crop species, initial canopy size per seedling (cc_o) is generally correlated with mass per seed. Take an example of three crops, the relative sizes of cc_o are: maize > wheat > tomato, the same ranking as the relative mass per seed for these crops. Another guiding principle is that crops of similar nature and similar seed size should have similar cc_o. Thus, the cc_o value for wheat should be a good starting point for cc_o of barley, and the cc_o value for cabbage should be a good starting point for cc_o of canola.

Maximum canopy cover (CC_x)

When the planting is sufficiently dense, the theoretical upper limit for CC_x is 1.0, but in practice CC_x seldom reaches 0.99 and often lies in the range of 0.95 to 0.99 even for unusually high plant densities. This range is referred to in this writing as full canopy cover and the time when this is reached is referred to as canopy closure. However, these terms are used rather loosely in the literature, and can be referred to CC substantially less than 0.95, as low as 0.9 or even lower in some writings. As a general guide, CC is 0.95 or higher when LAI exceeds about 4.5 or 5.0 (Figure 1), with some exceptions. One exception is species exhibiting strong sun-tracking behaviour, such as sunflower, which requires an LAI of 3.5 to achieve full canopy cover. Another exception is if the crop is planted in clumps, or very close to each other in rows that are spaced widely apart. In this case LAI significantly higher than 5.0 is necessary to achieve full canopy cover.

As plant density is reduced below a particular level, the density is insufficient for the canopy to close and CC falls substantially below 0.95. This point depends on the kind of crop, each with its particular limit of potential leaf area per plant. Ideally, for each kind of crop a curve of CC_x vs. plant density, based on experimental data, should be constructed for use in *AquaCrop* simulations. Unfortunately, for some species, the required experimental data are lacking. If the user has CC_x measurements of his/her crop at the plant density in question under optimal growth conditions, these CC_x values are obviously the best to use in the simulation. Otherwise CC_x needs to be estimated. One way is simply visual, judging the extent of CC by eye around the time when CC is maximum. A word of caution here, viewing the canopy from the side or even at a downward angle (or photograph taken from similar positions) tends to overestimate the CC because this view may include too many plant layers. Viewing the canopy from directly above, or viewing the proportion of the soil shaded by the canopy when full sun is directly overhead, is the better way to make the estimate. Estimates can also be made based on general knowledge of the crop or similar crops.

If the CC_x of a particular crop is known for a particular plant density (reference planting), to estimate CC_x of a planting of the same kind of crop but planted at a different density (d_p), one can start by estimating the maximum LAI of the planting of known CC_x (LAI_{ref}) from Figure 1 (or a similar relationship if more accurate), and calculating first the LAI of the planting assuming leaf area per plant is independent of plant density, then make a rough adjustment for the impact of change in plant density. This is summarized as an equation:

(1)
$$LAI = LAI_{ref}\left(\frac{d_p}{d_{ref}}\right)\left(\frac{1}{F_{adj}}\right)$$

where d_{ref} is the plant density of the reference, and F_{adj} is the adjustment factor.

F_{adj} is limited between the range of d/d_{ref} and 1.0, for cases where $d_p > d_{ref}$, as well as where $d < d_{ref}$. To illustrate, first take the case of $d_p > d_{ref}$. If the $d_p/d_{ref} = 1.3$, F_{adj} would be limited to the range of 1 to 1.3. At one extreme where $F_{adj} = 1$, the leaf area per plant would be independent of plant density. At the other extreme where $F_{adj} = 1.3$, the leaf area per plant is reduced by the increase in plant density so much that the LAI of the planting remains the same as LAI_{ref}. In the case of $d_p < d_{ref}$, if $d_p/d_{ref} = 0.7$, F_{adj} would be limited to the range of 1 to 0.7. Obviously, in most cases, the limit values of F_{adj} should not be used to estimate LAI. The extent the plant adjusts its leaf area in response to crowding is related to how determinate the crop is in growth habit. So the more indeterminate the crop is, the more F_{adj} should deviate from 1.0, either smaller or larger.

After LAI of the planting is estimated, the corresponding CC can be read off Figure 1 or similar relations, and used as CC_x for the simulation. As is obvious in Figure 1, for cases where the canopy is full or nearly full and the plant density is not widely different from that of the reference, the CC_x estimate made with the above procedure should be accurate within a few percentage points. The estimates become less and less reliable as the difference in density becomes greater, or if CC_x or reference CC_x is substantially less than full cover. On the other hand, for cases where there is little interplant competition for PAR because of a sparse canopy (e.g. CC < 0.5), Equation 1 can be used along with Figure 1 to obtain a reasonable estimate of CC_x by setting F_{adj} close to 1.0.

Canopy growth coefficient (CGC)

CGC is a measure of the intrinsic ability of the canopy to expand. A CGC of 0.11, for example, means that each day the CC is 11 percent greater than the CC of the day before during the first half of canopy development. CGC is virtually a constant when temperature effects are accounted for by using GDD as the driver and there is no stress. Because CGC is based on first order kinetics (Bradford and Hsiao, 1982), a good way to derive CGC is to plot the log of CC vs. time and take the slope of the linearly fitted curve to be CGC, provided that only CC data measured from shortly after seedling emergence to approximately 60 percent cover, that do not include periods of heavy fruit load on the crop, are used. If CC data are too limited for the period specified above, but additional data have been collected up to canopy closure or near full cover, CGC can be parameterized using the canopy growth components of *AquaCrop*. Instead of running the model, which is more time consuming, a simple Excel programme limited only to canopy growth is available on the FAO *AquaCrop* website for this purpose.

Commonly, both cc_o and CGC would be unknown, requiring trial-and-error iterations to find the best values for the two parameters. As general guiding principles for parameterizing CGC, the main considerations appear to be whether the crop is C_3 or C_4, and whether the crop is more efficient in the capture of PAR. For maize and sorghum, two important C_4 crops already parameterized for *AquaCrop*, the CGC is 0.17 per day on a calendar time basis and 0.013 on a GDD basis. For a number of C_3 species, the CGC is around 0.09 to 0.12 per day on a calendar time basis. There are exceptions. One is the C_3 crop sunflower, its CGC is in the order of 0.22 per day (calendar time), presumably because of its solar tracking ability to capture more PAR per unit of canopy. In the trial-and-error runs to parameterize cc_o and CGC, several scenarios of outcome are possible when the simulated CC over time are compared with the measured data. These are listed in the first column of Table 3. In the second column are given possible causes for the lack of agreement and adjustments to make.

If the comparison of simulated vs. measured data does not follow any of the scenarios in the table, it is possible that either the experimental data are questionable, or the weather data may be deficient. The weather data are particularly suspect if 10-day or monthly minimum and maximum temperature are used instead of daily values

AquaCrop has built in an alternative to estimate CGC, based on the time required for CC to reach CC_x. This feature is provided for users who want to simulate roughly the production and water use of a crop with some or many of the crop parameters not known. It should not be relied on to parameterize CGC, because in such cases cc_o and plant density or initial canopy cover (CC_o), which are equally important in determining the time to reach maximum cover, are most certainly not known.

TABLE 3 Comparison of simulated with measured canopy cover and possible adjustments in the model parameters to improve the match.

Agreement between simulated CC (CC_{sim}) and measured CC (CC_{meas})	Possible cause(s) of discrepancy and suggested remedial action
CC_{sim} is either lower or higher than CC_{meas} from time of emergence to CC_x. Same CC_x reached but at different times. Slopes of the two curves for the period of rapid canopy growth are similar	Either cc_o is too low or plant density is too low, or, respectively, cc_o is too high or plant density is too high. Check plant density data and try larger (or smaller) cc_o. CGC and CC_x probably OK
CC_{sim} coincides with CC_{meas} early in season but gradually becomes either lower or higher. Same CC_x reached but at different times	CGC is either too low or too high, respectively. Make the appropriate adjustment in CGC. CC_x and cc_o probably OK
CC_{sim} is either lower or higher than CC_{meas} early in season but the trend reverses gradually later and the same CC_x is reached but at different times	Either cc_o is too low or plant density is too low, or, respectively, cc_o is too high or plant density is too high. CGC is either too high or too low respectively. Check plant density data and try larger (or smaller) cc_o and lower (or higher) CGC. CC_x probably OK
CC_{sim} coincide well with CC_{meas} over the season	Values of cc_o, CGC, and CC_x are good for this set of experimental data

Canopy decline coefficient (CDC)

After the canopy begins to senesce, CC is reduced progressively by applying an empirical canopy decline coefficient (CDC) (*Raes et al., 2011*). If there are LAI data spanning the senescence phase, they should be converted to CC using Equation 1 and a value for CDC selected to match the simulated CC decline with the measured values. Regrettably, in many studies detailed LAI data are lacking for this phase. In this case, CDC may be set initially according to observations of the canopy's speed of yellowing, and then refined by trial-and-error simulations to find the CDC that gives the best fit of the measured biomass data during the senescence phase. In terms of predicting biomass and yield, *AquaCrop* is not very sensitive to the extent of CC decline near maturity, because the model assumes a continuous decrease in the efficiency of converting normalized Tr to biomass for that period.

Normalized water productivity (WP*)

The water productivity (WP) of concern here is the ratio of biomass produced to the amount of water transpired ($WP_{B/Tr}$), and the normalized water productivity (WP*) is the ratio of biomass produced to water transpired, normalized for the evaporative demand and CO_2 concentration of the atmosphere.

WP normalized for evaporative demand

Transpiration, the denominator of WP, is extremely difficult to measure and separate from soil evaporation in the field. Fortunately, there are numerous sets of data on biomass production vs. consumptive water use, which can be used to derive $WP_{B/Tr}$, and hence WP* if the required weather data are available. Plots of biomass vs. normalized ET, based on sequential sampling over the season, should exhibit a portion of rising slope at the beginning followed by a straight-line portion of near constant slope, and then ending with the slope being reduced for one to several data points sampled near the end of the crop life-cycle. The slope at any given point, of course, is the water productivity at that point in terms of normalized ET, not just normalized transpiration. The early rising slopes represent a period of low water productivity, when CC is small and much of the soil is exposed, and soil evaporation accounts for much of the ET. The middle portion of the plot, encompassing the data points collected from the time when the crop canopy covered more than about 70 percent of the ground to the time when about one-fourth of the maximum LAI has senesced as maturity is approached, are to be fitted with a linear equation. The slope of this linear regression is the WP normalized for evaporative demand, but only after a correction is made for soil evaporation. Once the canopy is nearly full, even when the soil surface is wet, evaporation may constitute only 12 to 18 percent of the total ET (Villalobos and Fereres, 1990). So, depending on how frequently the soil is wetted by rain or irrigation during the period spanning the middle portion of the plot, its slope should be reduced by 5 to 15 percent to obtain normalized WP.

For the plotting of biomass vs. normalized ET, ET_o is used to normalize for each time interval encompassing a biomass sample (Steduto *et al.*, 2007) according to the equation:

(2) $$\text{Normalized ET} = \sum_{i=1}^{n}\left(\frac{Tr}{\overline{ET_o}}\right)_i$$

where i is a running number designating the sequential time interval between two adjacent biomass samples, Tr is the cumulative transpiration within that interval, and $\overline{ET_o}$ is the mean of daily ET_o within that interval, and n is the number of the biomass sample in question. The interval may not be fixed in duration and represents the time preceding the biomass sampling to the previous sampling time, e.g. for i = 5, the relevant time interval is the time between sample No. 4 and No. 5. For each biomass sample (n), the summation starts at the beginning (i = 1) and ends when i = n. If there are no ET and weather data for the time preceding the first biomass sample (i = 1), they can be assumed to be zero.

The reason for using Equation 2 to normalize is to account for any variation in ET_o among the different time intervals. If daily weather data are lacking and the weather is relatively stable, plots of biomass vs. ET instead of normalized ET can be used to obtain WP in a way analogous to the procedure above. Then the WP can be divided by a mean ET_o calculated from less detailed weather data to estimate normalized WP. However, this clearly is a rough approximation.

Normalization for atmospheric CO_2

The concentration of CO_2 in the atmosphere increases each year with time and impacts WP of crops. *AquaCrop* accounts for this effect by normalizing WP for CO_2 in a general way based on conceptual understanding and empirical data (Steduto *et al.*, 2007). The WP already normalized for evaporative demand is multiplied by a factor, f_{CO_2}, defined by Equation 3 below, to obtain WP*.

(3) $$f_{CO_2} = \frac{(C_a/C_{a,o})}{1+0.000138\ (C_a - C_{a,o})}$$

In Equation 3 C_a is the mean air CO_2 concentration for the year of the experimental data, and $C_{a,o}$ is the mean CO_2 concentration for the year 2000 (equals 369.77 μLL^{-1}), both measured at the observatory at Mauna Loa, Hawaii. The C_a measured for the years 1980 up to present, are listed in *AquaCrop* in the climate file under the atmospheric CO_2 *tab*. The numerical values of the measured data can be found in the Mauna Loa CO_2 file in the SIMUL subdirectory of *AquaCrop*. The C_a of future years varies with the selected greenhouse gas-emission scenario (e.g. A2, A1B, B2 and B1 storylines). Users can enter their own projections or select one of the CO_2 files available in the DATA subdirectory of *AquaCrop*.

Reference harvest index (HI_o)

The value of reference harvest index is chosen as the middle high end of HI values reported for the majority of the given crop species or class. This value should be carefully chosen and not altered without good reason, because a change in reference HI would require the recalibration of the parameters modulating water stress effects on HI. In terms of guiding principles, reference HI can be 0.50 or even slightly higher for modern high-yielding cultivars of grain crops, but considerably lower for earlier cultivars and land races. Over the last century plant breeders selected for high HI by selecting for higher-yielding ability (Evans, 1993). For example, HI for wheat and rice were in the range of 0.33 at the beginning of the twentieth century and rose to as high as 0.53 in the 1980s (Evans, 1993). Since the 1980s only marginal improvements have been made in the HI of the major crops (Evans and Fischer, 1999). The reason could be that the limits for stems strong enough to support the grain weight and for the amount of leaves needed to support photosynthesis have been reached (Hsiao *et al., 2007*). It should be noted that HI considerably higher than 0.50 for grain crops have been reported from time to time in the literature. These values should be viewed with caution, to see if there is any indication of substantial loss of biomass such as the old and dead leaves to the wind just before harvest.

HI for oil seed crops and root crops differ from those of grains. Because it takes approximately 2.5 times as much assimilate to make a gram of oil as compared to sugar or starch, HI for oil seed crops are substantially lower than for grain crops, between 0.25 to 0.4. HI for root crops, on the other hand, are usually much higher, with the range of 0.7 to 0.8 being common for high-yielding cultivars of potato, sweet potato, and sugar beet, presumably because strong stems are not required to support the harvestable product.

WATER STRESS RESPONSE FUNCTIONS (K_S)

Water stress effects on leaf growth, stomata conductance, and accelerated canopy senescence are mediated through the stress response function (K_s) for these processes, with their characteristic thresholds expressed in terms of the fractional depletion (p) of the potential total available water in the root zone (TAW). As elaborated in Steduto *et al.* (2009), of the three processes leaf growth is the most sensitive to water stress; hence, its upper threshold (p_{upper}) should not be much below field capacity of the root zone soil (very small depletion) for virtually all the crops. Leaf growth is stopped completely at the lower threshold (p_{lower}), a point where water content in the root zone is still considerably above PWP, i.e. depletion is considerably smaller than complete. For stomatal conductance and accelerated senescence, p_{upper} should be considerably larger than that for leaf growth, and p_{lower} is fixed as 1 (complete depletion) in *AquaCrop*. Depending on the tendency to senesce of the kind of crop, p_{upper} for conductance may be the same, slightly or substantially smaller than that for senescence. Senescence is presumably much less sensitive to water stress in ‘stay green’ cultivars. A guiding principle is that crops possessing strong osmotic adjustment capability should have larger p_{upper} for conductance and senescence than those that do not. But p_{upper} for leaf growth may not be that different, although p_{lower} could also be larger. In setting the thresholds, it is not necessary to base the values too literally on results reported in short-term physiological studies, because *AquaCrop* runs in daily time steps and the thresholds represent integrated values over a diurnal cycle.

The shape of each stress response function (K_s vs. p) also needs to be parameterized. In most cases the shape should be convex. The convex shape may be interpreted as a reflection of crop acclimation to water stress, with earlier responses under milder water stresses being modulated by acclimation, and the limits of acclimation as stress becomes more and more severe.

During trial-and-error runs of *AquaCrop* to calibrate the stress response functions, the choices are to adjust either the thresholds or shape of the curve, or both. Obviously, if the time of the start of the stress effect is either clearly ahead or behind the effect shown by the measured data, the first adjustment should be in p_{upper}, by making it larger and smaller, respectively. After the starting times of the effect are matched between the simulated and measured, the degree of convex curvature can then be adjusted to match the progression of the stress effects between the simulated and measured. The more convex the curve is, the more gradually the stress effect intensifies initially as soil water depletes (p increases), but the stress effect intensifies more readily as p approaches the lower threshold. In the case of the stress function for leaf growth, p_{lower} may also need to be adjusted.

Because at the same soil water status plants experience more severe stress on days of high transpiration and less stress on days of low transpiration, *AquaCrop* automatically adjusts the various stress thresholds according to the evaporative demand of the atmosphere, represented by the daily ET_o. In most cases the default setting for this adjustment should suffice. Only in the rarest cases, where good data indicate a clear need, should this setting be changed under the Programme Setting *tab sheet*.

WATER STRESS EFFECTS ON HARVEST INDEX (HI)

AquaCrop accounts for three different effects of water stress on HI. The first is the effect related to accelerated senescence of canopy, shortening the life-cycle of the crop. In *AquaCrop* HI increases linearly with time shortly after the start of flowering to the time of maturity, when the reference HI value is reached (provided there is no modulation due to stress along the way). This increase is stopped automatically when CC drops to a threshold value (default value is 5 percent of the maximum CC reached). Early senescence of the canopy reduces HI by shortening the time available for HI to increase, because of the shortened life-span of the crop. If the resultant final HI simulated by the model does not match the measured HI, the match may be improved by altering the parameters that affect the timing and acceleration of canopy senescence, or by changing the threshold of percent CC remaining for stopping HI increase. The latter, however, should not be done unless there are good data supporting the change. Before making either alteration, it is prudent to first examine the impact of the other two stress effects on HI, discussed next, to see if their parameter values and simulated impact on HI are reasonable.

The next stress effect on HI to discuss is apparently the result of the competition for assimilates between vegetative and reproductive growth. A part of this effect is what accounts for higher HI under the right water-stress conditions. This beneficial water-stress effect is well known for cotton, and somewhat less well known for tomato and other vegetable fruit crops such as pepper and eggplant. The increase of HI over time would be accelerated for this situation as long as stress is not severe enough to inhibit photosynthesis. When stress is severe enough to markedly reduce photosynthesis, the increase of HI would be reduced. Three parameters in *AquaCrop* determine the sensitivity and extent of the changes in HI caused by the vegetative/reproductive competitions. The first parameter (*Before* f *owering* tab sheet under *Water stresses*) determines the increase in HI as the result of a minor reduction in biomass (reduction in leaf growth) caused by water stress for a short period before the start of flowering. This is based on empirical data, but may possibly be the result of flower bud formation and development being stimulated by accumulated assimilates. In many cases, this enhancement should be only a couple of percent. The next two parameters are in the During yield formation tab sheet. On *View corresponding HI adjustment* the values of the two parameters, 'a' and 'b', can be changed. Increase 'a' to reduce the enhancing effect on HI of leaf growth inhibition, and decrease 'b' to enhance the reduction of HI caused by stomatal closure.

The third effect of stress on HI is because of failures of pollination and fruit set. The literature often state that pollination is sensitive to water stress. It turns out, however, that in detailed studies pollination and fruit set were found to be resistant to water stress, requiring stress levels much stronger than those inhibiting stomatal opening. Accordingly, in *AquaCrop* the threshold for pollination failure should be set close to the PWP (e.g. 85 percent depletion of TAW).

Most crops have an excess of potential fruits for the available assimilates to fill, so a portion of the embryos is aborted after pollination. For a stress to diminish HI by inhibiting pollination, it must be sufficiently severe to reduce the number of potential fruits below the number that can be filled by the available assimilates. Hence, the impact of stress on HI depends on the proportion of excessive potential fruits. The default proportion of excessive potential fruits is given in the model for a given crop, but is adjustable by the user on the *Water stress/Harvest index/During* f *owering* tab sheet.

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3.4 Herbaceous crops

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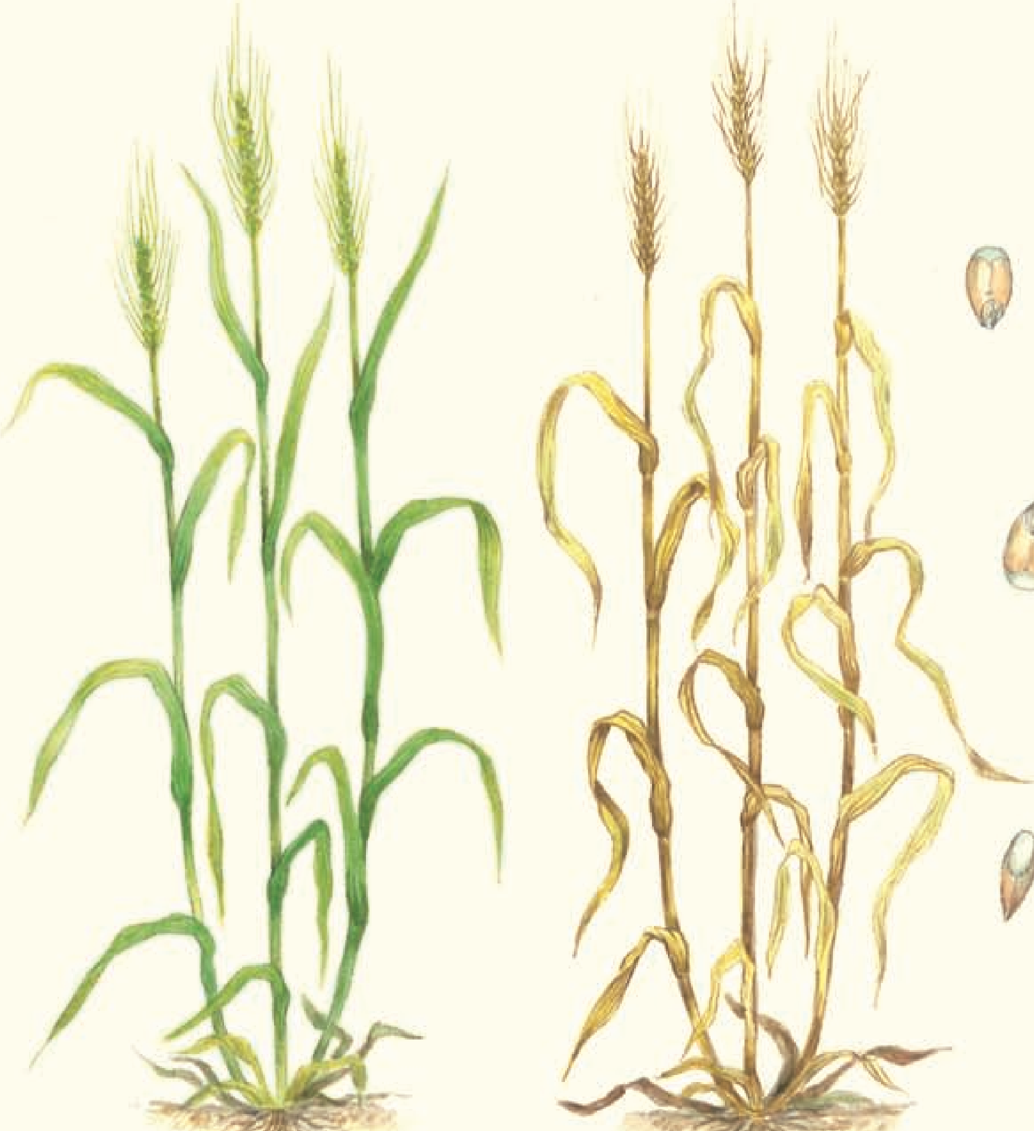

Wheat

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Wheat

GENERAL DESCRIPTION

Bread and durum wheat (*Triticum aestivum* and *Triticum turgidum durum*, respectively) comprise the third largest crop in the world. In 2009, 226 million ha were sown to wheat, producing 685 million tonne of grain at an average grain yield of 3 tonne/ha (FAO, 2011). Over the last 50 years, the average yield per hectare has increased dramatically, particularly between the 1950s and 1980s. Since the area cropped has remained relatively constant, global production has reflected the increase in yield (Figure 1).

Wheat is a cool season crop originating in the Fertile Crescent but now widely spread around the world. It is grown in arctic and humid regions as well as the tropical highlands and from sea level on the Dutch Polders to 4 500 m altitude in Tibet. The growing conditions are very diverse, not only because of the widespread climatic regions and altitudes, but also because of variability of soil types and crop management. Currently, the countries with the largest wheat production are China, India, the Russian Federation, the United States, France, Canada, Germany, Pakistan, Australia and Ukraine in that order. These countries totally cover more than two-thirds of the global wheat production (Figure 2).

In many annual cropping areas, wheat is grown in rotation with a variety of other winter annuals such as other cereals, oilseed crops, and pulses, although wheat following wheat often occurs. In other cases it is sown as a second crop after summer cereals or cotton. Two systems of particular importance are the rice-wheat and maize-wheat systems.

GROWTH AND DEVELOPMENT

Winter wheat is sown in autumn, while spring wheat is sown in autumn or spring. Winter wheat requires a cold period or chilling (vernalization) during early growth for normal heading under long days. Wheat is usually sown at a depth of around 5 cm, although greater depths may be used under dry conditions, to attempt to place the seed into moist soil. While this can be successful, it delays emergence and growth and in extreme situations may reduce stand density. Sowing is usually into moist soil but in some dry environments 'dry sowing' may be practised shortly before the expected start of the rainy season. Plant densities range from 50 to over 500 plant/m^2

with the lower densities being used in drier environments. Row spacing ranges typically from 0.15 to 0.25 m, depending on the production system. Sowing is by broadcasting in some cases. In many developing countries the use of reduced tillage and stubble retention systems is increasing but in developed countries multiple pre-sowing cultivations are more common. Stubble retention and the degree of cultivation influence the rates of infiltration, evaporation, and runoff. The impact of soil type and management, particularly cultivation and irrigation, on soil compaction has a profound effect on the depth of root exploration, and hence access to soil water, and the frequency of anaerobic conditions resulting from waterlogging.

The length of the total growing period (life cycle) of spring wheat (sown in spring) ranges from 100 to 170 days while winter wheat needs about 180 to 300 days to mature. In some exceptional cases, season lengths of more than 300 days have been recorded. Day length and temperature requirements are key factors in cultivar selection. Cultivars can be grouped as winter or spring types according to chilling requirements, winter hardiness and day length sensitivity. Some winter wheat cultivars in early stages of development exhibit a strong resistance to cold temperature, surviving down to -20 °C. The resistance is lost in the active growth period in spring, and during the head development and flowering period frost may lead to loss of spikelets, and in extreme circumstances, loss of the whole head.

In areas with severe winters, cold winds and little snow, spring wheat cultivars are planted after winter. Spring wheat is also sown in the autumn to over-winter in regions with winter dominant rainfall and mild winter temperatures such as some arid and Mediterranean regions, as well as in the cool season of high lands in the tropics. Spring wheat requires little or no chilling to initiate head development. Winter wheat and some spring wheat cultivars are also photoperiod sensitive, which delays the end of the tillering phase to long sunshine days.

Crop development or phenology is dependent on temperature (Porter and Gawith, 1999). For crop growth, minimum mean daily temperature for measurable growth is about 5°C for winter and spring wheat. Mean daily temperature for optimum growth is between 15 and 23 °C. In *AquaCrop*, the growing degree day (GDD) for wheat is calculated with a base temperature of 0°C and an upper temperature of 26 °C. This means crop development speeds up as the mean daily temperature increases from 0 °C to 26 °C, and further increase above 26 °C does not enhance growth and development. Maximum canopy is often reached before heading at booting stage while flowering of individual heads can last between one and 10 days. Grain filling usually occurs into the warming part of the year when average maximum temperatures are between 20-30 °C. Prolonged periods below 5 °C can cause dormancy in winter wheat. Vernalization requirements and photoperiod sensitivity vary substantially between cultivars and alter the duration of the tillering phase. Table 1 shows the duration from sowing to

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FIGURE 1 World wheat harvested area and average yield over the period 1961-2009 (FAO, 2011).

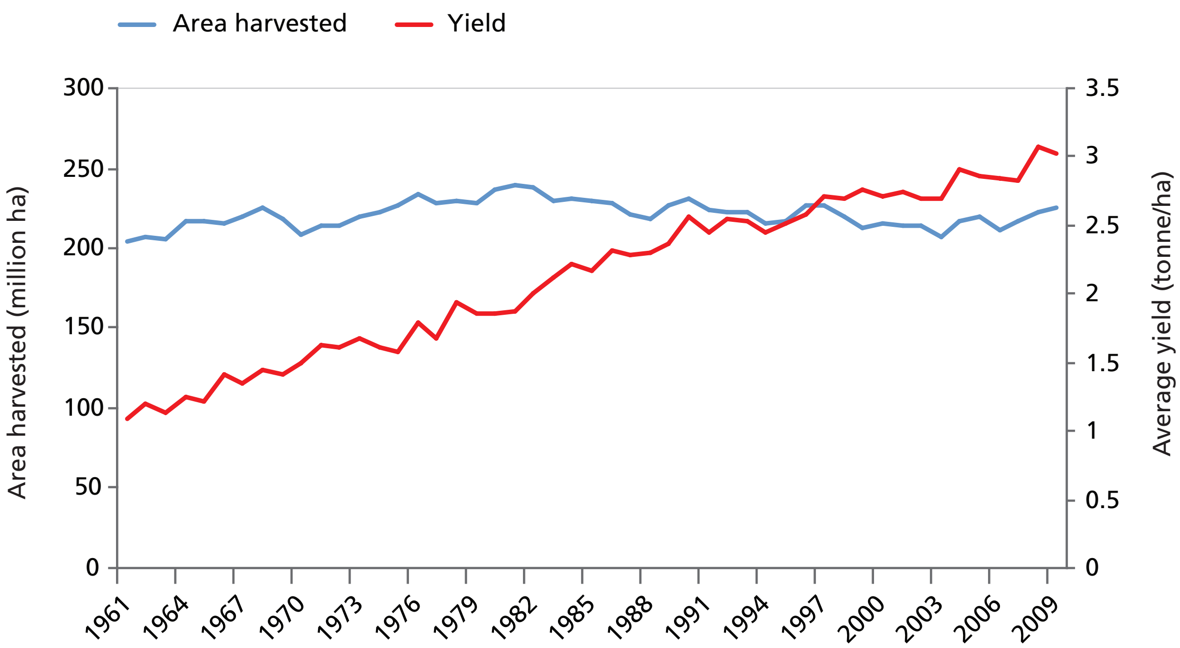

FIGURE 2 Wheat harvested area (GAEZ, 2011).

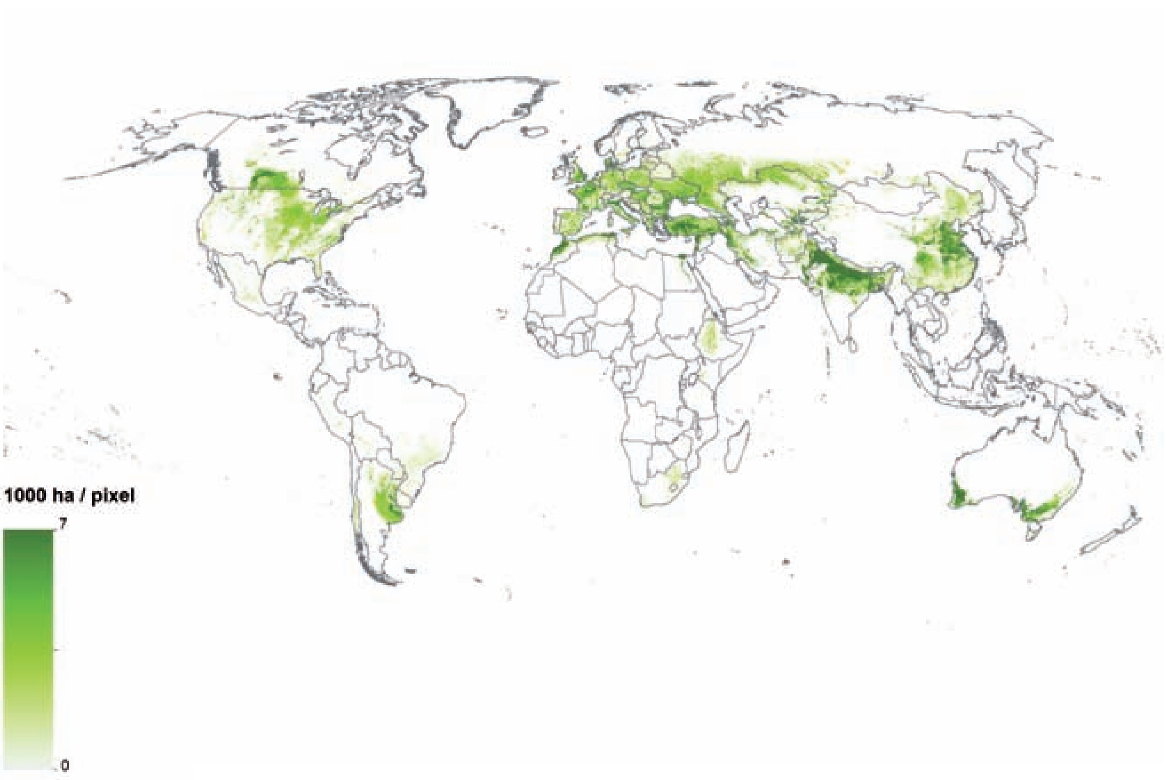

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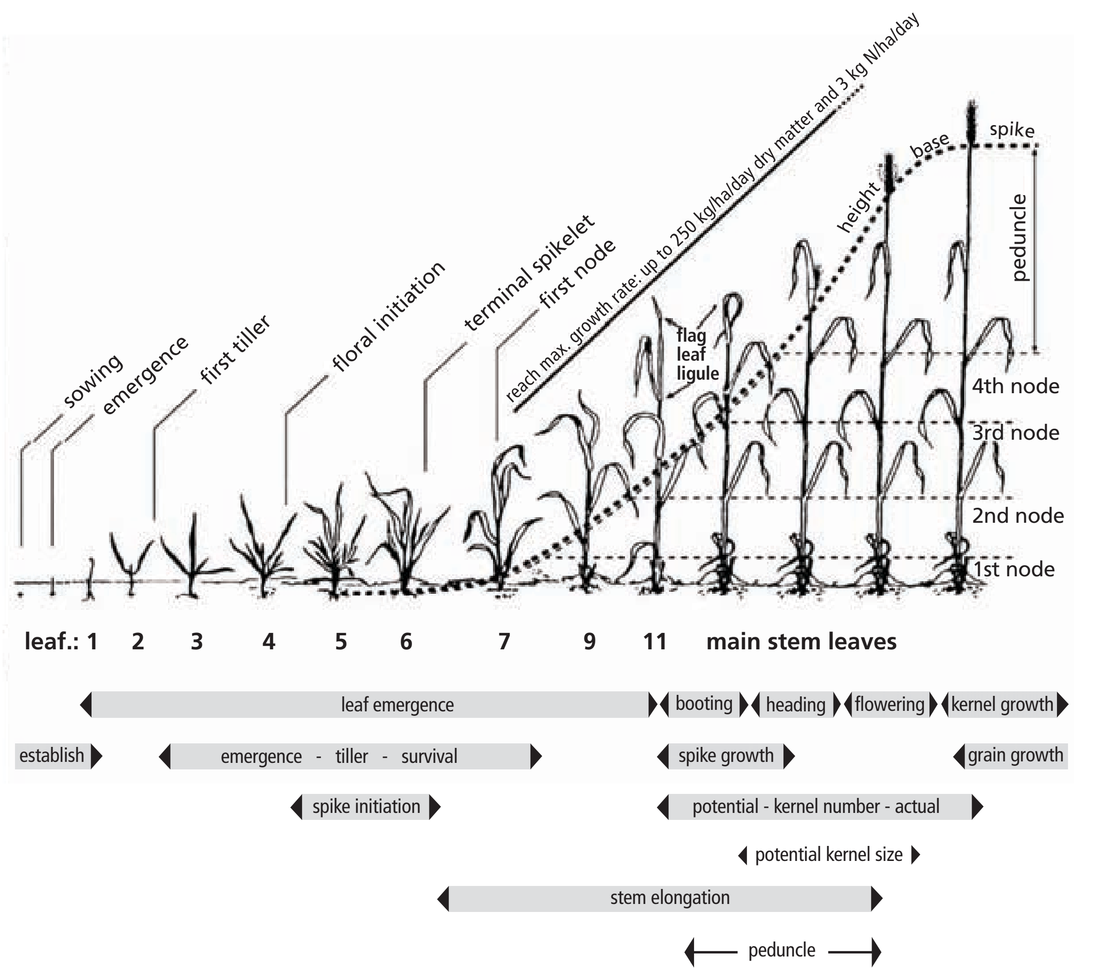
TABLE 1 Duration of the main phenological phases of wheat in days from sowing (S) for various wheat producing areas.

Wheat areas	S-Emergence	S-Heading	S-Anthesis	S-Maturity	Cultivar type
Central and Northern Europe	12-48		54-250	71-280	spring, winter
Italy	12-19	62-166	67-170	100-213	spring
China		67-	-217	83-251	spring, winter
India	4-	ca. 77	70-103	85-145	spring
Russia		39-		76-305	spring, winter
North Africa and West Asia	6-16	116-138		158-178	spring
USA		55-210		113-310	spring, winter
Canada	5-15	50-250		90-300	spring, winter
South America	6-12		70-135	112-186	spring
Australia	7-17	35-90	60-170	90-215	spring, winter

FIGURE 3 Typical developmental stages of wheat.



various developmental phases for wheat in different wheat growing regions. Figure 3 shows typical development of a wheat plant.

Wheat can be grown on a very wide range of soils from deep sands and shallow soils to loams to heavy clays. Maximum rooting depth can vary from 0.30 m in duplex soils of Western Australia with impermeable B horizons or other soils with high or low pH, high salinity or toxicities such as boron in the subsoil, through to 2.80 m on deep sands with root deepening rates of 0.7 to 2.0 cm/day.

WATER USE & PRODUCTIVITY

Total cumulative evapotranspiration (ET) of wheat crops typically ranges from 200 to 500 mm, although it can be less in non-irrigated semi-arid areas and reach 600-800 mm under heavy irrigation. The slope of the plot of grain yield vs. ET can be taken as the water productivity in terms of yield and consumptive use ($WP_{Y/ET}$). If the x-intercept of this relationship is taken as a measure of cumulative soil evaporation, then the slope can be interpreted as the water productivity in terms of transpiration ($WP_{Y/Tr}$). On this basis, $WP_{Y/Tr}$ is typically reported to be around 1.0-1.2 kg/m^3 (10-12 kg/ha per mm) for grain production (French and Schultz, 1984). An international analysis has indicated the maximum achievable efficiency (for grain) in current wheat systems is likely to be around 2.2 kg/m^3 (Sadras and Angus, 2006).

The proportion of water used as transpiration varies widely. When crops are grown on stored soil moisture with little in-season rainfall, soil evaporation can fall to as little as 20 percent of ET. With frequent, small, in-season rainfall events, soil evaporation can increase to as high as 75 percent, in cases of very sparse crop cover. Soil type, stubble cover, weather and early crop vigour also influence the proportion of soil evaporation.

Cultivars vary little in terms of dry matter production per unit ET. Cultivar variation in yield is typically related more to differences in total water use, mostly through changes in crop duration, or to changes in harvest index.

Early in the growing season, daily water usage can be very low (< 2 mm/day) because of cool temperatures and, in Mediterranean conditions, high humidity. Transpiration as a proportion of total ET is also low because of the small canopy size. For winter wheat in temperate environments, this situation can continue for some months. As the canopy enlarges during tillering and stem elongation, the rate of water usage increases and typically peaks around anthesis at rates between 5 and 8 mm/day. The ratio of actual to reference ET peaks at around 1.0 to 1.2 during the period from stem elongation to anthesis and declines during grain filling and maturation. As the canopy senesces markedly towards maturity, the ratio falls rapidly.

RESPONSE TO WATER STRESS

As for all cereals, wheat yield can be considered as the product of three components: the number of ears per unit area, the number of grains per ear, and the size of the grains. Both the number of ears and the number of grains are the product of the number produced and the proportion surviving. To a large extent, the components are developed sequentially and the timing of moisture stress dictates which of the components are affected. The potential number of tillers, and hence ears per unit area, is determined earliest followed by the number of grains per ear and finally grain size. So, broadly speaking, early stress limits tiller number and stress after anthesis reduces the size of the individual grains and the grain number through abortion of the developing grains (Passioura and Angus, 2010).

Studies to determine the developmental stage at which yield is most sensitive to water stress have produced inconsistent results. However, in most situations, yield is correlated to grains per m^2. Hence, the number of grains per unit area and thus tillers per unit is generally the most important determinant of yield. Consistent with this, the periods during which wheat yield is usually considered to be most responsive to moisture stress are (a) the period when tillers are developing and their abortion rates are highest; (b) when florets are being formed and grains are set; and (c) from early to mid-grain filling when young developing grains can be aborted due to a lack of assimilate (Turner, 1997).

In broad terms, apart from the seedling stage, sensitivity to water stress generally appears to decline with development. However, it is important to maintain a degree of balance throughout growth, particularly in terms of pre- and post-anthesis water use (Fischer, 1979). If all the water is used before anthesis, when limited rainfall is expected later in growth, severe terminal drought can result in a serious impact on grain filling with reduced yield, grain number, grain size and grain quality; with a consequent reduction in harvest index (HI) (Passioura, 1977). Further, the plants can acclimate to water stress to some degree. So, low levels of stress during the pre-anthesis phase appear to reduce the impact of stress around anthesis and shortly after.

Excess water can cause waterlogging during vegetative growth and can reduce yield substantially. Reduced levels of soil oxygen for as little as three days can damage roots, reduce nutrient uptake and reduce tiller numbers. The capacity to recover depends on the timing of the waterlogging event and the subsequent growth conditions. Serious damage to roots can limit the depth of soil explored and can therefore reduce the access to mineral nutrition and soil water. This exacerbates the impact of any subsequent water limitation.

SOIL FERTILITY

Soil fertility levels can only be determined in relation to yield potential and also depend on soil type. As a rough guide, for each tonne of yield per hectare, wheat needs to take up about 25-40 kg/ha N, 3-5 kg/ha P and 15-30 kg/ha K. The uptake of N not only influences yield but also grain protein percentage which affects the suitability of the grain for different end uses. To meet a specific uptake demand for a targeted yield, 150-200 percent of the required crop N uptake has to be available for the crop from the combined amount of soil mineralization and fertilizer application. Note that soil N content is highly dynamic and N can easily be lost through nitrate leaching particularly on sandy soils with low water-holding capacity. Soil N content can therefore change several fold during a growing season. P and K are less dynamic, but uptake efficiency is often less than for N. Therefore, similar amounts of plant-available P and K (150-200 percent of uptake requirements) might be required to achieve potential yield for specific growing conditions.

When nutrition is limiting, yield potential and canopy expansion are constrained, reducing the total water requirement of the crop. Excessively high nutrient levels, particularly N, result in luxuriant vegetative growth and high water consumption but usually without a commensurate increase in grain yield. A possible cause is reduced HI since an excessive number of tillers are formed and many of them either do not have time to form heads or die off as a result of heavy shading by older tillers.

TEMPERATURE

Temperature requirements of wheat, especially with respect to cold temperature, have already been discussed under Growth and Development. Temperatures above 34 °C are possible in most wheat-growing regions during grain filling. Such temperatures accelerate senescence and can cause significant reduction in grain yield through reduced grain size and increase the proportions of shrivelled and undersized grain. Cultivars are available that can tolerate high temperatures to some degree, to minimize heat stress damage.

SALINITY

Wheat is considered moderately tolerant to soil salinity. The reduction in shoot growth with increasing sodium concentration in a sand or solution culture is approximately linear with a concentration of 100 mM (about 10 dS/m) reducing shoot growth by around 45 percent in bread wheat and about 50 percent in durum. By comparison, the reduction in barley is around 40 percent and in rice about 75 percent. Wheat cultivars with higher salt tolerance are becoming available.

IRRIGATION PRACTICE

While much wheat is grown solely under rainfall and stored soil water, the importance of fully or partially irrigated production is very high in some countries. Irrigation practices for wheat production are diverse. In arid areas, or when grown in the dry season of monsoonal regions, wheat may be grown under full irrigation. In Mediterranean and semi-arid systems, supplemental irrigation may be used to alleviate intermittent drought or to reduce the impact of increasing water deficits as spring progresses (Oweis, *et al.*, 1999).

On a global scale the most common method of application is flood irrigation in bordered basins. Furrow application and overhead application by a variety of sprinkler methods are also used. Irrigation is frequently applied to wheat with little knowledge of its moisture requirements or the available soil moisture at the time of application. Because wheat is so widely grown, a variety of scheduling systems and tools have been developed including methods based on water budgets, in-field soil moisture measurement and canopy temperature. However the extent of their use in commercial production is very limited, particularly in less economically developed countries. Where rainfall is low and irrigation water supply is limited, the preceding crop and the interval between the crops, in combination with the rainfall pattern and soil water characteristics, dictate whether there is a need for irrigation at or before seeding to establish a crop stand. Subsequently, generally speaking, irrigation should be managed to avoid or minimize water deficits during the three periods already mentioned: (a) tillering to stem elongation, (b) time of flowering, and (c) early to mid-grain filling. After the development of a reasonable canopy, subsequent irrigations may be scheduled such that up to 50-60 percent of total available soil water (TAW) is depleted between applications without a notable negative impact on yield (Geerts and Raes, 2009).

Over irrigation is common in wheat, even under supplemental irrigation: two or three irrigations are sometimes applied in a short interval with little consideration of soil water status or crop demand. Excessive water supply results in lower water productivity in terms of yield per unit of water applied. In extreme situations, excessive water (from rainfall or irrigation) results in waterlogging which, as mentioned earlier, can substantially depress growth and yield. Over-generous water supply during the vegetative period, particularly in combination with high fertility, produces luxuriant vegetation and may result in lodging after head formation. Lodging may also occur if an excessive amount of water is applied in a single irrigation late in development, particularly with sprinkler irrigation.

YIELD

Wheat grain yields (at 11 percent moisture) can vary from crop failures in seasons with less than 100 to 150 mm available water, to 1-3 tonne/ha in water limited rainfed conditions (Mediterranean, arid, dry-season subtropical environments) and 4-10 tonne/ha in rainfed temperate (western and northern Europe) climates or irrigated systems (China). Exceptionally, grain yields can reach a maximum of 15 tonne/ha in cool, long season (life cycle of over 300 days) environments with high solar radiation input such as southern New Zealand, Southern Chile, Ireland, England and some regions of China. In 2009, average country yields ranged from less than 0.5 tonne/ha in Honduras, Lesotho, Somalia, Venezuela and Eritrea to more than 9 tonne/ha in Belgium.

A major factor contributing to the improvement in yield over the last century is the increases of HI brought about by breeding for shorter statue. Under favourable conditions with no stress, HI ranges between 0.45 and 0.55 for modern wheat cultivars (Austin, 1999). However, when there is water stress after flowering or when the cultivar is poorly matched to the production environment, HI can fall to as low as 0.20 to 0.30.

The balance of water supply before and after flowering can have a substantial effect on grain quality. Water stress during grain filling leads to shrivelled grain with a low milling percentage (flour produced per grain input). On the other hand, high water supply late in the season leads to increased yield with low protein concentration. These changes alter the suitability of the grain for various end uses.

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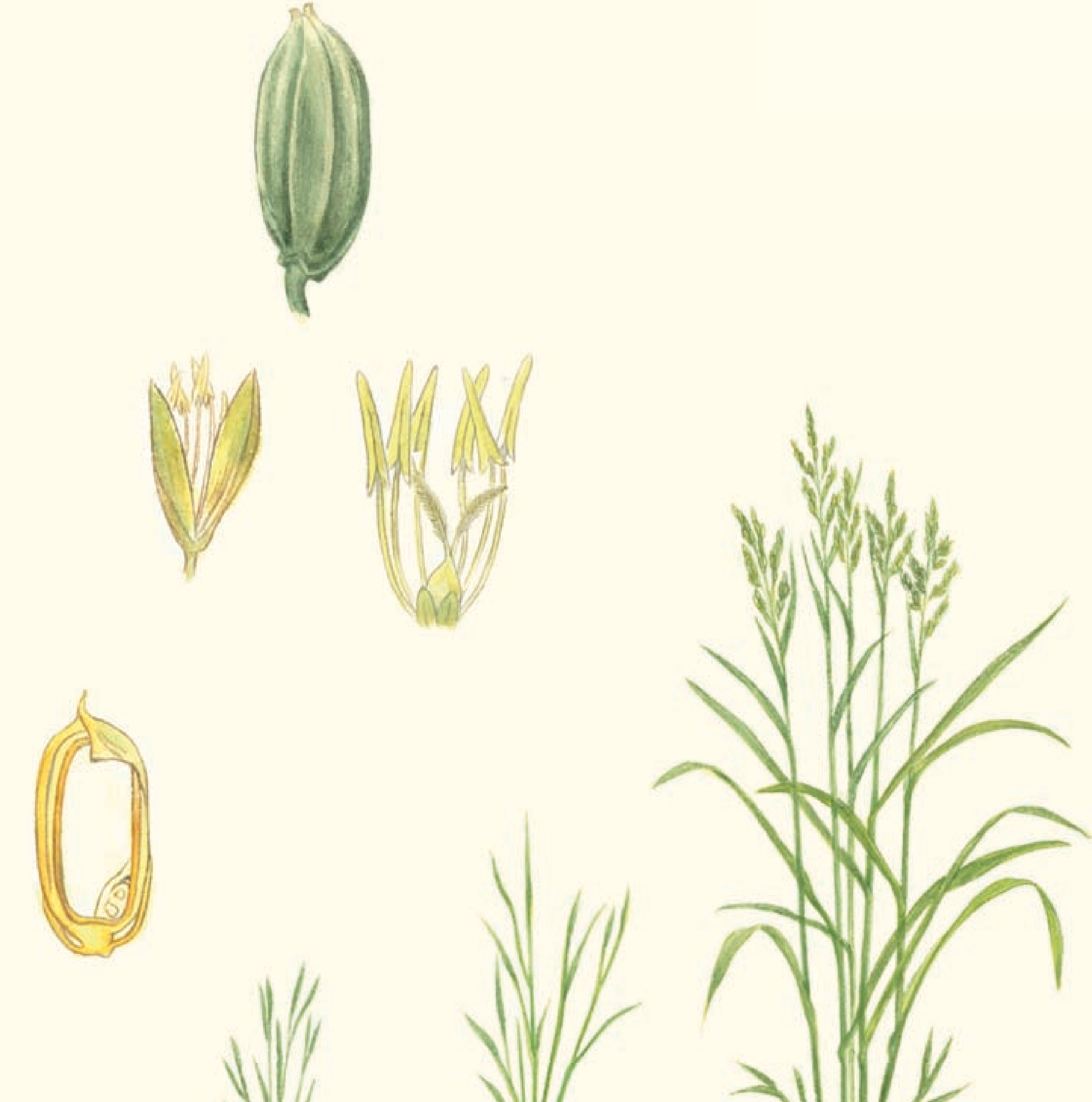

Rice

Rice

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GENERAL DESCRIPTION

Cultivated rice is represented by two main species: (i) *Oryza sativa*, grown worldwide, with its two ecogeographic races *indica*, adapted to the tropics, and *japonica*, adapted to temperate regions and tropical uplands; and (ii) *Oryza glaberrima*, grown in parts of West Africa. In the mid-nineties, a new rice called NERICA (New Rice for Africa) was developed from crosses between *O. glaberrima* and *O. sativa* species specifically targeted at the upland and dryland areas of sub-Sahara Africa (Jones *et al.* 1997). Two main rice growing environments are distinguished: lowland (or paddy) rice, where fields have saturated soils with ponded water during crop growth, and upland rice, where fields have well-drained, nonsaturated soils without ponded water. Rice is grown throughout the year in the tropics, and in the summer in the subtropics and temperate regions.

Rice represents the food of 3 billion people worldwide. The global annual production of rough (unmilled) rice is about 650-700 million tonne, of which 90 percent is produced and consumed in Asia (Figure 1). Main cropping countries are China, India, Indonesia, Bangladesh, Viet Nam, Myanmar, Thailand and Philippines (FAO, 2011). Worldwide, there are about 158 million ha of lowland rice (including double cropping), of which 101 million ha are harvested for irrigated rice and provide 75 percent of the world's rice production, while the remaining 57 million ha of rainfed lowland rice contribute 19 percent to the world's rice production. Some 11 million ha of lowland rice area is prone to uncontrolled flooding. These include deepwater areas, low-lying coastal areas subject to daily tidal submergence, and areas affected by flash floods of 1-2 weeks, where the problem is often excess water but not necessarily prolonged submergence. About 14 million ha of upland rice are usually not equipped with irrigation facilities, and contribute 6 percent to the world's rice production. (Figure 2).

In most tropical irrigated areas, rice is grown as a monoculture with two crops per year, while three crops per year occur in places like the Mekong Delta in Vietnam. In Pakistan, India, Nepal, Bangladesh, and central China, rice is often grown under irrigation over the summer, in rotation with a range of other crops in winter, including 15-20 million ha of rice-wheat systems. In China, some 19 of the 30 million ha rice are planted to modern hybrid rice cultivars, which usually outyield the best parent. Rainfed lowland rice is mainly grown in the monsoon season, with large areas in Eastern India, northeast Thailand, Laos, and Cambodia. Upland rice was

FIGURE 1 World rice harvested area and average yield over the period 1961-2009 (FAO, 2011).

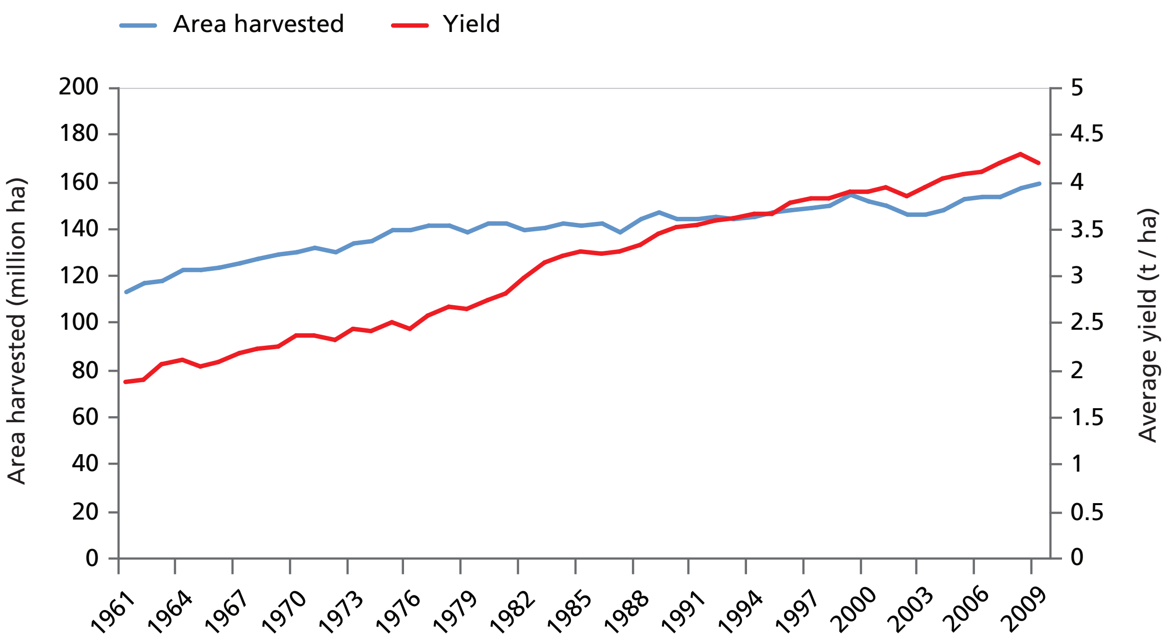
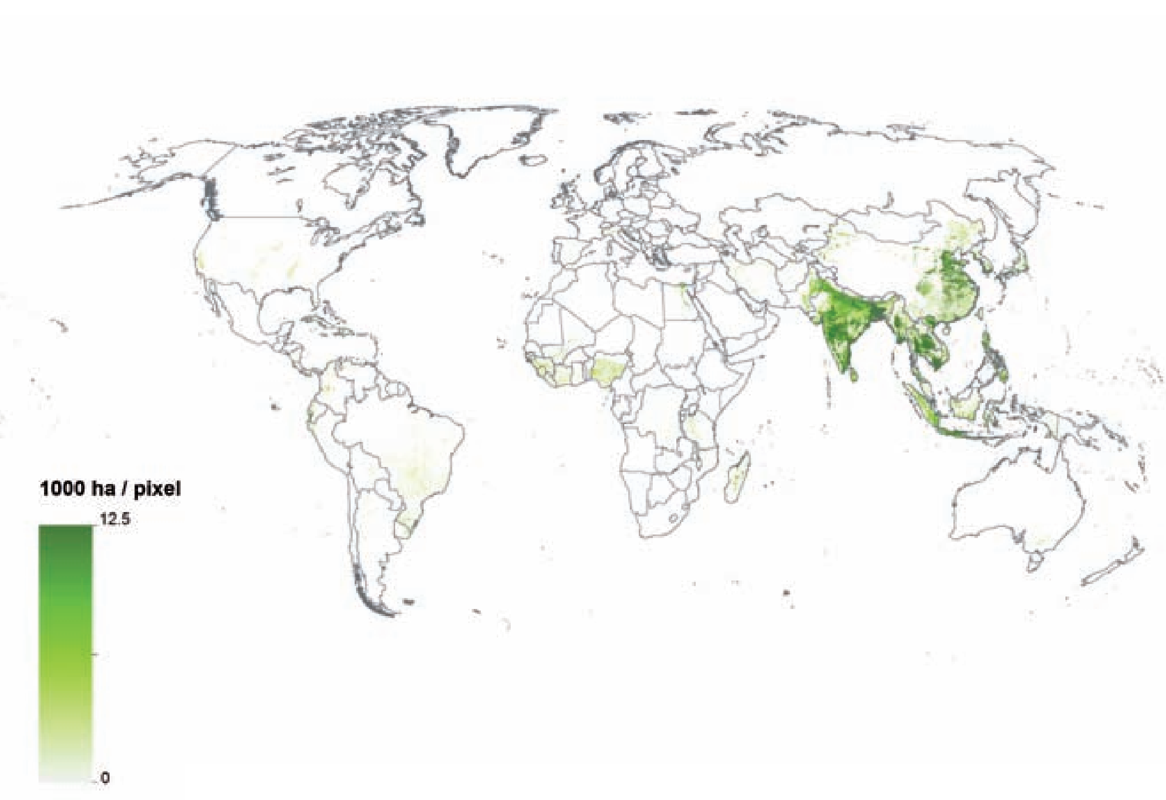


FIGURE 2 Rice harvested area (GAEZ, 2011).



Reference year 2000

historically grown under shifting cultivation with long fallow periods (more than 15 years). At the turn of the twentieth century, most of Asia's upland rice areas have made the transition to permanent systems where rice is grown every year, while 14 percent of the Asian upland rice area still practises shifting cultivation with shorter fallow periods (3-5 years). In Central and West Africa, the rice belt of Africa, upland areas represent about 40 percent of the area under rice cultivation but involve about 70 percent of the region's rice farmers.

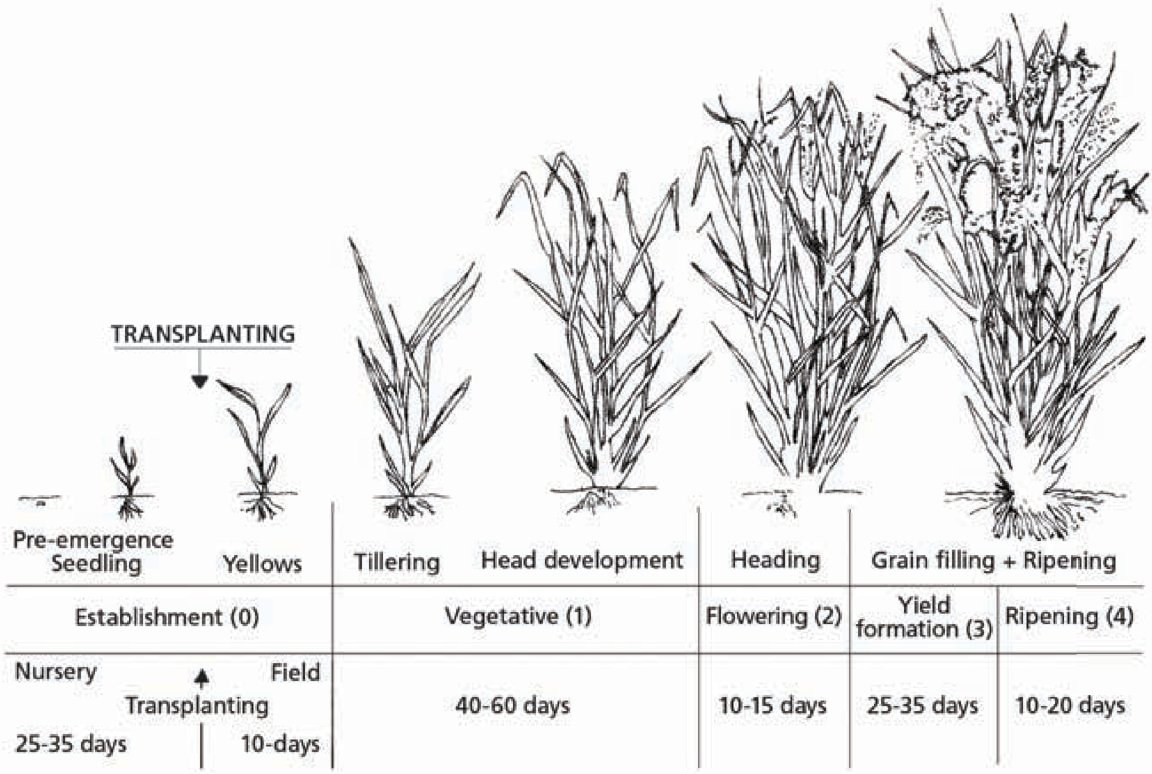
GROWTH AND DEVELOPMENT

Lowland rice is usually grown in 'puddled' fields. Puddling consists of harrowing or rototilling under shallow submerged conditions, and is done to control weeds, to reduce soil permeability, and to ease transplanting. After puddling, land is levelled under wet conditions. A typical vertical cross-section through a puddled rice field shows a layer of 0-0.10 m ponded water, a puddled, muddy topsoil of 0.10-0.20 m, a plow pan that is formed by decades or centuries of puddling, and an undisturbed subsoil. Rice roots are usually contained within the puddled layer and are quite shallow.

The dominant method of crop establishment in most rice areas is by transplanting. Rice is first raised in a separate seedbed. Seeds are pre-germinated and are broadcast into either a flooded or wet soil surface in the nursery at a rate of 500 to 800 kg/ha. At transplanting (12-25 days after establishment for modern cultivars, whereas it takes 40 days or more for traditional cultivars), the plant densities are equivalent to seeding rates of 40-50 kg/ha. Two to three seedlings are normally hand transplanted in hills 0.15 to 0.30 m apart. Hybrid rice is usually transplanted as one seedling per hill, while some local cultivars are planted with 5-6 seedlings per hill. Each plant develops three to seven tillers, dependent on nutrient status, cultivar, and seedling density. In a good crop stand, the number of grain-bearing panicles will reach 400-600/ m^2 in the dry season, and 300-400/m^2 in the wet season (for common *indica* cultivars in the tropics).

Rice can also be established directly in the field by wet or dry seeding (broadcasting pre-germinated seeds onto wet or flooded soil or sowing dry seeds in dry or moist soil). Seeds are broadcast or sown in rows of 20-30 cm spacing, at the rate of 80 to 250 kg/ha (Rice Knowledge Bank, IRRI). In recent years the trend in Asia is toward more direct seeding. In commercial production fields of the United States and Spain, seeds are commonly broadcast from airplanes. The duration of the growing cycle (from germination to maturity) of rice depends on cultivar and location, ranging from 90 days for short-duration modern tropical cultivars, to 180 days for traditional or modern cultivars in subtropical and temperate environments. Cultivar differences in growth duration are determined by changes in the time from germination to beginning flowering (60 to 150 days), while the time from beginning flowering to maturity is pretty constant and lasts about 30 days in the tropics but can go up to 65 days in cool, temperate regions The growth and development of rice is temperature dependent (Kropff *et al.*, 1994), stopping at average temperatures below the base temperature, which is tentatively set at 8 °C for rice in *AquaCrop*. Most tropical cultivars die when, in the early vegetative growth phase, the average daytime temperature drops below 12 °C for more than three consecutive days. Generally, damage to the pollen occurs when the temperature at flowering is outside the range of 8 to 35 °C. Though many traditional rice cultivars are photoperiod sensitive (shortening day lengths induce flowering), most modern high-yielding ones are not. (See Figure 3 for typical development).

FIGURE 3 Typical developmental stages of rice.



WATER USE & PRODUCTIVITY

Because of the flooded nature of lowland rice, its water use and water productivity are different from those of upland rice and other cereals. Irrigated rice receives 34-43 percent of the total world's irrigation water, or about 24-30 percent of the entire world's developed fresh water resources (Bouman *et al.*, 2006). Water is used for land preparation and to match the outflows from the field by seepage, percolation, evaporation and transpiration. The amount of water used for wet land preparation can be as low as 100-150 mm but can approach 1000 mm in large-scale irrigation systems. Typical percolation rates vary from 1-5 mm/day in heavy clay soils to 25-30 mm/day in sandy and sandy loam soils (Bouman *et al.*, 2007). In midseason when there is complete canopy cover of the ground, rice evapotranspires at a rate slightly higher than the reference evapotranspiration (ET_o). Common daily ET rates from rice fields average 4-5 mm/day in a tropical wet season and 6-7 mm/day in a tropical dry season, but on some days can reach as high as 10-11 mm/day in subtropical regions before the onset of the monsoon, and in semiarid regions. Seasonal ET vary from 400 to 700 mm in the tropics and from 800 to 1 100 mm in temperate regions. The total estimated ET of world rice fields (including both lowland and upland rice) is some 860 km^3/year.

Modern rice cultivars, when grown under flooded conditions, have a water productivity with respect to transpiration for grain yield ($WP_{Y/Tr}$), of about 2 kg/m^3 (Bouman *et al.*, 2006). The water productivity with respect to evapotranspiration ($WP_{Y/ET}$) ranges from 0.6 to 1.6 kg/m^3, with a mean of 1.1 kg/m^3 (similar to that of wheat). Water productivity with respect to total water input (irrigation plus rainfall) is around 0.4 kg/m^3 (range from 0.2 to 1.2).

RESPONSE TO STRESSES

Because rice evolved from a semi-aquatic ancestor, it is extremely sensitive to water shortage. The main reason is its shallow root system; in terms of sensitivity of rice organs to low water potential, it is actually not that different from many other crops (Hsiao *et al.,* 1984). Leaf and canopy expansion are reduced soon after the soil dries below saturation in most cultivars; even in upland cultivars, expansion begins to be inhibited when only a small fraction of the total available water (TAW) has been depleted (Lilley and Fukai, 1994; Wopereis *et al.*, 1996). Rice is susceptible to large yield losses at the time of flowering because of reduced water availability. The spikelets scheduled to pollinate on a day when panicle water potential is low (e.g. -1.8 MPa) do not open to shed pollens, causing spikelet sterility and reducing the harvest index (HI). Another stress is combined high temperature and strong wind at flowering time. Spikelets of newly emerged panicles have low epidermal resistance to water vapour apparently related to the slow formation of epicuticular wax. On days of high temperature and wind, such spikelets desiccate and die and turn white (O'Toole *et al.*, 1984), symptom referred to as 'white heads' or 'blasting'. This again reduces HI. A large part of rainfed lowlands are frequently affected by drought, the largest and most frequently and severely affected areas being eastern India (about 20 million ha) and northeastern Thailand and Laos (7 million ha).

Although rice is adapted to waterlogging, complete submergence can be lethal. Most rice varieties can survive complete submergence of only 3-4 days though some rainfed lowland rice varieties can survive up to 14 days (depending on depth, temperature, and turbidity of the water). Recently, a gene has been discovered (sub1) that confers tolerance to submergence in the early vegetative growth stage of up to 14 days, and which has successfully been introduced into a number of popular lowland varieties using marker-assisted breeding techniques. Tall plants tend to lodge when the water level recedes, resulting in additional yield losses and poor grain quality.

Rice is salt-sensitive (Shannon, 1997). Some 9-12 million ha of lowland rice area in South Asia is estimated to be affected by salinity and/or alkalinity (Bouman *et al.*, 2006) either from sea water intrusion in the coastal areas or from water and/or soil salinity inland. The threshold for yield reduction is 3 dS/m of soil electric conductivity (EC_e), with 90 percent yield loss at 10 dS/m EC_e. Rice is relatively salt tolerant during germination, tillering, and toward maturity, but is sensitive during early seedling and at flowering and grain filling.

Fertilizer needs depend on targeted yield, the fertility of the soil, residue management, and the amount of nutrients coming into the rice field by irrigation water and atmospheric deposition. The rice crop needs the following uptake of major nutrients to produce 1 tonne of grain per hectare: 15-20 kg N/ha, 2-3 kg P/ha, and 15-20 kg K/ha (Rice Knowledge Bank, IRRI).

IRRIGATION PRACTICE

Lowland rice

Irrigated lowland rice is mostly grown with supplementary irrigation in the wet season (monsoon), and is entirely reliant on irrigation in the dry season. Fields are bunded with small dykes about 0.20 m high and 0.20-0.30 m wide to keep ponded water in the field (basin). Farmers with access to irrigation aim to maintain 50-100 mm of ponded water ('floodwater') as this assures the crop of optimal water supply and helps control weeds and pests. The soil is usually kept ponded until a week or two before harvest. Total seasonal water input to rice fields (rainfall plus irrigation) depends heavily on percolation rate of the soil, and is up to 2-3 times more than for other cereals. It varies from as little as 400 mm in heavy clay soils with shallow groundwater tables to more than 2 000 mm in coarse-textured soils with deep groundwater tables. Around 1 300-1 500 mm is a typical value for irrigated rice in Asia (Bouman *et al.*, 2006).

Farmers faced with water scarcity are unable to keep their fields continuously flooded and adopt various water-saving technologies such as alternate wetting and drying (AWD) (Bouman *et al.*, 2007). In AWD, the field is flooded intermittently; hence, the field is alternately flooded and drained. The number of days of drained soil between irrigations can vary from one to more than 10 days. AWD is also the water-management practice used in the system of rice intensification (SRI). SRI is a cultivation system based on the use of young seedlings, wide row spacing, careful transplanting of single seedlings, transplanting in squares, alternate wetting and drying, manual or mechanical weed control, and large amounts of organic fertilizer use (Stoop *et al.*, 2002). Under rainfed conditions, lowland rice fields are intermittently flooded in an uncontrolled manner.

Upland rice

The management of upland rice generally resembles that of other cereals. Land preparation is under dry conditions, no puddling takes place, and the soil is not saturated or flooded during crop growth. Typical traditional upland rice fields may be flat or sloping without provision of irrigation facilities. After dry land preparation, seeds are hand-dibbled. Usually, no fertilizers, herbicides, or pesticides are applied.

An emerging production system is aerobic rice, in which especially developed high-yielding cultivars are grown in flat, well-drained, non-puddled, and non-saturated soils. The aerobic rice systems are practised in Brazil (250 000 ha) and on the North China Plain (80 000 ha) (Bouman *et al.*, 2007). The usual establishment method is dry direct seeding, either broadcast or seeded in rows of 0.20-0.30 m spacing. Irrigation is applied by flood or furrow irrigation (or raised beds), or sprinklers. Unlike irrigated lowland rice, the applied water does not flood the soil, but just brings the soil of the root zone to field capacity.

YIELD

Rice yield is usually expressed as rough rice with 14 percent moisture content. Rough rice includes a hull (about 20 percent by weight) and the whole grain. 'Brown rice' is the least processed form of rice in which the outer hull is removed, but the outer bran layers of the grain (11 percent by weight of rough rice) are still there. Milling removes all or part of the bran and germ from the rough rice, and results in 'white rice' (69 percent by weight of rough rice) which consists of the germ and starchy endosperm.

Country-average irrigated lowland rice yields in Asia range from 3 to 9 tonne/ha (rough rice), with an overall average of about 5 tonne/ha. Under continuously flooded conditions, short-duration (100-115 days) modern tropical cultivars can yield 8-10 tonne/ha in the dry season and 6-8 tonne/ha in the wet season. Good yields of long duration (120-150 days) cultivars in subtropical and temperate climates are around 12 tonne/ha, while maximum yields of up to 17 tonne/ha have been reported (Yunnan province in China, and in Australia), although such reported record yields are often open to question. Significant yield improvement has recently come only from the development of hybrid rice, which has increased yield potential by 5-15 percent over inbred cultivars in the same environment (Peng *et al.*, 1999). Lowland rice with uncontrolled flooding has average yields of around 1.5 tonne/ha, most likely the result of occasional water deficit, as well as deprivation of oxygen supply when flooded excessively. For good conditions yields of rainfed lowland rice average 4-5 tonne/ha. With frequent abiotic stresses (mainly drought), however, yields are considerably lower, only around 2 tonne/ha. Average upland rice yields are around 1 tonne/ha, while aerobic rice with application of around 90 kg N/ha can reach 4-6 tonne/ha.

HI varies with cultivar, location, season, and growth conditions. HI of modern, short-duration tropical cultivars is about 0.45 to 0.5 (45 to 50 percent) in the dry season and 0.35 to 0.4 in the wet season. The HI of many long-duration cultivars used in rainfed lowlands is about 0.35. HI of modern hybrid rice in China range from 0.4 to 0.5. With drought, HI decreases and can reach close to zero in extreme situations.

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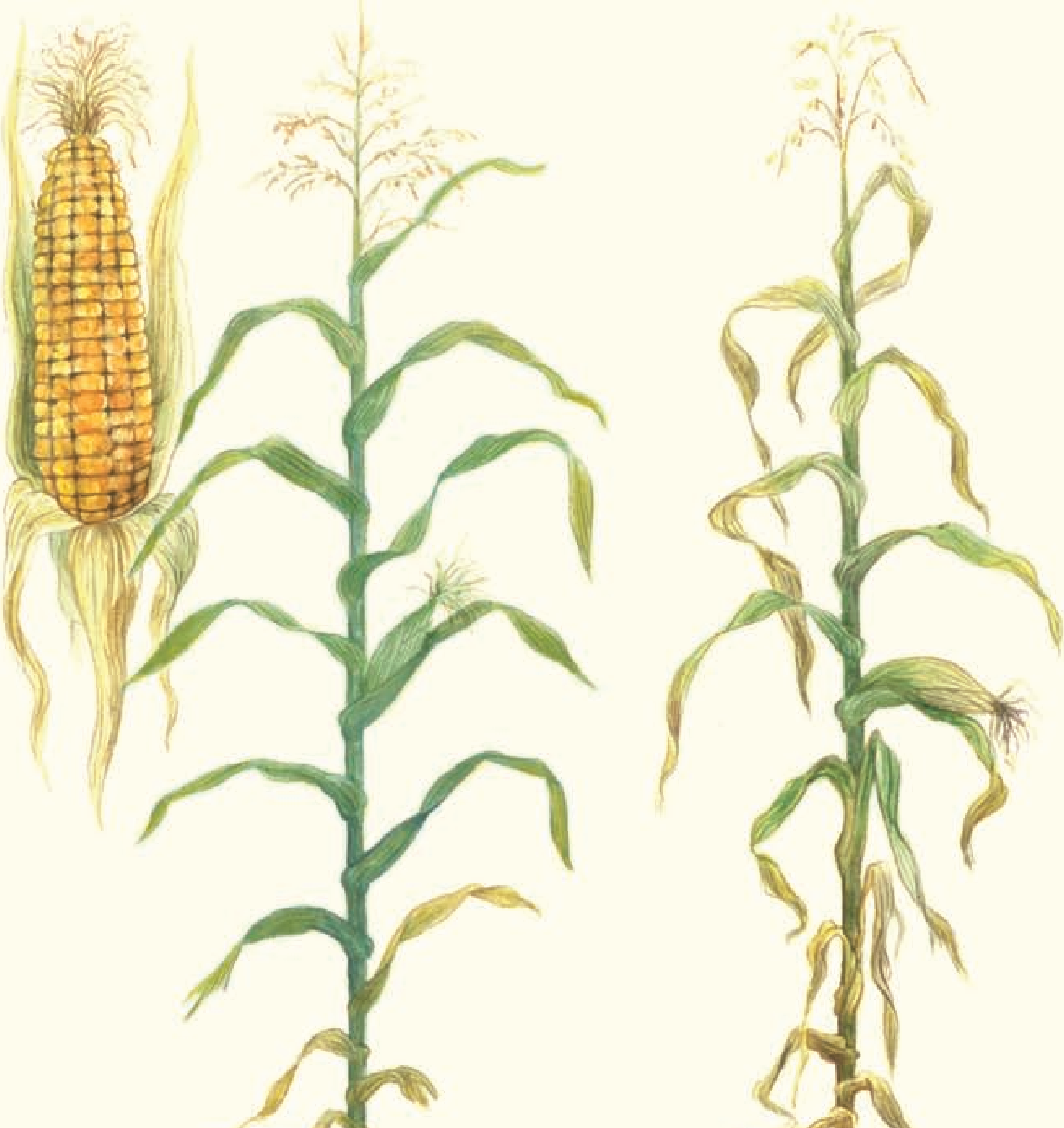

Maize

Maize

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GENERAL DESCRIPTION

Maize (*Zea mays* L.) ranks as the most important crop worldwide in terms of grain production; although wheat and rice are the most important for direct human consumption. Maize seeds are consumed by humans directly or after processing, and are often the main component of animal feed. Vegetable oil, sugar syrup, alcohol as biofuel, and feedstock for the manufacturing of plastic are commonly derived from maize seeds. The area devoted to maize and the yield per hectare have been increasing over time (Figure 1), total production was 819 million tonne in 2009 (FAO, 2011), the last year of available statistics. The grain production of wheat and paddy rice that year were each about 16 percent less than that of maize, with rice planted on about the same of area as maize and wheat planted on 30 percent more than maize. Nearly all the high-yielding maize cultivars are hybrids. The increasing use of hybrids in the 1930s led to a clear acceleration in the yield increase over time. Maize is a C_4 species, which originated in a climate with warm summers. It is grown, however, extensively in temperate regions for grain (Figure 2) as well as for silage. For the latter, the crop is harvested before full maturity, when the grains are in the late phase of filling and the vegetative material still mostly green, is coarsely chopped and partially fermented as animal feed. Even in areas with a growing season too short for grain to mature, maize is popular as a crop for silage and forage. The dominant producer of grain maize is the United States, with about 41 percent of the world's total, followed by other top producing countries China (20 percent), Brazil (6 percent), Mexico, Indonesia and India (2 percent).

The crop originated in Central America, where it is traditionally planted in hills. Nonetheless, most of the world's maize is grown as a row crop and as single crop. In Mexico and some subtropical countries in Africa and America, maize is frequently grown intercropped with beans. In the corn belt of the United States, it is often grown in rotation with soybean. On the northern plain of China, it is commonly grown in rotation with winter wheat. Other crops grown in rotation with maize include other winter cereals, and several forage and grain legumes.

GROWTH AND DEVELOPMENT

Maize germplasm is very diverse (Duncan, 1975), with a wide range of seed size, plant height, tillering habit, number of leaves per stem, number of

FIGURE 1 World maize harvested area and average yield over the period 1961-2009 (FAO, 2011).

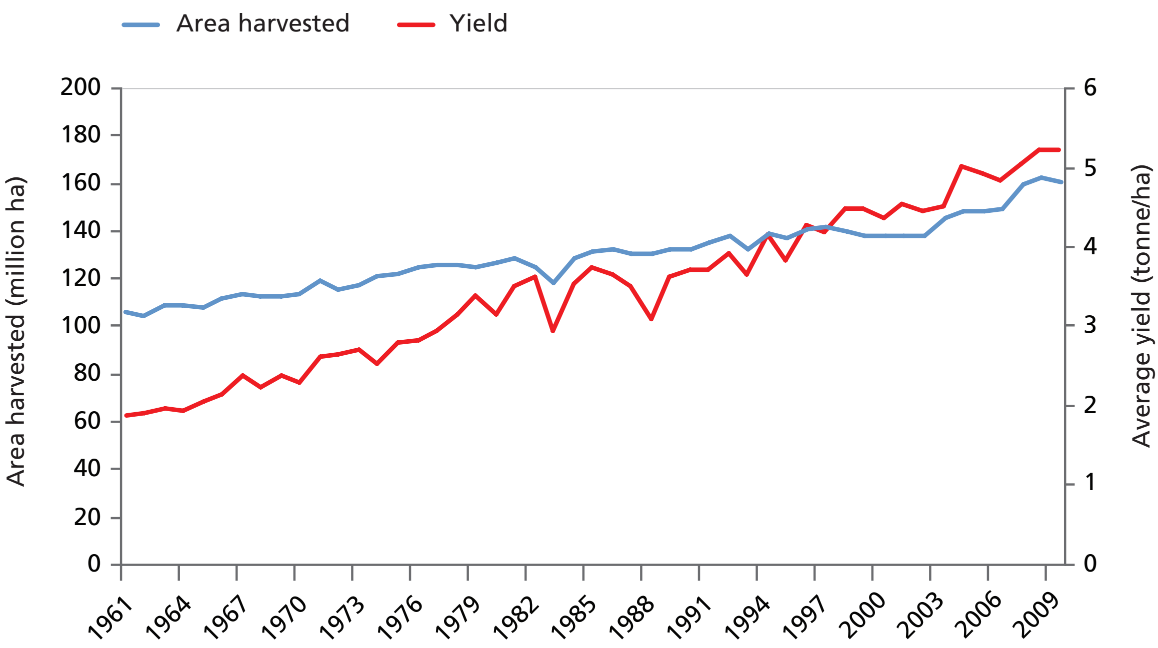
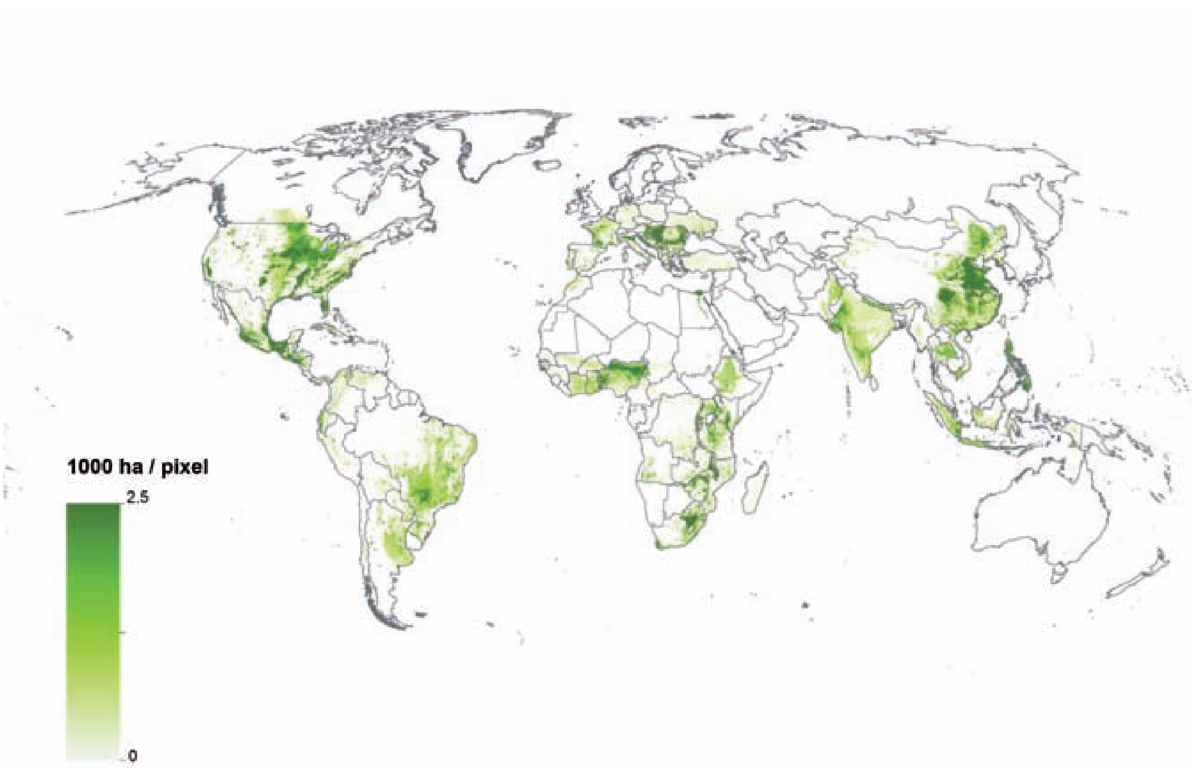


FIGURE 2 Maize harvested area (GAEZ, 2011).



Reference year 2000

ears per plant and ear size. Breeding and selection for high yield, however, have drastically narrowed the ranges, making the crop highly determinant. The description here is confined to modern well-developed cultivars, virtually all hybrids. Some land races and open-pollinated material may not fall within the range of this description.

Maize seed is large (0.2 to 0.3 g per seed) and with this large reserve the seedling is able to develop a relatively large leaf area a few days after emergence. This accounts for the large initial canopy size per seedling (large cc_o). Modern maize cultivars do not tiller when planted at sufficient density for high production, although many do tiller at much reduced density. Only one ear is produced per plant when planted at high density. The exceptions are plants at the edge of the field, which often produce two ears because more radiation is available for photosynthesis, and prolific cultivars, which produce more than one ear (but smaller in size) per plant.

Maize leaves develop and expand according to their sequential position on the nodes of the stem. Cultivars vary in the total number of leaves (number of nodes on the stem) largely according to their life-cycle length, with more nodes and leaves for the longer-season cultivars. The more common number of high-yielding cultivars varies from 18 to 22 leaves (Rhoads and Bennett, 1990). Because fewer leaves usually means a smaller total leaf area per plant, shorter season cultivars need to be planted at a higher density to reach the same maximum canopy cover (CC_x) as a longer-season cultivar. Density of commercial plantings varies from 40 000 to 110 000 plant/ha, and high yields are achieved at densities no less than 70 000 plant/ha. In areas of limited rainfall and no irrigation, or when soil nutrients are limiting, plant density should be reduced to match the available resources. As a C_4 crop, the relative growth rate of leaves is high, leading to a high canopy growth coefficient (CGC). During the early part of canopy development, the typical rate of canopy growth is about 16 percent (of existing canopy cover) per day for optimal conditions. As is the case for most other crops, expansive growth of leaves and hence canopy growth is highly sensitive to water stress.

On good soils, the root deepening rate of maize can average 2.5 cm per day, with effective rooting reaching a depth of 2.8 m or deeper near the time of maturity (Hsiao *et al.*, 1976). The more commonly observed rooting depth, especially in regions with cold winter temperatures, however, is less; in the order of 1.5 to 2 m. Rate of deepening can be markedly restricted by impeding (either physically or chemically) layers in the soil, poor aeration and cold soil temperature. The rate of deepening is important in situations where there is substantial amount of water stored in the deeper layers during periods when there is little or no rainfall and irrigation.

Maize is monoecious, with its male organ (tassel-bearing anthers) located separately from the female organ (ears with stigmas called silks) on the tall (1.6 to 3.4 m) plant. Tassel is located terminally on the stem and emerges from the flag leaf (last leaf on the stem) enclosing it, when the leaf area of the plant has reached near maximum with only the flag leaf and possibly the next leaf below still expanding. The ear is formed at the leaf axil many nodes below (e.g., node number 11) and ahead of the tassel. However, silks emerge from the husk of the ear after tassel emergence, and after the tassel begins to shed pollen. Because tasselling occurs only after all the leaves are grown, the cultivars have a higher number of leaves would flower and pollinate later than those with fewer leaf number, other things being equal. For current cultivars with a 120 to 135 day life cycle under favourable conditions, the time interval from emergence to flowering is about 65 to 70 days; the start of canopy senescence is about 105 days. Short-season cultivars for more northern latitudes flower 10 to 15 days earlier. Maximum canopy cover (CC_x) is achieved at flowering if plant density is 70 000 plant/ha or less; and under good conditions full canopy cover is achieved sooner if the density is substantially higher, because the leaf area per unit land area (leaf area index, LAI) needed to close the canopy is reached earlier, before flowering.

The emergence of all the silks on an ear and their pollination may take 7 or 8 days when temperature and water regimes are favourable. Because of heterogeneity of a field plant population, the overall pollination time for a field may last at least twice as long as that for a single ear.

Kernel weight increases after pollination (Duncan, 1975) follows the classical time course curve for cereal grains. The grain maturation process is associated with declines in kernel water content and full maturity is generally considered to be at the time when a 'black layer' forms at the base of the germ of the kernel (Daynard, 1972). At full maturity and under favourable conditions, the grain of modern cultivars comprises around 50 percent of the above-ground biomass produced by the crop, that is, the harvest index is close to 0.50 (or 50 percent). For unimproved cultivars or land races, the harvest index may be as low as 0.3. The *AquaCrop* simulation recommends that HI be set to increase until the time of full maturity, with the latter taken to be the time when green canopy cover declines to 10 percent of the maximum canopy cover reached. As for many other crops (Evans, 1993), maize grain yield is often correlated with green leaf area duration (Wolfe *et al.,* 1988a). Reduced green leaf area duration may be the result of the leaf growth rate being reduced and/or premature leaf senescence, caused by water stress or the nitrogen or other nutrients deficiency, as discussed below.

IRRIGATION, WATER USE AND PRODUCTIVITY

In the United States corn belt, where rainfall amount and distribution are usually favourable and the soil is deep with a high water-holding capacity, maize is grown without irrigation or only with supplemental irrigation. In the more arid areas of the United States, maize is irrigated. In northern China, where rainfall coincides with the maize-growing season, the crop can be rainfed or grown with supplemental irrigation. The common application methods include furrow and centre pivot irrigation. Seasonal maize water use varies according to evaporative demand of the atmosphere, and hence according to climate, time of season when the crop is grown, life cycle length of the crop, and water availability. For well-watered situations, seasonal ET ranges from less than 500 to more than 800 mm, the typical seasonal ET of a cultivar of medium-season length grown in a temperate climate at latitude of 35° to 40° being around 650 mm.

At midseason, when there is complete canopy cover of the ground and water and mineral nutrients are not limiting, maize transpires at a rate slightly higher than the reference ET (ET_o). Detailed data (Steduto and Hsiao, 1998) show the crop coefficient (K_c) is slightly less than the values used earlier, only in the range of 1.07 to 1.12. This presumably is the result of lower stomatal conductance of maize leaves relative to most broad-leaf crop species. As a C_4 crop, maize water use efficiency is high (de Wit, 1958; Steduto *et al.*, 2007), mostly because of the high rate of photosynthesis, with only a minor contribution from the slightly more restricted transpiration rate. Contrary to earlier opinions, maize under favourable conditions responds positively to increases in atmospheric CO_2, as shown by increases in leaf area (Hsiao and Jackson, 1999) and biomass at least up to 520 ppm CO_2. Hence, *AquaCrop* adjustments normalize water productivity (WP*) according to atmospheric CO_2 concentration, year-by-year. For example, maize WP* was adjusted from 32.4 g/m^2 in 1990 to 33.7 g/m^2 in 2000.

RESPONSES TO STRESSES

Water stress develops when rain and irrigation are absent and the water stored in the root zone is depleted to the point where plant processes are affected. In *AquaCrop*, the threshold level that triggers stress responses are set for different key processes. As for virtually all crops, leaf expansive growth of maize is the most sensitive of all the stress responses (Bradford and Hsiao, 1982; Hsiao and Xu, 2000) and its stress response threshold in *AquaCrop* is set not far below soil field capacity. Very mild water stress, lasting for many days can lead to a much smaller canopy cover during the vegetative stage. If stress is sufficiently more severe, stomatal conductance are also reduced, and at a similar stress level senescence of older leaves begins to accelerate. Crop transpiration and photosynthesis would be reduced both as the result of less green canopy cover (because of reduced growth or more senescence) and lower stomatal conductance. This of course leads directly to reduced rate of biomass production, and hence reduced grain yield. An added negative effect is that the acceleration of canopy senescence would reduce the canopy duration and shorten the grain-filling period. There would not be sufficient time for the harvest index to build up and reach its normal maximum. The end result is that the percentage reduction of grain yield would be even more than the percentage reduction of biomass.

As a result of the monoecious nature of maize, fairly severe to severe water stress can cause a peculiar problem of reproduction. In addition to expansive growth of leaves, expansive growth of stems as well as silk and tassel are also inhibited by the stress. The slower silk growth or elongation leads to delayed emergence of silk from the husk. Tassel emergence is also delayed by water stress, but the delay is less than that for silk (T.C. Hsiao, personal observation). This difference in delay can cause pollination failure as, by the time the silk emerges, there may not be sufficient pollen left to fully pollinate the crop. On the other hand, the failure to pollinate the late silks on an ear and the very late ears of a plant population must be substantial to negatively impact yield because in dense plantings the number of grains (kernels) a plant is able to mature is only 65 to 75 percent of its number of silks, and the late emerging silks do not form mature kernels even when pollens are ample (Duncan, 1975; T.C. Hsiao, unpublished). Also, the very late ears are formed by the smallest plants in the population and their contribution to yield is minimal even when pollinated. The time interval between tassel emergence and silk emergence appears to vary with different genetic lines (Bolaños and Edmeades, 1996), but is minimal for lines well-adapted to the local environment. As the severity of water stress increases, however, this interval is lengthened more and more and grain yield can be drastically reduced as a result of pollination failure (Bolaños and Edmeades, 1996). As mentioned, modern maize is highly determinant with a narrow time interval for pollination. This means there is no opportunity to make up for reduced pollination with later flowers when rain or irrigation comes.

Overall, and relative to other crops, maize is considered to be sensitive to water stress. Maize does not osmotically adjust as well as cotton, sorghum or wheat to low water status. In addition and as already discussed, its high determinancy makes it harder to make up for the loss in productivity after the period of water stress is released by irrigation or rain.

With respect to salinity, maize is considered to have medium sensitivity (Ayers and Westcot, 1985). Its responses to salinity stress are similar to its responses to water stress, namely, slowing of leaf expansive growth, reduction of stomatal conductance and photosynthesis, and acceleration of leaf (hence canopy) senescence, with the same relative ranking of sensitivity of these parameters similar to that of water stress.

Deficiency of mineral nutrients can markedly impact maize productivity. The most common deficiency is nitrogen, although potassium or phosphorus deficiency can be equally or more important in some soils. Maize grain contains about 1.3 to 1.8 percent nitrogen. With a fair grain yield of 10 tonne/ha, 130 to 180 kg of nitrogen would be removed from the soil by the grain alone. For maize to produce reasonably good to high yields, nitrogen removal by the whole crop for the season is in the range of 180 to 340 kg/ha (Wolfe *et al.,* 1988a; Rhoads and Bennett, 1990). As for all crops, the photosynthesis rate of maize leaves in favourable environments are linearly related to leaf nitrogen content (Evans, 1993). The photosynthesis rate is reduced by about two-thirds as leaf nitrogen content drops to less than 1.5 percent, and approaches zero as the content decreases below 1 percent (Wolfe *et al.*, 1988b). The common fertilization rate in countries such as the United States (Rhoads and Bennett, 1990) and China are in the order of 200 kg of nitrogen per ha or somewhat higher. For many developing countries the rate of fertilization is usually less than half that amount. This is almost certainly one major reason for the low world average yield. In the field the effects of water stress are often confounded by nitrogen deficiency. The reason is that fertilizer nitrogen is applied to the top layer of the soil, which dries up first when water stress develops and essentially nitrogen becomes unavailable (Wolfe *et al.*, 1988a).

Being a C_4 and warm-season crop, maize is sensitive to cold. In *AquaCrop*, for the calculation of growing degree day (GDD), the base temperature (T_{base}) for maize is set at 8 °C, and the upper temperature threshold (T_{upper}), the temperature above which crop development no longer increases with an increase in temperature, is set at 30 °C. The minimum GDD for full biomass production per unit of transpiration is tentatively set at 10.

YIELD

Over the last few decades grain yield for maize has continued to increase. Much of this increase is because of higher planting density, improved fertilization, optimal canopy structure, and late-maturing cultivars with longer life-cycles. Yields around 17 tonne/ha for late-maturing maize cultivars, grown with optimal water and mineral nutrients supply under ideal conditions and excellent pest and weed control, have been reported in experimental studies and in farm tests. Farm yields between 11 and 14 tonne/ha are normally achieved under full irrigation and high fertility. The average country yields are generally much lower, except for a few countries; for instance, it was slightly over 10 tonne/ha for the United States, and over 9 tonne/ha for France, in 2009. Average yields in Argentina, China and South Africa were only about a half of this, and in Brazil slightly above one-third; but all show clear rising trends over time. On the other hand, average yields in a number of less industrialized countries are only in the range of 1-2 tonne/ha, and do not yet show a clear trend of improving.

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Soybean

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Soybean

GENERAL DESCRIPTION

Cultivated soybean (*Glycine max* (L.) Merr.) is a major oilseed and protein rich annual legume crop grown on about 99 million ha and producing 223 million tonne of grain worldwide (*FAO, 2011*). The crop originated in China and is closely related to *Glycine soja*, its wild progenitor. Soybean represents nearly 50 percent of the total area cropped with seeds providing approximately 56 percent of the total edible oilseeds and 30 percent of vegetable oil production worldwide. Over the last 50 years, world production has increased eight times as a result of the substantial increase in average yields and the expansion in cultivated area (Figure 1).

Soybean is grown from the equator to latitudes 55° N or S and as high as 2 000 m. However, main soybean production is concentrated between 25° and 45° N regions, and generally grown below 1 000 m altitude (Singh *et al.*, 2009) (Figure 2). The five top producers of soybean, the United States, Brazil, Argentina, China and India, in that order, account for more than 93 percent of global production. Soybean cultivation is also increasingly popular in Paraguay, Canada, Bolivia, Ukraine, Uruguay, Indonesia, Russian Federation and Nigeria.

Today most commercially grown soybeans are the yellow-seeded field cultivars used for animal feed, oil production (for food and industrial uses), and as a protein-rich food. Other cultivars are available for special use: forage and hay (with an abundance of stems and leaves) and as a vegetable (large-seeded, various coloured varieties).

Soybean fits well into crop rotations and intercropping systems. Most prominent cropping sequences are soybean-maize and soybean-wheat in the United States, Brazil and Argentina. Soybean-chickpea, soybean-mustard, soybean-wheat sequences and soybean intercropping with pigeonpea or cotton are common in India and China. In Indonesia double or even triple cropping is practised with rice(-rice)-soybean, where soybean is grown on the residual moisture in rice fields in the dry season. In Vietnam soybean is grown as a late summer crop for fodder after the rice harvest. Work by International Crop Research Institute for the Semi-arid Tropics (ICRISAT) in India had shown that yield increases with soybean-chickpea and soybean/pigeonpea sequential and intercrop systems was possibly because more nitrogen is made available when one legume crop follows another. If soybeans have not been grown in a particular location for

FIGURE 1 World soybean harvested area and average yield over the period 1961-2009 (FAO, 2011).

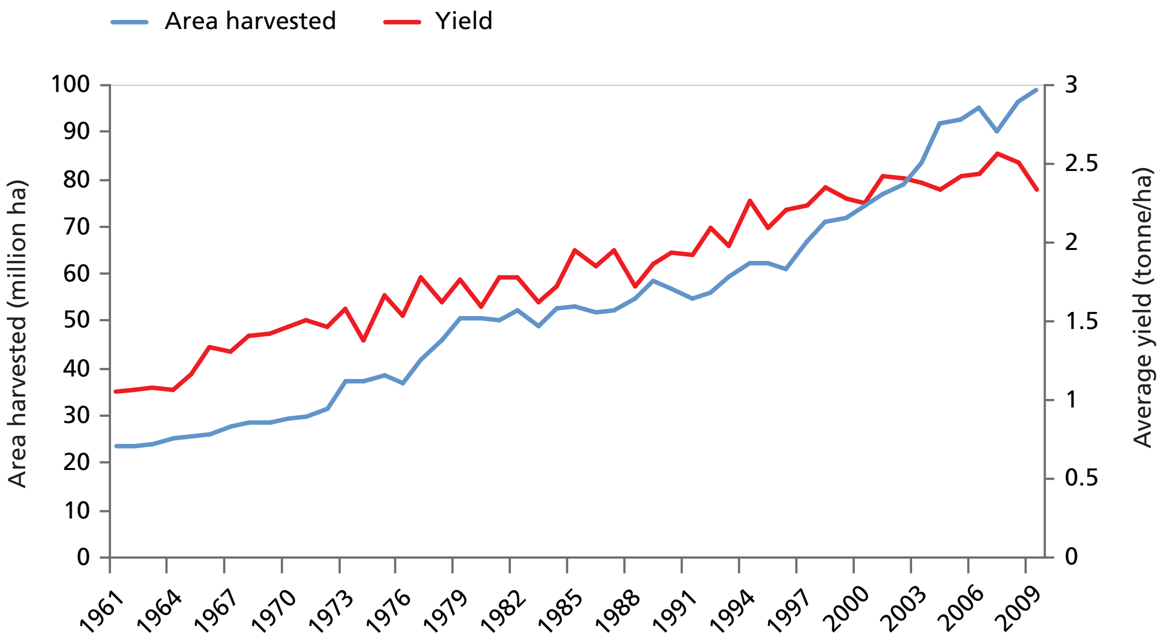
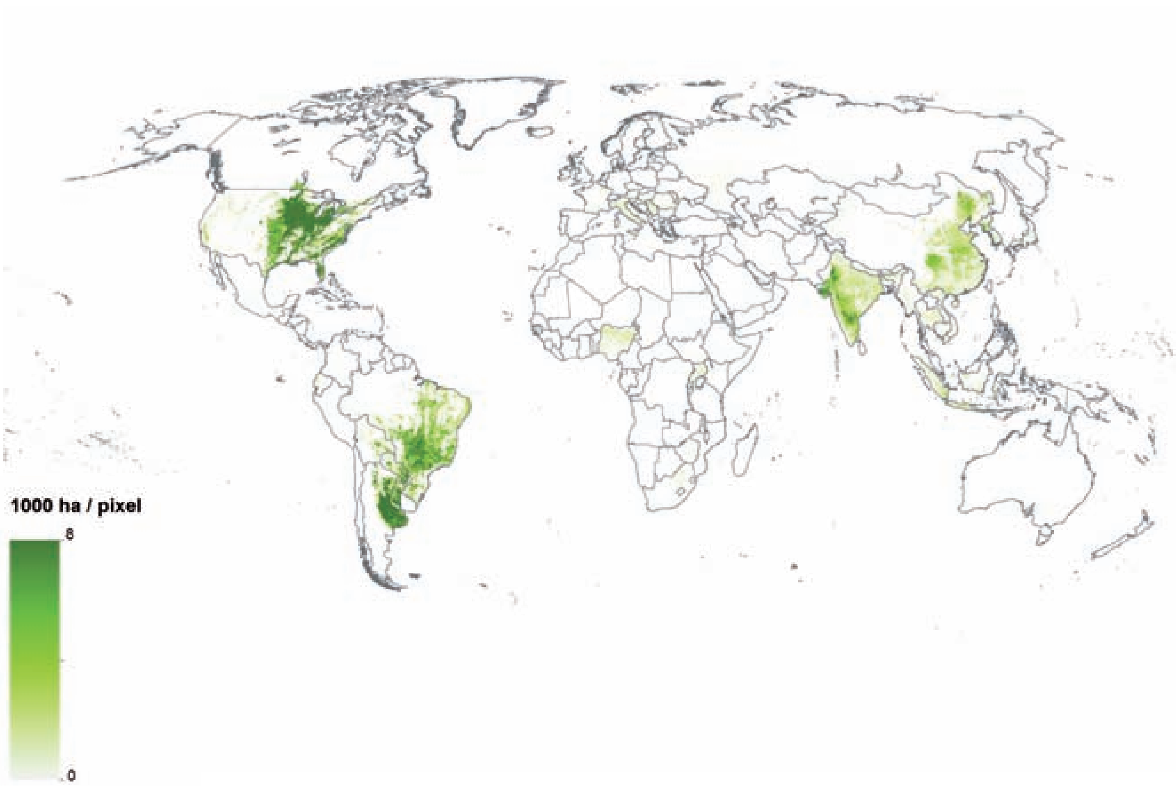


FIGURE 2 Soybean harvested area (GAEZ, 2011).



Reference year 2000

three or more years, it is best to inoculate the seed with an effective strain of nitrogen-fixing bacteria (*Rhizobium*).

GROWTH AND DEVELOPMENT

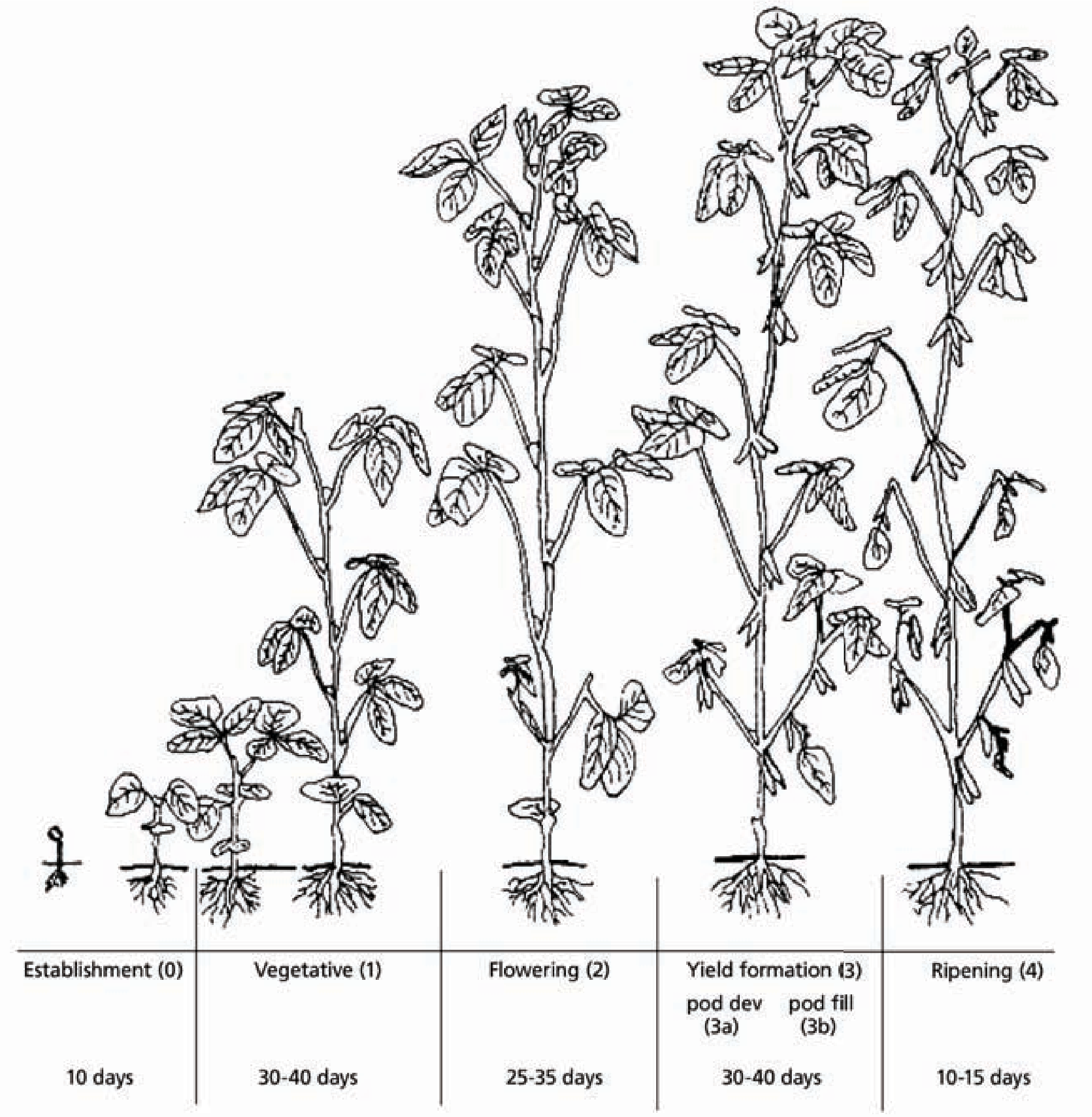
Soybean cultivars vary from being highly determinate to indeterminate. Indeterminate plants are those that continue to produce leaves, new flowers and pods for several weeks after the start of flowering. They typically grow taller, to 1 m, and are more common at higher latitudes with short growing seasons. Growth is stopped by cold temperature near the season's end. Determinate plants complete their growth in height and then produce the flowers at about the same time. They are usually one-half to two-thirds (0.45 to 0.6 m) as tall as indeterminate cultivars. There is however no correlation between plant height and seed yield (Figure 3).

Soybean is grown mainly under rainfed conditions in late spring or summer, when there is rain. In India and China, soybean is mostly sown in May/June to early July but may be grown in spring and sown between February and March in the southern regions. In the United States, Brazil, and Argentina sowing season starts in May and ends by mid-July as the summer crop or is planted after winter wheat. Late plantings generally have smaller canopies and produce less than early plantings. In areas of high rainfall, raised seedbeds in the form of broad-bed and furrow or ridge and furrow land forms are well suited to draining out excess water from Vertisols and to providing good aeration of the root zone. Planting density ranges from 150 000 to 500 000 plant/ha, depending on seed cost and environmental factors. In India, optimum plant population of 330 000 plant/ha is recommended, and it can be achieved with a seed rate of 80-100 kg/ha based on seed size. In the United States, common row spacing is 0.50 m, while in Brazil, Argentina, China and India, rows are often narrower (0.33 m). Sowing depth of 2.5 to 4.0 cm is optimum for good germination. Optimum average air temperature for rapid germination is approximately 30 °C.

Soybean is very adaptable to different cropping systems, as there is wide variation in the length of the life cycle, between 70 and 140 days depending on the cultivar and season. Because of variation in season length with latitude and the need to fit into a particular time span in crop rotations, life cycle length was important enough to prompt the designation of soybean cultivars by maturity groups in North America. The designation uses Roman numerals up to X, with the duration to maturity increasing as the numeral increases. The breeding of lines with even shorter life cycles later caused the extension of the low end of the maturity groups, from I to 0, 00, and 000. Soybean flowering is determined by photoperiod and thermal regime. Cultivars in late maturity groups, grown in lower latitudes, initiate flowers at shorter day length (e.g. 10 hours), whereas cultivars in early maturity groups, grown in higher latitudes, initiate flowers at longer day length (e.g. 13 hours). It is important to grow locally-adapted cultivars at a given latitude. For example, if a cultivar suitable for a higher latitude is grown at a lower latitude, it would flower and mature too early and yield less.

Short duration cultivars, ranging from 95 to 115 days, are popular in India, the USA, China (Heilongjiang province and Huai river valley), while even shorter life cycles are used in Korea. Medium duration cultivars of 120 to 140 days are grown in China (Northeast and Loess plateau). Brazil and Argentina prefer the longer season cultivars, which produce up to 20

FIGURE 3 Typical developmental stages of soybean.



percent higher yield than the early maturing. Most cultivars suitable for the rainy season are medium maturing, between 95 and 115 days. For cultivars of this maturity range, indicative duration of the different growth phases is as follows:

- sowing to emergence: 6 days;
- sowing to maximum canopy: 50-55 days (depends on plant density);
- sowing to onset of canopy senescence: 80 days, and time from onset to completion of canopy senescence: 25 days;
- sowing to physiological maturity: 105 days; and
- sowing to flowering: 36-45 days, and flowering duration: 14-20 days.

Determinant cultivars reach maximum canopy cover and height at early reproductive stages (between R1 and R3 of soybean growth stages), while the canopy of the indeterminate type can continue to grow after this. Maximum canopy cover varies between 65 and 95 percent depending mostly on row spacing and plant density. Soybean flowers are white or purple, very small and borne in short clusters. Only about 25 to 60 percent of the flowers actually produce pods, which become prominent one to two weeks after the flowers appear. Pod setting lasts two to several weeks, longer for the indeterminate cultivars. When conditions are not limiting, a pod produces three to four seeds and they fill in about one month.

As for all crops, soybean preferentially grow roots relative to shoot at germination to shortly after emergence. Maximum depth of rooting for soybean is about 1.3 to 1.8 m deep and can reach up to 2.40 m, depending on water status, soil type and temperature, and life cycle length of the cultivar (Kanemasu, 1981). Most roots are located in the upper 0.3 m of soil, but prolonged dry periods cause roots to proliferate more in the deeper soil layers. As is the case for other crops, water stress increases the root to shoot ratio, and tends to increase total root length. Soybean genotypes vary in their growth and development of root systems.

WATER USE & PRODUCTIVITY

Depending on climate, soils, crop cultivar, and management practices, evapotranspiration (ET) of soybean varies between 300 mm and 800 mm. In India, soybean ET was reported to be around 450 mm. Seasonal water use of 330 mm to 760 mm has been reported in the United States, and similar values in Australia. *FAO Irrigation and Drainage Paper* No. 56 presented values between 450 and 825 mm. Peak daily water use of soybean is about 8-9 mm/day, which normally occurs as maximum canopy cover is reached (near full bloom to beginning of pod filling).

Biomass water productivity ($WP_{B/ET}$) of soybean, i.e. slope of the linear relationship between biomass and cumulated ET, has been found to vary from 1.2 to 1.6 kg/m^3 in studies carried out in different parts of the world. Higher $WP_{B/ET}$ values were observed in the United States/ Canada studies while lower values were found in India. The difference may be due to limitation of nitrogen and other mineral nutrients in the latter. For oilseed crops such as sunflower and soybean, $WP_{B/ET}$ decreases after anthesis because the protein and oil in the seed require more energy and photosynthetic assimilates to make than cell walls or starch. Soybean showed significant increase in seed yield with elevated atmospheric CO_2, by up to 35 percent.

RESPONSE TO STRESSES

Water, temperature, nutrient stresses affect the growth and development of soybean. Vegetative (leaf and stem) growth is very sensitive to water deficits. Water stress that occurs at the beginning of podsetting to full seed-filling has a greater negative impact on yield than when it occurs at other stages. The seed-filling period is very critical to yield. If environmental conditions are adverse (drought, hail, or disease), seed-fill will be restricted and yields will be cut severely (Doorenboos and Kassam, 1986).

Soybean is very sensitive to frost at seed emergence and pod filling, but losses due to frost in grain yields for indeterminate cultivars are less compared to other cultivars because of the extended flowering period.

A number of studies indicate that soybean yields are not substantially affected until the root zone soil has been depleted below 60 percent of total available water (TAW), provided canopy development has not been hampered by prolonged mild water deficits during the vegetative phase. Water stress during grain filling reduces seed size considerably, and water stress after flowering and during pod filling is most critical (Doss and Thurlow, 1974). In addition to the usual inhibitory effects on leaf expansion, transpiration and photosynthesis, water deficits also inhibits nitrogen fixation in soybean.

Excess moisture severely affects germination and early growth of soybean. However soybean tolerates flooding or waterlogging up to 7 days, but yield can be reduced by more than 40 percent if prolonged flooding occurs at floral initiation or beginning of the seed filling stage. In addition to being detrimental to root activities, flooding reduces nodulation. Soybean exposed to flooding for more than 8 days produce adventitious roots on the stem with aerenchyma tissue which facilitates oxygen diffusion to the submerged apical root portion (Mayaki *et al.*, 1976).

Soybean can be grown in a wide range of soils, except those that are very sandy, with optimum growth in alluvial soils high in organic matter. Usually, the fertilizer phosphorus and potassium requirements are 35 to 70 kg/ha P_2O_5, and 36 to 84 kg/ha K_2O. Soybean is often assumed to be capable of fixing atmospheric nitrogen to meet its requirement for high yield; although benefit from a starter dose of 10 to 20 kg/ha N is recognized. However, this assumption may not hold under conditions of high yield potential but with a soil low in organic and mineral nitrogen. A soybean crop at maturity contains on average 70 kg of N, 30 kg of P_2O_5, and 60 kg of K_2O per tonne of grain produced. So a yield of 3 tonne/ha would require at least 210 kg/ha of N by symbiotic fixation and uptake from the soil. A number of studies have shown that even under favourable conditions, symbiotic fixation usually supplies not much more than half of the N, with the rest coming from the soil. Nitrogen fixation is reduced under water stress; irrigation and rainfall distribution greatly affect N accumulation and N supplies from those fixed.

Soybean cultivation is successful in climates with warm summers, and optimum growing conditions at mean temperatures of 20 °C to 30 °C. Days to flowering of soybean were shortest at 30 °C, and an increase in days to flowering at 25 °C, 35 °C and 20 °C has been observed. At 20 °C self pollination without opening of the flowers has been reported for various cultivars, so has abortion of flower and newly set fruit at 35 °C. High canopy temperature (approaching 40 °C) reduces CO_2 assimilation rate, and low stem temperature slows translocation, which stops in soybean at 2 °C to 3 °C.

Soybean is generally sensitive to salinity, but cultivars differ substantially in their salt tolerance. Some moderately tolerant cultivars exclude chloride from their leaves. High phosphate supply in the growth medium increases sodium uptake and reduces salt tolerance of some cultivars.

IRRIGATION PRACTICE

Soybean is commonly grown under rainfed conditions; for example, only 8 percent of the total area in the United States is irrigated. Efficiency of applied water is highest when irrigation is applied during the reproductive stage (around R3 stage) relative to applications before flowering. Irrigation during pod filling also prevents or stops accelerated canopy senescence caused by water stress, ensuring good green canopy cover to continue photosynthesis and maximize translocation of assimilates and minerals from leaves to seeds. As with other crops, the irrigation requirement of soybean varies, depending on rainfall, climate, water storage capacity of the soil and rooting depth. The number of applications varies from a minimum of 2 to a maximum of 8 irrigations in the season to ensure that the crop is not exposed to substantial stress once pod setting has begun. Irrigation scheduling, based on 60 percent depletion of TAW, consumes less water without severely affecting crop yields if soil water content is adequate at sowing. In many cases a single irrigation at late bloom is most beneficial compared to any other growth stage.

Surface irrigation by flooding, ridge and furrow, basin, and border application methods are commonly practised. Sprinkler irrigation by center-pivot, side-roll, traveling-gun, tow-line, and solid-set, is also practised in some countries. When soil water is deficient, irrigation increases plant height, leaf area, leaf number and length of primary root, as well as the dry weight of stems, leaves, reproductive organs and roots (Rhine *et al.*, 2009).

YIELD

Soybean yield averages around 2.0 to 2.5 tonne seed/ha (at 13-14 percent seed moisture content) for major producing countries but in developing countries, a large yield gap exists between farmers' yields and achievable soybean yield. Average soybean yields in the United States approach 3 tonne/ha, and in Brazil, 2.7 tonne/ha (Bhatia *et al.*, 2008; Singh *et al.*, 2009). In Europe, Italy has the highest average yield, at 3.5 tonne/ha. The yield is 1.6 tonne/ha in China while it is only 1 tonne/ha in India. The yield potential of cultivars of variable duration (65-130 days) in India ranges between 1.2 to over 4 tonne/ha with low to high input crop management (Singh *et al*. 2009). In the United States, top yields of over 5 tonne are not unusual in some areas. This difference in yield is probably related to differences in management practices and to the different nutrient status of the soil, including nitrogen, with a tendency of the crop to be exposed to nutritional stress in low-yielding farming systems. Soybean is primarily utilized as the source of protein and oil. The seeds contain 40-42 percent protein and 17.5 percent to 20 percent oil, with polyunsaturated fatty acids such As oleic and linoleic acids dominating. Soybeans grown in different locations can vary substantially in protein, amino acids and lipid concentrations, as indicated by a study comparing the chemical compositions of beans grown in China with those grown in the United States and Brazil (Grieshop and Fahey, 2001). It appears that environmental conditions under which soybeans are grown can significantly impact chemical composition and nutritional quality.

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Barley

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Barley

GENERAL DESCRIPTION

Barley (*Hordeum vulgare L.*) ranks fourth among cereals in terms of total world production. In 2009, around 54 million ha of barley were harvested, producing 152 million tonne of grain at an average yield of 2.8 tonne/ha (FAO, 2011). Over the last 50 years, the average yield per hectare has increased noticeably. However, because of changes in the area cropped, total production rose only to the 1980s, followed by a decline in the 1990s, and possibly stabilizing since then (Figure 1). Barley is the main feedstock for beer and also an important feedstock for whisky. The fluctuation in area harvested may partly be the result of changing market demand.

Barley was one of the first domesticated cereals, originating in the Fertile Crescent area of the Near East about 10 000 years ago. It is adapted to and produced over a wide range of environmental conditions. It is a cool-season crop cultivated in the spring and summer at higher latitudes and in the tropics at high elevations, and in the winter and spring at lower to semitropical latitudes. The main production countries are the Russian Federation, Ukraine, France, Germany, Spain and Australia (Figure 2).

Two botanical types can be distinguished, two- and six-row barleys, depending on the number of fertile and developed spikelets at each node of the rachis. Spikelets alternate on nodes along the rachis. In wild relatives, the two lateral spikelets are infertile and only the central spikelet is fertile, giving the appearance of having two-rows of spikelets, one at each side. Cultivars that retain this wild characteristic are two-row barleys. In six-row barleys, mutations resulted in the lateral spikelets being fertile, with three (one central and two lateral) spikelets at each node of the rachis.

The two main uses of barley grains are as animal feed and as malting for beer and whisky. In general, six-row barley tends to have higher protein concentration than two-rowed barley and, therefore, it is better suited for animal feed. Two-row malting barley has been traditionally grown in Europe, Australia, South America, and some other regions of the world, while six-row malting barley is more common in North America. Currently, two- and six-row malting barley can be found in all growing areas of the world.

Barley is similar to wheat and consequently several aspects of the crops` management are analogous. Although direct comparisons between the

FIGURE 1 World barley harvested area and average yield over the period 1961-2009 (FAO, 2011).

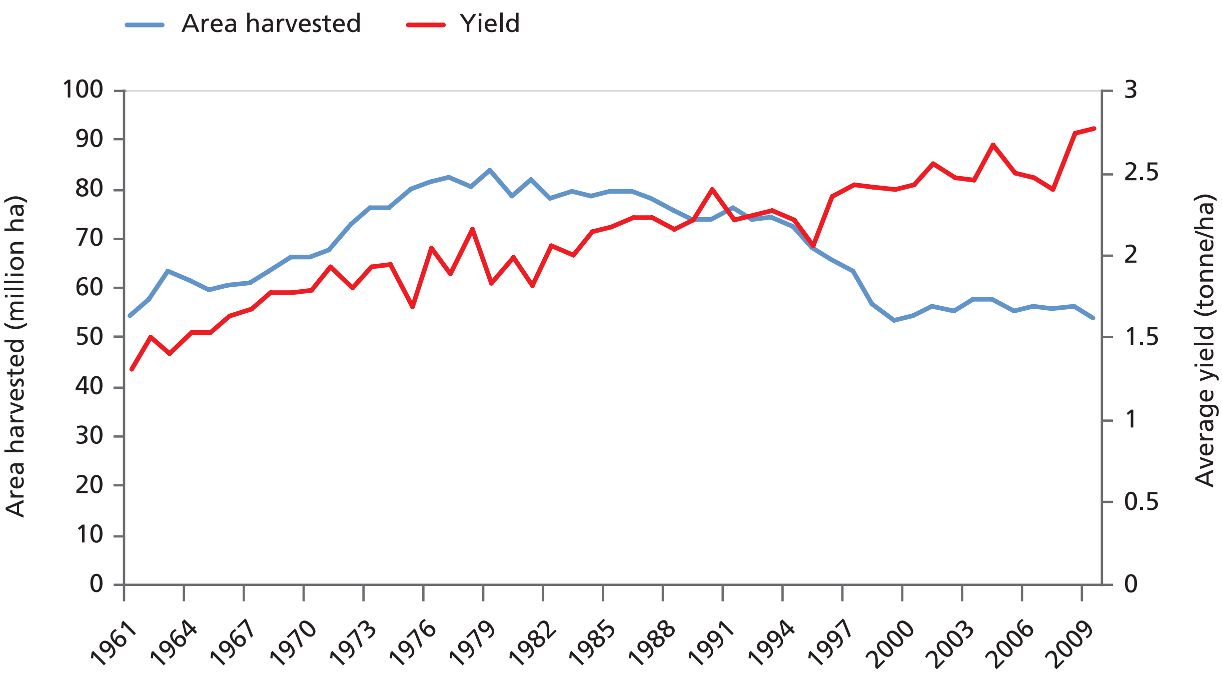
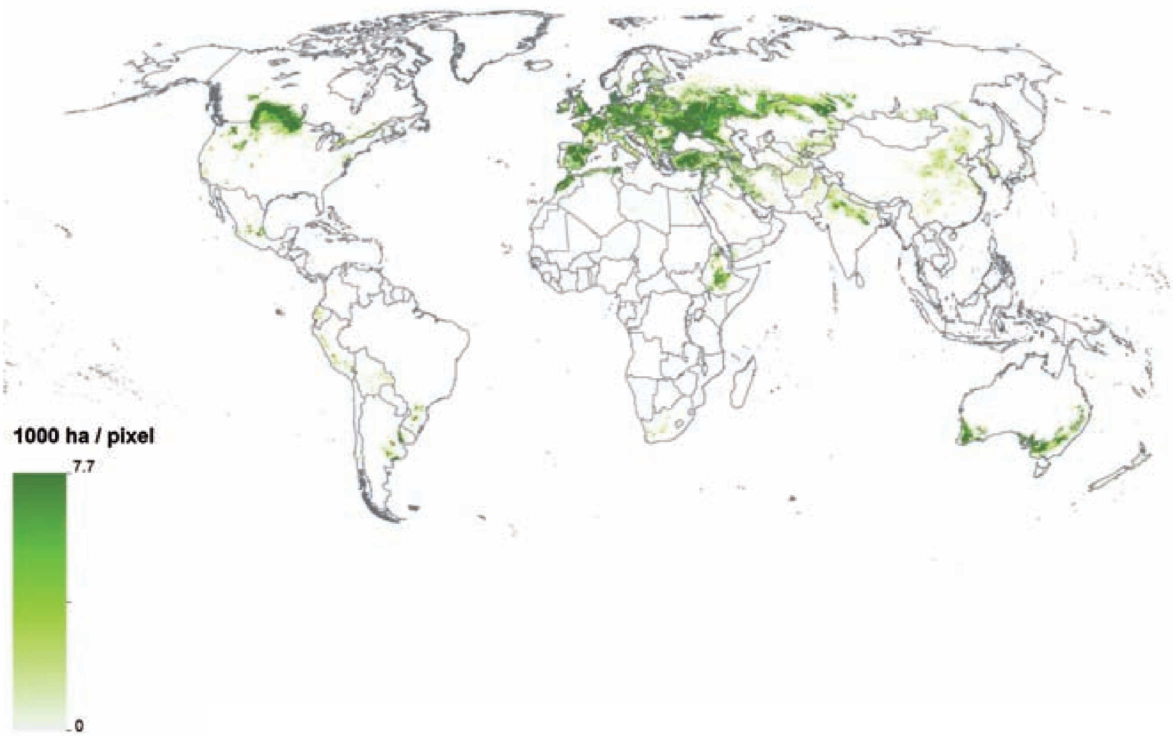


FIGURE 2 Barley harvested area (GAEZ, 2011).



Reference year 2000

two cereals are scarce, one of the main differences is that barley is generally believed to be better adapted than wheat to stressful situations and therefore it is normally sown in harsher environments than wheat (see Cossani *et al.*, 2009). In many areas, where one crop is produced per year, barley is grown in rotation with a variety of other winter annuals such as other cereals, oilseed crops, and pulses; but in dry environments barley monoculture is common (i.e. in the Mediterranean basin in areas where annual rainfall is less than 350 mm). The season length of barley tends to be shorter than that of wheat, making it more suitable for double cropping. For instance, barley may be followed immediately by either maize or soybean.

GROWTH AND DEVELOPMENT

Barley genotypes are generally grouped into two categories according to their sowing time: winter and spring cultivars. Winter barley is sown in autumn and requires a cold period (vernalization) during early growth for flowering under long days, and matures in late spring to early summer. This ensures flowering when the risk of late frost is low, leading to a long yield formation period that maximizes potential yield. In areas where winter is harsh enough to kill a significant number of seedlings, instead of winter barley, spring barley, not requiring vernalization, is sown in the spring when soil temperatures are adequate for germination and seedling emergence and it is also photoperiod sensitive. Because of the much shortened duration in the field, spring barley has lower yield potential than winter types. In environments with quite mild winters, winter type may be sown in the middle of winter and still flowers (mid-spring) and matures (early summer) under favourable conditions to give yields similar to those obtained when winter types are sown in autumn. This practice of sowing winter types late is traditional for much of the barley growing region of the Mediterranean Basin, particularly in North Africa, and the cultivars can be termed Mediterranean genotypes. They are usually facultatively sensitive to vernalization (facultative barleys). It is generally accepted that within the normal growing season a delay in sowing date has a negative effect on grain yield. The season length of a spring type ranges from 90 to 130 days while a winter type needs about 180 to 250 days to mature, and Mediterranean types are intermediate. Samples of duration of various growth phases are given in Table 1.

TABLE 1 Sample duration (calendar days) of different stages of Mediterranean, spring and winter barley from the literature. Data are averages of different cultivars.

Barley type	Sowing-emergence	Sowing-heading*	Sowing-maturity	Reference
Mediterranean	10-12	107-118	137-150	Abeledo *et al.*, 2003; Abeledo, 2009 unpublished
Spring	10-14	45-52	91-96	Muurinen *et al.*, 2007; Peltonen-Sainio, P., pers. Comm.
Winter, Southern Europe	14-16	144-169	172-212	Albrizio *et al.*, 2010; Cossani *et al.*, 2009
Winter, Northern Europe	-	225	280	HGCA, 2006

*****pollination in barley, unlike in wheat, occurs at heading*

Barley development may be thought of as occuring in three phases, vegetative, reproductive and grain filling. During vegetative phase all leaves are initiated and then emerge continuously until the final leaf emerges. Tillers are initiated after leaf 3-4 emerges from nodes on the main shoot and continues until stem elongation. During the reproductive phase, spikelet differentiation starts in the apex and continues with the development of floret primordia within previously differentiated spiklelets and finishes with the determination of fertile florets. During the second half of the reproductive phase the stems, and later the spikes, grow rapidly while some tillers die and some of the initiated spikelets do not progress in their development towards a fertile spikelet at heading. During this period dry matter of the juvenile spike is accumulated and this growth of the spike is related to the survival of floret and spikelet primordia. This is the reason why there is a close relationship between grain number per unit area and the dry weight of the heads at anthesis (Prystupa *et al.*, 2004), provided there is no post anthesis stress. Barley florets are self-pollinating and anthesis starts as the head emerges from the flag leaf sheath.

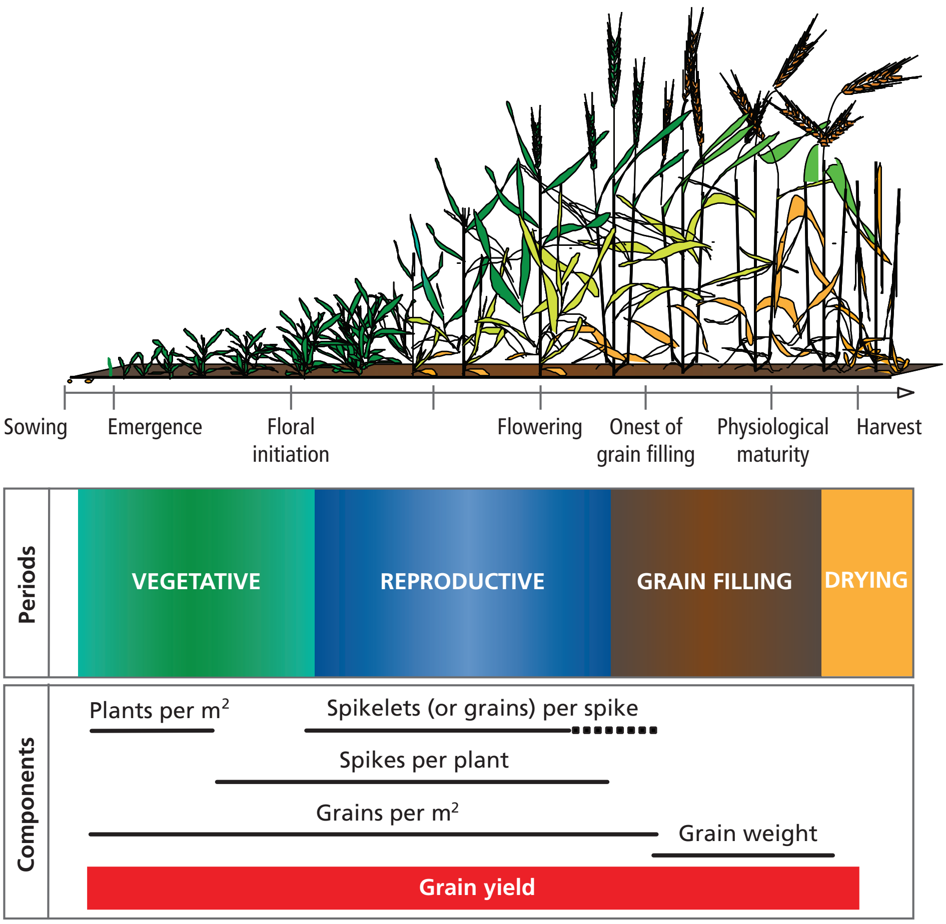
In the grain-filling phase, grains accumulate dry matter up to their final grain weight. Again, if assimilates are limiting, some of the potential grains may be aborted early or fail to develop fully.

The major environmental factors affecting barley phenology are temperature and photoperiod. As for all crops, temperature affects the rate of progression through the various phases, and is accounted for when *AquaCrop* is run in the growing degree day (GDD) mode. The base temperature and upper temperature for barley should be similar to that of wheat, 0 °C and around 25 °C, respectively. Another key temperature effect is on vernalization, which requires cold temperature. Vernalization, together with photoperiod, largely determines the time of heading and flowering of winter cultivars. Figure 3 shows typical development of a barley plant, illustrating the particular developmental phases.

Plant density is a management practice that modifies the crop canopy size and development, and hence ability of the crop to capture photosynthetically active radiation. As for other temperate cereals with tillering habits, plant densities may range widely, with low density being compensated for by more tiller formation. For this reason, planting densities are normally higher for spring than for winter or Mediterranean type. Actual sowing rates aim to establish stands of 50 to 300 seedlings/m^2, with most common densities being between 150 and 250 plants/m^2 for temperate zone with adequate rainfall. For rainfed semi-arid and arid areas, the sowing rates would be at the low end of the range. Row spacing is typically between 0.15 and 0.25 m. When barley is grown as a forage crop, the optimum plant density is higher than that for grain production.

The pattern of root growth can be described as exponential between sowing and the onset of stem elongation (when more assimilates are used for stem and spike growth), and then continues some past anthesis. Maximum rooting depth can vary from 0.30 m in shallow soils to more than 2 m on deep sands and loams. Root growth patterns are strongly modified by fertilizer locations in the soil and soil moisture conditions. Barley, like wheat, can grow on a wide range of soils from deep sands and shallow soils to loams to heavy clays.

FIGURE 3 Typical developmental stages of barley: sowing, seedling emergence, floral initiation or 'collar' stage, awn initiation, flowering, beginning of grain-filling period, physiological maturity and harvest. Boxes indicate different phases and yield components formation (adapted Garcia del Moral *et al.* 2002).



WATER USE AND PRODUCTIVITY

Water is often the resource that most significantly limits barley yield, depending on severity of the deficiency. Seasonal evapotranspiration (ET) of barley ranges from 100 to 500 mm. The relationship between grain yield and ET is usually linear with the intercept on the abscissa taken as an estimate of soil evaporation. Hence the slope of the linear relationship can be interpreted as the transpiration yield efficiency of the crop ($WP_{Y/Tr}$), which is reported to be around 1.2-1.4 kg/m^3.

As is the case for all crops, the response of barley to water stress depends on timing, duration, and severity of the stress. Therefore, stress effects on yield may range from slight enhancement, to virtually no effect, to different ranges of yield reduction, and even to crop failure. In terms of yield components, it has been well established for both wheat and barley that yield is determined largely by the number of grains per unit land area, and, to a substantially lesser degree, by the weight per grain. Of course, the number of grains per unit land area is the product of plant density, fruitful shoots per plant, and grains per fruitful shoot (head). The number of grains per head is particularly sensitive to stress occurring during the period from the onset of stem elongation to the end of anthesis, when stress may limit the number of fertile florets produced from the florets initiated, and the proportion of the fertile florets pollinated and set. During the grain filling period, yield is also reduced by water stress strong enough to inhibit assimilation, leading to reduced weight per grain. In terminal drought situations common to the Mediterranean climate, yield loss is most likely the combined result of fewer grains resulting from early abortion of young developing embryos, and reduced weight per grain. In addition to reducing stomatal opening and photosynthesis, terminal drought also accelerates leaf and hence canopy senescence, causing premature cessation of assimilate production. Consequently, harvest index is reduced because vegetative biomass is formed mostly in the early part of the season when water is not as limiting whereas grain biomass derives largely from that assimilated during the late part of the season under drought.

Yield is also significantly affected by stresses during the early part of the grain filling period when potential grain size is being determined and grain number may be reduced by abortion of the developing embryos. Before the onset of stem elongation, the detrimental effects of stress are due to either poor stand establishment and/or slow tiller and canopy development. Either a poor stand or slow canopy development reduces radiation captured for photosynthesis, and hence, biomass accumulation rate. Slow development of tillers also reduces the number of heads per unit of land area. That is why for instance an early control of weeds is essential to avoid yield penalties.

Various aspects of temperature effects have already been discussed under Growth and Development. An additional effect is that on grain filling. In most temperate conditions grain filling occurs when the weather is getting hotter. High temperatures (above 30-32 °C) accelerate seed development towards maturity, shortening the grain filling period and hence reduces weight per grain at harvest. The effect is noticeable even if periods of high temperature are short (even only 3 days). Another possible negative effect of high temperature late in the season is acceleration of canopy senescence, although this may partly be the indirect effect of water stress induced by high transpiration under high temperature. In addition to lower yields, stresses over grain filling may reduce grain quality for malting, by increasing the proportion of grains smaller than 2.5 mm, increasing protein percentage and reducing the malt extract.

Salinity is a prominent stress for barley production in some irrigated areas. However, barley is considered to be the most salt tolerant of cereals. Regarding mineral nutrients, soil fertilization requirements can only be determined in relation to achievable yield and soil type and native fertility. As a rough guide, for each tonne of yield per hectare, barley needs to take up about 30 kg of N, 5 kg of P and 20 kg of K. The amount of actual uptake depends on the availability of the native and fertilizer nutrients as well as the crop uptake efficiency. Broadly speaking, uptake efficiency is seldom higher than 0.6. The crop N status not only influences yield but also grain protein percentage. Low protein percentage is more suitable for malting, whereas high percentage is more suitable for animal feed.

IRRIGATION PRACTICE

Barley is usually grown under rainfed situations. In some cases, however, full or partial irrigation may be applied, especially when barley is grown for malting or where double cropping is practised, with an early-maturing barley followed by late-sown maize (or soybean).

The seasonal water requirements for barley depend on cultivar, target yield and crop management. Malt barley requires better water management than food barley to meet the standards set by the industry. During initial growth stages, crop water use ranges from 1 to 3 mm/day, rising to 5 - 8 mm/day after canopy approaches complete cover (usually at the appearance of flag leaves), and remains high until the beginning of canopy senescence. Although winter rainfall is sufficient in many climates to supply the full barley water requirements in the early vegetative phase, effective rootzone soil moisture should not be depleted beyond 50 percent of total available water from emergence until flag leaf, after which depletions should probably not exceed 60 percent of the total available soil water until the soft dough stage. Normally, with adequate winter rainfall, border or flood irrigation of malt barley will require 2 to 3 irrigations on heavier soils corresponding with the critical growth stages. Light, sandy soils would require more frequent irrigations.

Excessive soil moisture during the jointing and boot stage, coupled with high nitrogen fertility, may promote vegetative growth that could result in lodging as the crop develops. Excessive irrigation after the crop is well developed also promotes lodging.

YIELD

Barley yields can vary from less than 1 to about 3 tonne/ha in water-limited rainfed conditions to 4-10 tonne/ha in rainfed temperate (such as western and northern Europe) climates. Potential yields up to 12 tonne/ha have been observed. As discussed earlier, barley yield is more sensitive to changes in growing conditions during the period when grain number is set, from stem elongation to just before the onset of grain filling. The cumulative growth during this phase is important enough to justify the assumption of some risk of frost at flowering; the sooner the flowering occurs the higher the crop growth throughout the phase from stem elongation to the onset of grain filling.

Harvest index for barley is similar or only slightly lower than for wheat, and ranges from 0.45 to 0.5 for modern cultivars under favourable conditions. As is the case for other cereals, the rise in yield over time owes much to the rise in HI as the result of plant breeding. Interestingly, the increase in HI over time for barley has been somewhat slower than that for wheat and rice (Evans, 1993), possibly because of the grain quality constraints imposed by brewers. There is no simple, clear and unanimously accepted quality standard based on a set of variables for malt barley. Quality requirements represent a consensus of specifications commercial brewers developed to ensure efficient production consistent with desired product properties or traditional methodologies (Savin and Molina-Cano, 2002), which vary with geographical regions. However, protein content is regarded as one of the main quality attributes. In general there is a negative relationship between protein content and malting quality; the target is to keep maximum grain protein content of malt barley around 10-12 percent.

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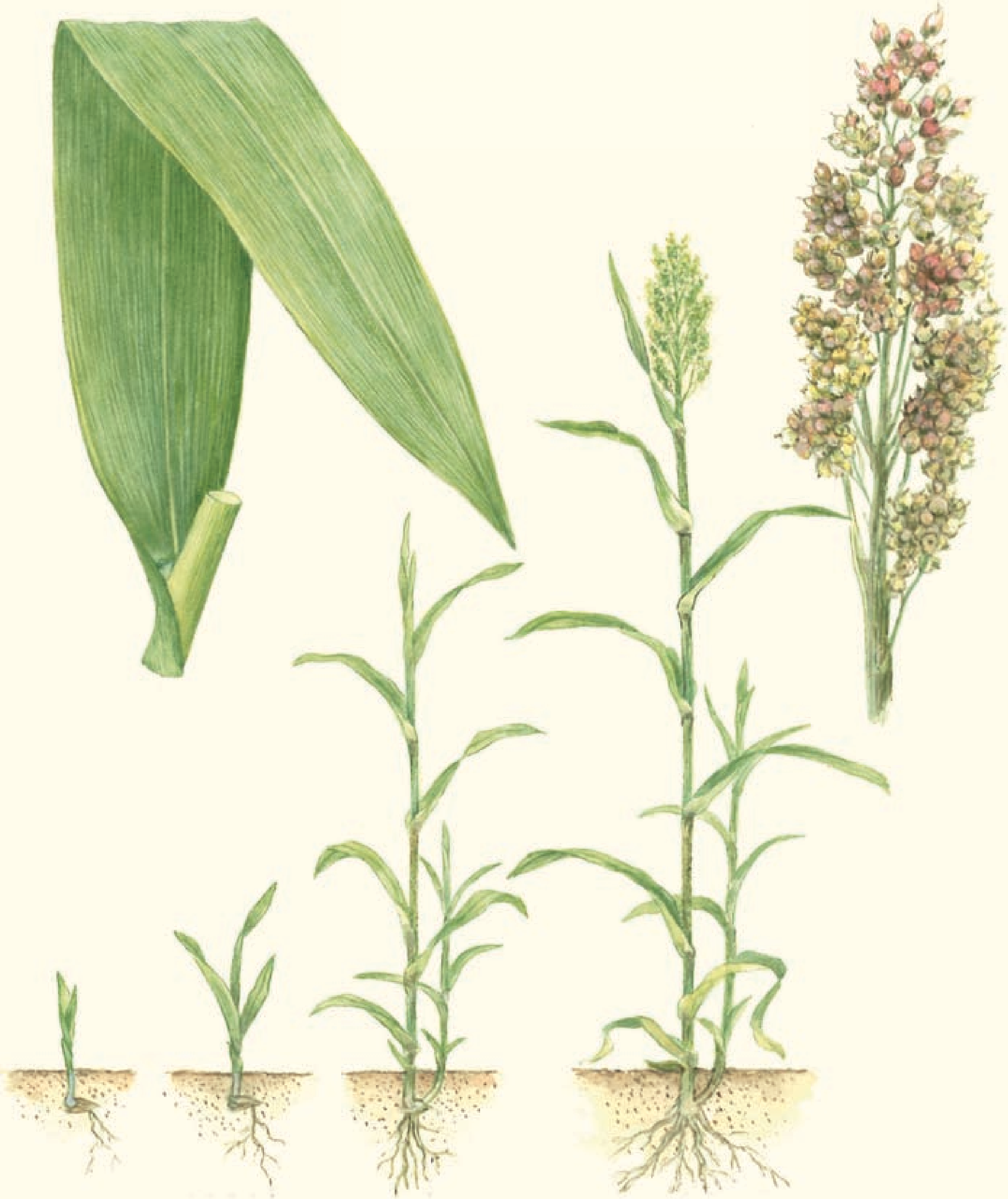

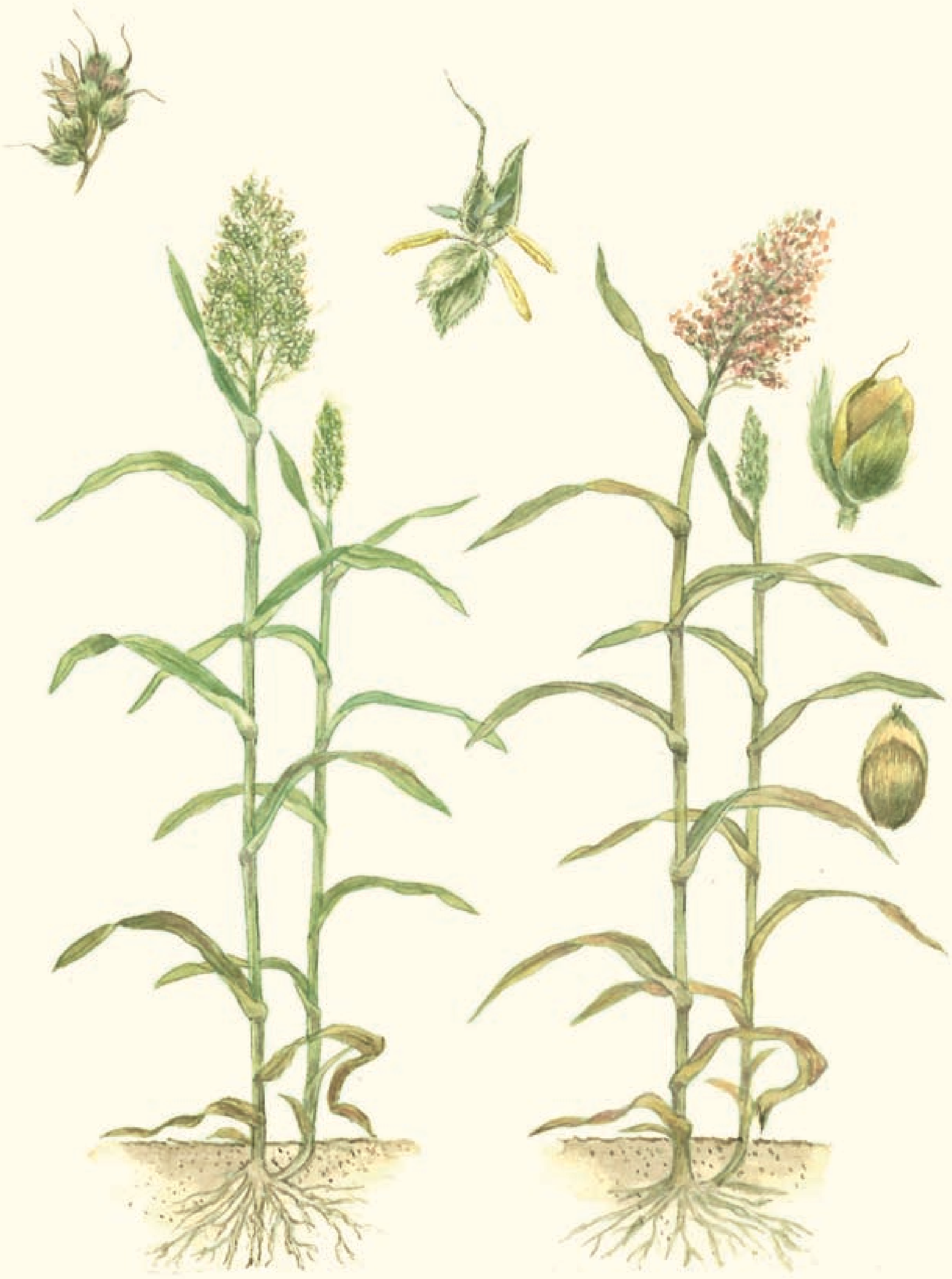

Sorghum

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Sorghum

GENERAL DESCRIPTION

Sorghum (*Sorghum bicolor* [L.] Moench) is a crop indigenous to Africa, where it appears to have been domesticated in Ethiopia about 5 000 years ago. It is now widely cultivated in dry areas of Africa, Asia, the Americas, Europe and Australia between latitudes of up to 50 °N in North America and Russia and 40 °S in Argentine. Sweet sorghum is a variant closely related to grain sorghum; it differs mainly in that its stalks are taller and juicier with higher sugar content than the grain sorghum type. Sorghum is the fifth most important cereal in the world after wheat, rice, maize and barley. In Africa it comes second after maize in terms of production. Sorghum is well adapted to tropical climates with several traits making it a drought-tolerant crop that survives under adverse climatic conditions, and thus is often relegated to poor soils and low-input management. It is extensively grown under rainfed conditions for grain and forage production. High production may be achieved when sufficient water and nutrients are applied especially at critical stages of crop growth.

World sorghum production during 2009 was about 59 million tonne of grain from 40 million ha with an average productivity of 1.4 tonne/ha (FAO, 2011), with the United States, India, Mexico, Nigeria, Sudan, Ethiopia, Australia, and Brazil as major producing countries, in that order (FAO, 2011) (Figure 1).

Sorghum is mainly cultivated in dry areas, often on shallow to medium deep, lighter to medium textured soils, and also on medium to deep soils of high water retention capacity as a post-rainy season crop (Figure 2).

In India, rainy season (*kharif*) sorghum is sown between the second week of June and the first week of July, with rains of the southwest monsoon. However, sorghums are prone to fungal attacks leading to grain *mould* if late season rains occur during grain maturity. Post-rainy season (*rabi*) sorghum is sown generally from the last week of September to second week of October, and is generally exposed to low winter temperatures at sowing resulting in low germination and poor stand establishment. Late sown *rabi* season crops are exposed to terminal drought when grown on black soils (Vertisols) with stored soil moisture and are prone to disease such as charcoal rot. Sorghum planting season in the United States starts from the second week of May to first week of August in Kansas and South Dakota, and from the last week of March until the first week of August on the Great Plains. In the subtropical and temperate regions of Argentina,

FIGURE 1 Typical developmental stages of sorghum (FAO 2011).

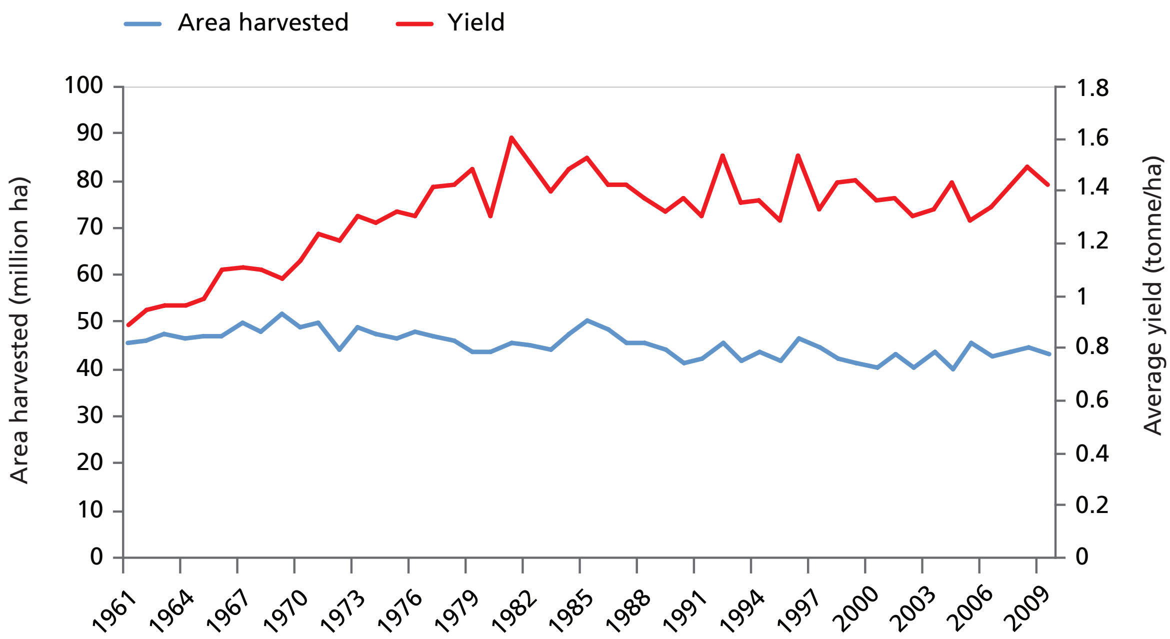
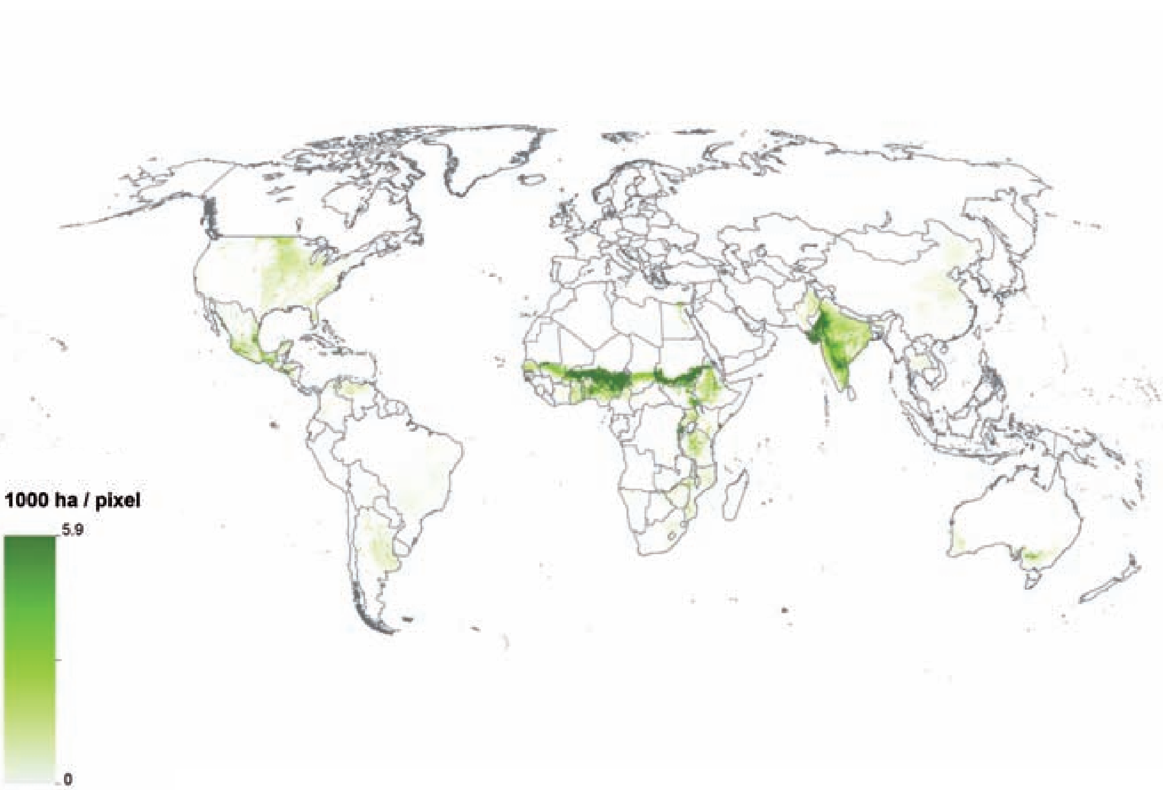


FIGURE 2 Sorghum harvested area (GAEZ, 2011).



Reference year 2000

sowing usually starts in late September and continues to October; although late sowing may take place between the end of November to the beginning of January. In Sudan and Burkina Faso, sorghum planting starts in late May and continues up to early July, but late plantings take place from late July until early August in areas of erratic rainfall in West Africa. Sorghum is normally planted from mid-October to mid-December in Southern Africa. Season length of early maturing sorghum cultivars, which include most hybrids, is 110 days or even less, whereas long season sorghum may last as long as 5 to 7 months.

In rainfed situations, plant populations may range from 50 000 to 150 000 plant/ha, with low densities in the low rainfall areas. Under irrigation or non-limiting moisture, 120 000 to 200 000 plant/ha are generally recommended. Overly high plant populations increase plant competition, increase the chances of charcoal rot, and may increase water use. The advantage of more heads per unit land area is counterbalanced by reduced head size, leading to very little increase in grain yield. On low fertility soils with low input management in some African countries, 50 000 plant/ha have been found to be optimal. As for sweet sorghum, 110 000 to 120 000 plant/ha have been found to be optimal for the rainy season in India.

Sorghum grown mixed with assorted pulse crops for domestic consumption is a traditional practice of poor dryland farmers in India and Africa. Sorghum intercropped with pigeonpea at 2:1 row ratio is a prevalent cropping system on Vertisols in India. Paired rows of sorghum intercropped with paired rows of groundnut at a 4:2 row ratio in India, and sorghum intercropping with cowpea at 2:2 row ratios in Africa, are also popular with farmers on Alfisols with short growing seasons. Post-rainy season sorghum, after rainy season fallow, is most common on Vertisols in India and Ethiopia. In China and the United States sorghum is frequently grown with irrigation after the first season soybean, or after winter wheat as a double crop.

GROWTH AND DEVELOPMENT

As a C_4 crop, sorghum does not tolerate cool temperature regimes. For seed germination, the minimum temperature is about 8 °C, and optimum temperature, 21–35 °C (*Peacock, 1982*). Under field conditions, a minimum soil temperature in the range of 15–18 °C is required for 80 percent emergence in 10-12 days. Normally in the field emergence takes 5–10 days. Panicle initiation takes place after approximately one-third of the growth cycle, after the last leaf has initiated and about one-third of total leaf area has developed. Rapid leaf development and stem elongation follow panicle initiation. Rapid growth of the panicle starts after all but the last two or three leaves emerge. By the time the flag leaf is visible, all but the final 3 to 4 leaves are fully expanded and light interception is approaching its maximum; a few lower leaves may begin to senesce if nitrogen is not plentiful or the crop is planted very densely.

The rate of leaf appearance in sorghum is closely related to thermal time. When temperature is not limiting, it takes about 2 days for each new leaf to emerge. For a cultivar with 18 leaves, in India a typical phenology and growth stages of 0 to 9 (as defined by Vanderlip and Reeves, 1972) are as follows: emergence (0); 3-leaf stage (6 days after emergence, 6 DAE/6); 5-leaf stage (16 DAE/10); panicle initiation (32 DAE/16, approximately 9 leaf stage); flag leaf appearance (50 DAE/18, tip of final leaf visible in the whorl); boot stage (head enlarges in flag leaf sheath, 60 DAE/10); 50 percent flowering (68 DAE/8, half of the plants complete pollination, from the tip downwards); soft dough stage (80 DAE/12 squeezing kernel between fingers results in little or no milk); hard dough stage (96 DAE/16 when seed cannot be compressed between fingers); and physiological maturity (106 DAE/10 black layer (spot) appearance on the hilum at the base of the seed).

Sorghum leaves are upright when young but blades tend to bend downwards with maturity. Sorghum leaves develop on either side of the stem, exactly opposite to one another. As for all crops, rate of dry matter production is strongly affected by radiation intercepted, which depends on leaf area, especially between emergence and panicle initiation. Number of leaves per plant varies widely, from 7 to 24 depending on cultivar and climatic conditions. Sorghum is a short-day plant and panicle initiation is hastened by short days and longer nights. Since panicle initiates only after all leaves have initiated, if panicle initiation and blooming is earlier, the plant would have fewer leaves. Panicle initiation can be strongly affected by temperature regimes in addition to photoperiod. There are rather complicated interactions between photoperiod and temperature regimes, as well as a dependence on the cultivar's maturity group (Morgan *et al.*, 1987). Generally within the temperature range favourable for growth, leaf number tends to decrease as temperature decreases in growth Stage I, especially when the decrease is in night temperature (Quinby *et al.*, 1973).

As for all crops, leaf area index (LAI) depends on plant density, leaf number per plant, and the stage of growth. Maximum light interception, hence full canopy cover, is reached at LAI of 4 to 5. The aim of grain sorghum is to achieve full canopy cover but avoid excessive LAI since excessive vegetative growth tends to reduce the harvest index. Fodder sorghums exceed LAI of 7 with populations of more than 150 000 plants/ha and high input management in the tropics. In short duration sorghum with reduced leaf number, maximum leaf area (and canopy cover) is achieved at 50 days or earlier after emergence under favourable temperatures. However, planting density must be substantially higher than that for long season cultivars to achieve full canopy cover because of fewer leaves per plant. Sorghum seeds are considerably smaller than those of maize, hence the initial leaf area (initial canopy size per seedling, cc_o) of sorghum seedling is smaller compared to that of maize. Sorghum develops less leaf area than maize under similar input, environment and plant density because of its smaller leaf sizes.

Sorghum head is a panicle, with spikelets in pairs. The inflorescence (panicle) is either compact or open, developed on the main stem (peduncle) with primary or secondary branches on which the florets are borne. The peduncle length varies from 75 to 500 mm in different cultivars. The floral structure is suited for self-pollination; however, approximately 6 percent cross-pollination occurs naturally with wind. Hybrid sorghum seed is produced utilizing cytoplasmic male sterility line as the female parent. Sorghum flowers begin to open and pollinate soon after the panicle has completely emerged from the boot. Pollen shedding begins at the top of the panicle and progresses downward for 6 to 9 days. Pollination happens soon after sunrise in the colder part of the day. At maturity, about 600 to 3 000 seeds have developed on the panicle, all enclosed in glumes varying in colour from black, red, brown to tan. The seed number per panicle, a key component setting yield, is determined mostly during the periods of panicle initiation and flowering.

Under seasonal average daily temperatures greater than 20 °C, early grain cultivars take 90 to 110 days and medium-duration cultivars, 110 to 140 days to mature. When mean daily temperature is below 20 °C, there is an extension of about 10 to 20 days in the growing season for each 0.5 °C decrease in temperature, depending on cultivar. At an average temperature of

15 °C, grain sorghum takes 250 to 300 days to mature. It follows that in cool climates, sorghum is grown mostly as a forage crop.

As for all cereals, the root system has two components, the seminal root system and a secondary root system that develops from nodes below and just above the soil surface. Nodal roots start appearing at the third and fourth leaf stage and branches both laterally and downwards. Roots initiated at nodes close to and above the soil (so called prop roots) develop and penetrate into the soil only when the surface soil is moist. The fully developed root system is approximately 1 m wide laterally and down to about 2 m into the soil, and can reach 3 m in very open subsoils. The maximum depth is generally approached at the time of flowering, but the roots continue to extend during the reproductive phase, at least under dryland conditions. When the soil profile is moist, most of the water is taken up from the top one-fifth of the root zone. As the soil water depletes and the upper part of the profile dries out, the uptake zone moves progressively downward. This uptake pattern repeats after each irrigation or heavy rain. Normally, when sorghum is full grown, nearly all of the water extracted is from the top 1 to 2 m of soil.

WATER USE AND PRODUCTIVITY

Rainfall of 500–800 mm well distributed over the cropping season is normally adequate for cultivars maturing in 3–4 months. Sorghum tolerates water logging and can also be grown in areas of high rainfall. The consumptive use (ET) of 110 to 130-day sorghum crops range between 450 and 750 mm, depending on evaporative demand. Seasonal water use is higher for late maturing genotypes because of longer growing periods. For rainy season sorghum in India, consumptive water productivity for biomass ($WP_{B/ET}$) ranges from 2.3 to 6.0 kg/m^3, and consumptive water productivity for grain yield ($WP_{Y/ET}$) ranges from 1.0 to 1.5 kg/m^3, in different environments. For post-rainy season sorghum in India, $WP_{Y/ET}$ ranges from 0.23 to 2.2 kg/m^3, with a mean of 1.2 kg/m^3 from several studies across many soil types and cultivars. An analysis of many years of data in Texas, the United States, yielded a mean $WP_{Y/ET}$ of 1.5 kg/m^3 (Krieg and Lascano, 1990). One study at the same location varying planting density and geometry found $WP_{B/ET}$ of dryland sorghum to be in the range of 3.0 to 3.6 kg/m^3, but $WP_{Y/ET}$ to be more variable, in the range of 0.8 to 1.3 (Steiner, 1986). Harvest index was different for different densities, accounting for the wider range of $WP_{Y/ET}$. In Nebraska, the United States, another study found $WP_{Y/ET}$ to be 1.2, 1.8, and 1.9 kg/m^3 for three different cultivars (Garrity *et al.*, 1982).

RESPONSES TO STRESSES

Sorghum is considered to be drought resistant, especially in comparison to maize. A part of the perceived resistance may be because sorghum cultivars grown in water-limited areas are the short-season type, thus their water requirement is less than that of maize, a crop generally with a longer life cycle. That said, there are real differences in drought-resistance traits. Sorghum with its tillering habit is much less determinant than maize, and therefore is more ‘plastic’ in reproductive development. If short water stress during the panicle initiation stage reduces the potential grain number of the main stem panicle, panicles on the tillers that are initiated later, after the stress is over, can produce more grain and make up for much of the loss. If water stress is severe enough at flowering to cause head blast (death of a portion or whole head) tillers may emerge from nodes high on the stem to form branch heads to produce grain and compensate for at least part of the loss, provided that harvest can be delayed (Hsiao *et al.*, 1976). Such compensations are not possible with modern maize cultivars having very limited tillering capacity. The flip side is that if water is ample during the vegetative period, many sorghum cultivars would tiller excessively, with a high portion of the tillers being barren, leading to high biomass produced but with a low harvest index.

Sorghum accumulates solutes and osmotically adjusts in response to developing water stress, apparently more so than maize (Fereres *et al.*, 1978). This would allow sorghum to maintain stomatal opening and carry on photosynthesis longer as the soil water depletes, and possibly also aid in delaying canopy senescence induced by water stress. In addition to stomatal closure, sorghum leaves roll noticeably under water stress, reducing the effective transpiration surface. The rolling is attributed to turgor changes in the rows of motor cells along the midrib and veins on the upper surface of the leaf. Motor cells are also present in maize leaves, but maize leaves roll only minimally under water stress. Leaf growth by expansion is highly sensitive to water stress in both sorghum and maize.

In terminal drought-prone areas such as the Mediterranean region and Australia, lodging of dryland sorghum as the crop matures is often a problem. Breeders have developed cultivars that maintain a green canopy longer at maturity, the so called 'stay-green' trait. Such cultivars apparently have better lodging resistance, presumably because less of the stalk material is remobilized and translocated to the grain at maturity. In terms of *AquaCrop* parameters, the canopy decline coefficient (CDC) would have to be adjusted to a lower value, and probably also the stress coefficient (K_s) for senescence, adjusted by making it less sensitive to water stress, for the stay-green cultivars.

Sorghum is moderately tolerant to salinity. As EC increased from 11 to 18 dS/m, grain yield was reduced from 50 percent to 100 percent. Much of the temperate effects on sorghum have already been discussed under Growth and Development. Leaf extension closely parallels air temperature to approximately 34 °C. Pollination and fruit setting may fail when night temperatures fall below 12-15 °C at flowering, and pollens produced below 10 °C and above 40 °C are most likely non-viable. Sorghum grain contains around 1.5 percent nitrogen and 0.25 percent phosphorus. For a high yield of 8 tonne, the grain alone removes 120 kg of N and 20 kg of P. To achieve this yield, fertilization must account also for the N and P in the stover residue and the efficiency of applied nutrients and native soil supply. For water-limited situations, fertilization rates would be adjusted downward. In areas prone to terminal drought, care must be taken to avoid too much N supply early in the season because the resultant fast early growth would exhaust water stored in the soil and accentuate the terminal drought damage.

IRRIGATION PRACTICE

In dry areas with low and/or erratic rainfall the crop responds well to supplemental irrigation. However, considerable differences exist among cultivars in their response to irrigation. The timing of irrigation should aim to avoid water deficits during the critical growth stages of the crop, the period that starts at panicle initiation and ends at early grain filling. Water stress during panicle initiation would reduce panicle size and potential grain number; severe stress at flowering would inhibit pollination; and stress at early grain filling would cause abortion of youngest developing grains and reduce weight per grain. Grain size is also reduced if stress occurs late during grain filling and causes early canopy senescence, with the consequence of premature ending of CO_2 assimilation. In terms of total available water (TAW) in the root zone, about two-thirds can be depleted before irrigation without significant effect on transpiration. Up to 75 percent may be depleted during the ripening phase. When water supply is limited, irrigation around booting/flowering, after moderate stress during the vegetative phase, and increasing stress during the ripening period is a deficit irrigation strategy that minimizes yield loss. For fodder sorghum, a late light irrigation maintains stalk quality at harvest. The number of irrigations normally varies between one and four, depending on climatic conditions, and soil texture. Methods of irrigation include furrow irrigation, often in alternate rows, and other surface methods (border, basin or corrugation).

YIELD

Average yield of sorghum varies widely from the high productivity country averages of 4.7 tonne/ ha in the the United States and Argentina, and 4.3 tonne/ha in China to productivity levels of 0.6 tonne/ha in Sudan, and 1.0-1.5 tonne/ha in India, Burkina Faso or Ethiopia. Modern high-yielding cultivars are bred with heads held high above the foliage for machine harvest. On small farms in developing countries, harvesting is mostly done by hand cutting the panicles placing them in sacks and taking them to the threshing floor for further drying to a moisture content of 12–13 percent. Sorghum grain can only be threshed when seed moisture is 20-25 percent or less, even though the seed is physiologically mature at higher moisture levels (around 30-35 percent). Some hybrids have a loose, open type of panicle, which hastens field drying. In India and for fodder production, sweet sorghum is harvested generally at milk-ripe stage and when sucrose content is in the range of 17 to 18 percent. Sweet sorghum yields between 35 to 45 tonne per hectare of fresh biomass and grain yields are in the range of 1-1.5 tonne/ha (Rao *et al.*, 2008). Productivity of post-rainy season sown (October-November) sweet sorghums are less than rainy-season sorghums in India (by 30-35 percent) because of short day length and low night temperature.

Average yield under irrigation is 5 to 7 tonne/ha while yield potential exceeds 12 tonne/ha, substantially less than a comparable maize crop. Average sorghum grain yields on farmers' fields in Africa are as low as 0.5–0.9 tonne/ha because sorghum is often grown in marginal areas under traditional low input practices based on landraces. Forage yields from open-pollinated and hybrid cultivars can reach 25 tonne/ha of dry matter.

Harvest index of sorghum is more variable than that of maize, mainly because of variable tillering in sorghum. Generally, reported HI of sorghum are more frequently low, between 0.3 to 0.4 (e.g. Muchow, 1989; Steiner, 1986). Higher HI (>0.5), however, have been observed and are apparently the result of vegetative (tiller) growth being inhibited by water deficit, which differ among cultivars (Hsiao *et al.*, 1976). High HI can also be deduced from the data of Garrity *et al.* 1982, Prihar and Stewart, 1991.

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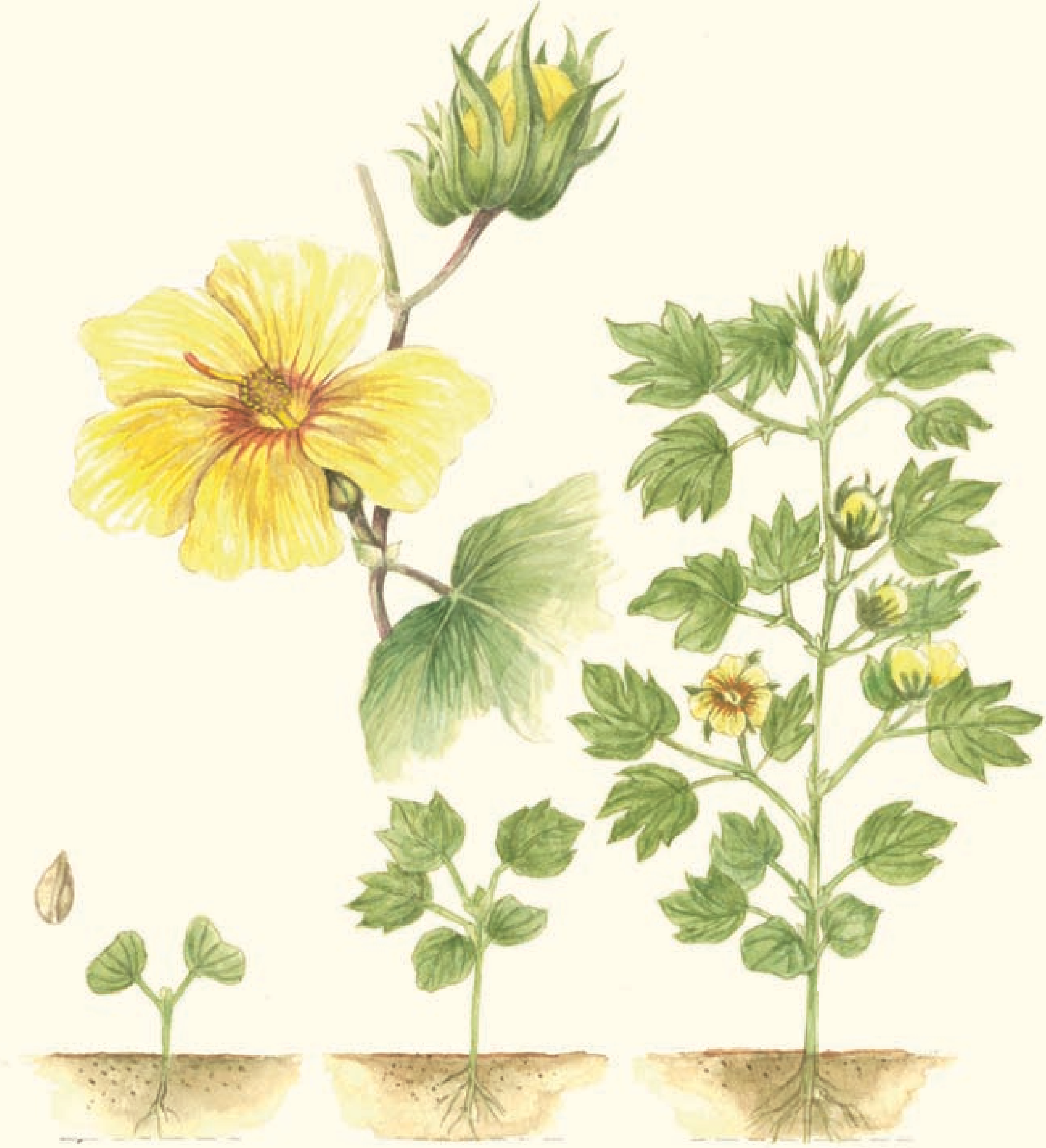

Cotton

Cotton

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GENERAL DESCRIPTION

Cotton is a woody, perennial, indeterminate plant with the C_3 photosynthesis pathway grown in warm and some temperate climates for fibre, but also for its seeds high in oil and protein content. Of the four cultivated species of cotton, the dominant one in production is *Gossypium hirsutum*, also known as Upland cotton, which is managed as an annual. Long staple (Pima) cotton (*Gossypium barbadense*) is also produced, but it accounts for <10 percent of cultivation. Since 1980, overall cotton production has increased 60 percent, while the area harvested worldwide remained stable (Figure 1). In 2007, world production was 24.2 million tonne of seed and lint. Cotton is grown around the world from the tropics to latitudes as great as 42° (Uzbekistan), with major producers being China (31 percent), India (20 percent), Pakistan and the United States (each 10 percent), Uzbekistan (6 percent), Brazil (5 percent), and Turkey (3 percent) (FAO, 2011). See Figure 2 for map of harvested areas.

Successful cultivation of cotton requires a long frost-free period, plenty of sunshine and warm temperature, and moderate rainfall or irrigation, usually from 600 to 1 200 mm. Being salt and drought tolerant, cotton does well in arid and semi-arid regions. Although rainfed production is well possible, optimal and consistent yields are usually obtained with irrigation.

Cotton is frequently grown as the principal cash crop, as a monoculture that is only modified when inclement weather, such as a late hail, forces establishment of an alternative crop. The crop for this unplanned rotation is often rapid maturing and has compatible herbicide tolerances, such as short season soybeans and sunflowers. As with most monocultures, the management of diseases, insects, and weeds (as noted for dryland cropping systems, Baumhardt and Salinas-Garcia, 2006) usually becomes problematic for cotton. Inoculums of Verticillium wilt and black root rot as well as nematodes increase in the soil as the cotton host is repeatedly grown. Likewise, populations of weeds resistant or adapted to common production herbicides can develop. The problem is ameliorated by crop rotation, with non-host crops for the pathogen or with crops that are resistant to the herbicides needed to control the weed species. Crops for this purpose include maize, sorghum, alfalfa and wheat. In China, more

FIGURE 1 World cotton harvested area and average yield over the period 1961-2009 (FAO, 2011).

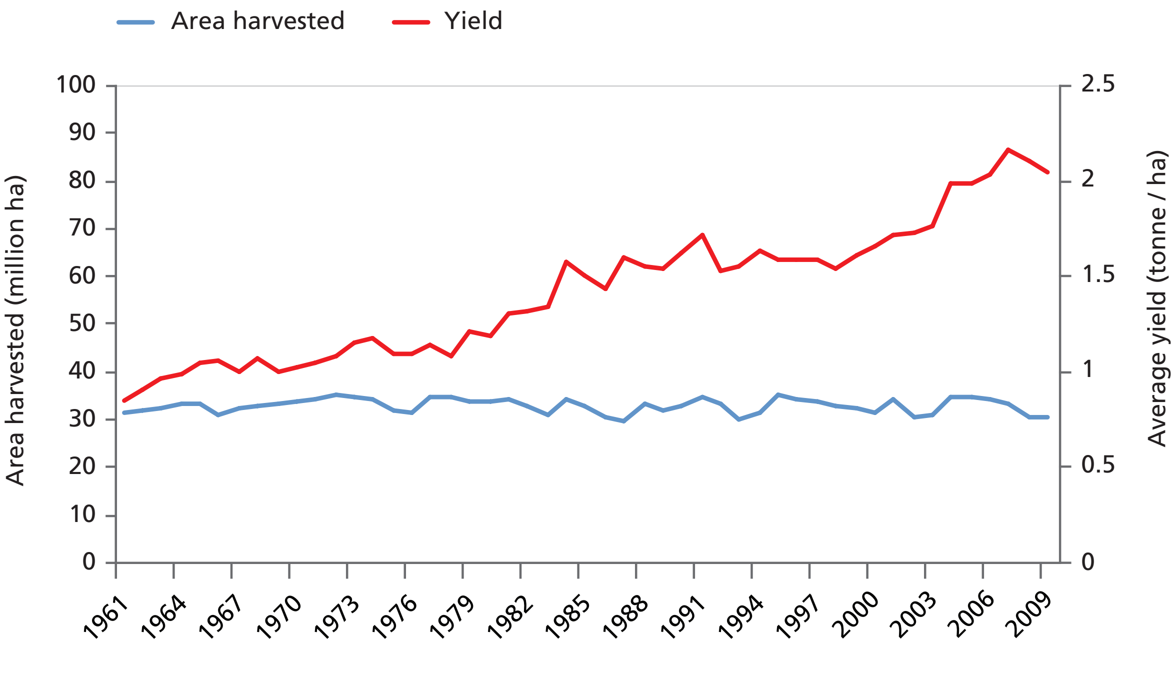
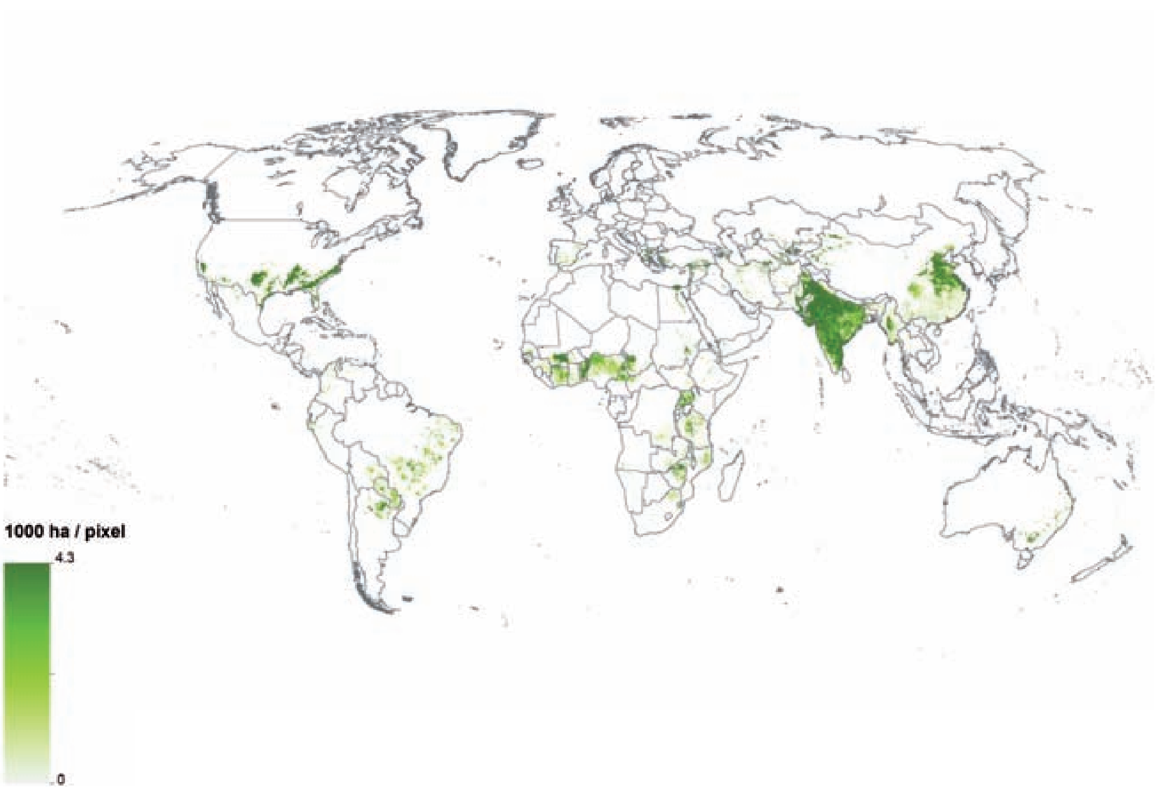


FIGURE 2 Cotton harvested area (GAEZ, 2011).



Reference year 2000

than 1.4 million ha of cotton are relay intercropped with winter wheat, cotton being sown in April during the reproductive phase of wheat in narrow strips left empty between swaths of wheat. Delayed plant development and fruit formation in this system has been tied to lower temperatures experienced by seedlings shaded by the wheat (Zhang *et al.,* 2008).

GROWTH AND DEVELOPMENT

Planting typically begins when soil temperature reaches 16 °C at 0.10 m depth in more temperate zones or 18 °C at 0.20 m depth in warmer regions. Though seeds germinate down to 12-14 °C, the optimum air temperature ranges from 31 to 33 °C, but the germination limiting temperature maximum is 40-42 °C. Emergence is optimal at 32-34 °C. Fungal diseases are prevalent when germination is delayed. Row spacing is often near 1.00 m, but spacing as narrow as 0.50 m has been used successfully. Spacing of 0.76 m is common in some areas. In several studies, narrower row spacing gave slightly higher yield because canopy cover and radiation interception were more complete early in the season. Traditionally, row width has been dictated by tillage and harvesting equipment in most cases. Plant densities vary from 6 to 20 plants/m^2. Cotton is often planted on beds because they promote drainage and soil warming. In some semi-arid locations cotton is produced in a skip-row pattern (two rows planted side by side and then one or two rows intentionally skipped or not planted).

Under optimal conditions, the number of days to emerge, develop flower buds, begin flowering, open bolls, and reach harvest may vary considerably (Table 1). For warmer climates there is greater consistency. Total growing period ranges from 150 to 180 days when soil temperature is >16 °C. Because cotton is indeterminate, crop growth stages overlap, rendering a distinction of growing stages difficult. Early vegetative growth depends on temperature, the daily maximum of which should be at least 20 °C, though 30 °C is better. First square, or flower bud formation, may occur at between 35 to 50 days after planting, depending on cultivar and temperature. Vegetative growth continues during flowering, which for common cultivars begins at 55 to 70 days after planting, and flowering continues during boll growth. Bolls begin to mature and open 100 to 120 days after planting or about 50 to 60 days after first flower. For genotypes ranging from very early to very late, time to 60 percent open bolls may range from 141 to 186 days for early planting and from 130 to 170 days for late planting (Bange and Milroy, 2004). As temperature increases, times to growth stages are shortened, but there is little change for mean temperatures >24 °C and little cultivar difference (Roussopoulos *et al.,* 1998) although development of early cultivars has complicated this picture. Days with similar mean temperatures but different amplitudes result in different growth rates[1].

Cotton plants form a strong tap-root, down to nearly 3 m on good soil. Suitable soil varies widely, but favoured soils are loamy to clayey, deep, well drained and with good water-holding capacity. On soils with hard pans, subsoiling is common to facilitate drainage and root deepening.

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1 Meaning that plant growth models based on heat units should consider time intervals <1 day (Roussopoulos *et al.,* 1998; Ng and Loomis, 1984).

TABLE 1 Days for development stage by cropping region.

Emergence	1st square	1st f ower	1st open boll	Harvest	Cropping region
5	38	59	116	140	Tifton, Georgia, USA (31.5°N)
7	45	65	110	152	South Texas, USA (Ko *et al.* 2009)
10	--	70	115	170	Khorezm, Uzbekistan (41°N), (Sommer *et al.*, 2008)
5–15	35–50	55–70	100–120	150–180	Southern Texas High Plains, USA (Gowda *et al.*, 2007)
9-12				155-181	Texas, USA (39°N) (Howell *et al.*, 2002)
			138-151		Henan, China (32-36°N) (Zhang *et al.*, 2008)
--	--	60	115	--	Egypt, Pakistan, California USA
--	--	60	115	--	Yemen

WATER USE AND PRODUCTIVITY

Water requirements vary widely depending on growing season length, climate, cultivar, irrigation method, and production goals, but may range from 700 to 1 200 mm. In regions with limited rainfall, yields increase linearly with irrigation application over the range of 600 to 900 mm, depending on the cultivar and provided the growing season is long enough to allow for complete boll and fibre development.

Cotton water use and water productivity (WP) can be affected by irrigation method and amount. In several experimental studies at different locations (Texas, California and Uzbekistan), $WP_{lint/et}$ as well as lint yield have been shown to be improved substantially (e.g., by 50 percent for $WP_{lint/ET}$) by using drip instead of furrow irrigation. Values of $WP_{lint/ET}$ ranged from 0.15 kg/m^3 to 0.33 kg/m^3. The improvement in $WP_{lint/ET}$ is most likely attributable to the enhanced yield as well as to reduced soil evaporation and transpiration. How these improvements come about are discussed in the following sections.

Water use (ET) varies from 410 to 780 mm per season depending on irrigation method (less for drip and low energy precision application (LEPA) drag socks compared with furrow irrigation) and how much deficit irrigation is applied; but the range is similar for several different climates: 410 to 720 mm and 560 to 780 mm on the United States southern high plains, 590 to 780 mm in the California Central Valley, and 430 to 740 mm in Uzbekistan (Ayars *et al.*, 1999 ; Colaizzi *et al.*, 2005; Grismer, 2002 ; Howell *et al.*, 2004; Howell *et al.*, 1987; Ibragimov *et al.*, 2007).

RESPONSE TO STRESSES

Cotton stands out among crops as one with extraordinary vegetative/reproductive growth ratio dependence on plant water status. High water status promotes vegetative growth and suppresses reproductive growth. Adequate water is essential for vegetation growth prior to and during flower bud formation. Conversely, overly abundant water supply during flowering, boll growth and fibre development will result in rapid and continued vegetative growth and the dropping of early flowers and young bolls. Alternatively, water stress at reproductive stage, if severe enough, also causes abscission of flowers and bolls. Abundant rainfall or irrigation late in the season can encourage ranky vegetative growth at the expense of boll maturation and fibre development. If water becomes limiting enough to restrict leaf growth markedly, but not yet sufficient to cause boll abscission, cotton then goes into a cutout phase. During this phase the existing bolls mature but almost no new flowers or bolls develop. After the existing bolls mature, the plant would resume producing flowers and bolls, especially if water became plentiful again. Thus, irrigation management of cotton has to strike a delicate balance at different times.

Fertilizer requirements will vary with crop yield and above ground biomass goals, which are typically greater under irrigation, and range from 100 to 180 kg N/ha, 20 to 60 kg P/ha and 50 to 80 kg K/ha. Fertilizers are typically applied at the beginning of the growing season and up to flowering. Excessive nitrogen encourages excessive vegetative growth, which may require applications of growth regulators to control (e.g. mepiquat chloride). Nitrogen application typically follows lint yield goals and is influenced by irrigation capacity and length of growing season. The N application rate ranges from 0.1 to 0.3 kg N/ ha per kg/ha cotton lint, with the lower rate applying to yield goals greater than 500 kg/ha. Phosphorus rates are typically 33 percent of N; and where needed, K is typically 75 percent of N for the first 500 kg/ha of lint yield and 33 percent thereafter. Potassium is important for achieving good fibre quality. Calcium demands are high and application of boron is necessary in some soils.

Much of the temperature effects on cotton have already been discussed in the Growth and Development section. Cotton is sensitive to temperature extremes, particularly soil temperature, with cool temperatures inhibiting fruiting and cool soil temperatures inhibiting emergence and rooting. Excessive water early in the season may cool the soil and inhibit growth as will saturated soil. It is very sensitive to frost. Variations in temperature tolerance of different processes within the cotton plant and with different cultivars, plus complicating effects of diurnal temperature oscillations and extremes, have led some studies to question whether cotton growth modelling should be based on growing degree days (Bange and Milroy, *2004*; Bradow and Davidonis, 2000; Constable, 1976; Sommer *et al.,* 2008). For instance, CO_2 assimilation varies with enzymatic activity and can decrease as leaf or canopy air temperatures exceed 35 °C.

Conversely when night temperatures exceed 21 °C, respiration rates increase markedly and during warm night substantial photosynthate is lost to respiration. Both high daytime and night-time temperature conditions limit the effectiveness of GDD for quantifying plant and boll development. The less extreme daytime temperatures and cooler nights during flowering and boll formation (which corresponds to August in the northern half of the Texas high plains and in Kansas) may explain the more rapid crop maturation in terms of GDD observed during the later growing season as compared with warmer, more southern growing regions (Alam *et al.,* 2008). Nevertheless, most tests with *AquaCrop*, using GDD, showed that the model closely simulated cotton growth and productivity. The effect of day length on flowering is temperature dependent. Flowering is curtailed in daytime temperatures <20 °C and night time temperatures <12 °C or in daytime temperatures >40 °C with night temperatures >27 °C. Soil pH of 7 to 8 is considered optimum; and tolerance to salinity is high, with yield decreases occurring at EC_e values >9 dS/m and yield approaching zero at 27 dS/m.

IRRIGATION PRACTICE

Early irrigation in temperate regions is a compromise between ensuring adequate soil water and minimizing cooling of the soil that inhibits plant growth. For this reason, pre-irrigation may be practised to fill the profile enough to provide for deep rooting between emergence and flowering, followed by a delay of irrigation before and after planting until the soil warms enough for germination, root deepening and early growth.

Because the cotton ratio of vegetative to reproductive growth is sensitive to plant water status, irrigation should meet crop demand (when growth is not limited by cool temperature) during the vegetative phase to speed up canopy development, but should be controlled at a slightly deficit level as the canopy approaches closure. As the time of harvest approaches, even more deficit may be needed to promote cutout, especially when the life cycle of the cultivar is substantially longer than the season of favourable temperature. Plant water status affects the interaction between vegetative and reproductive growth in this indeterminate species such that the growing season is prolonged or shortened depending on rain and irrigation management.

Cotton is grown using practically all irrigation methods. Furrow irrigation is extensively used around the world, but in some regions this method is being replaced by centre pivot (75 percent of irrigated area in the Texas Panhandle) and drip irrigation. Systems that avoid wetting the entire soil surface can result in warmer seed beds early in the season and better early root development and plant growth (Colaizzi *et al.,* 2006*;* Alam *et al.,* 2008). Such systems include subsurface drip irrigation and low energy precision application (LEPA) drag socks on moving irrigation systems when water is applied to between every other row. Scheduling for full irrigation can follow general guidelines, but deficit irrigation will require adjustments for local conditions (Howell *et al.,* 2004*;* Hunsaker, 1999; Hunsaker *et al.,* 2005).

YIELD

Cotton yield consists of lint plus seeds, with lint being typically 37-39 percent. The oil content of cotton seed is approximately 18 percent by weight, but perhaps only 16 percent is recoverable. Cotton seed oil is widely used for cooking after refining to remove gossypol. Cotton seed meal, the end product after oil has been pressed out, contains approximately 40 percent protein, which makes it a valuable animal feed or organic fertilizer.

Typically, harvest takes place even though immature bolls are still on the plant. Harvesting by mechanized cotton pickers is typically done once, sometimes twice. Where harvesting is done manually, two to four harvests or more may occur over a six-week period. Lint yield ranges from 0.65 to 1.3 tonne/ha for surface and sprinkler irrigation, and from 0.9 to 1.6 tonne/ha for drip irrigation in the United States southern high plains, depending on irrigation level, versus an average of 1.3 tonne/ha for Upland and 1.1 tonne/ha for Pima in the Central Valley of California. This contrasts with lint yields ranging from 1 to 1.7 tonne/ha in sub-humid Alabama where irrigation is supplemental (Balkcom *et al.*, 2006). Excessive irrigation (> 700 mm or total of irrigation + precipitation > 900 mm) causes yield declines. Narrow row (< 0.76 m row width) cotton may increase yields by 10 to 30 percent in many environments. Yield levels in other cotton production regions of the world range from 0.5 to 1.9 tonne/ha. The impact of irrigation and water regimes on yield can be caused at least in part by changes in harvest index which is increased (up to 0.46, for yield of lint plus seed, (Garcia-Vila *et al.*, 2009) by water deficit sufficient to inhibit vegetative growth but not enough to suppress substantially photosynthesis per canopy area. Alternatively, yield is reduced by high plant water status stimulating rank growth and biomass production (down to HI=0.35 with biomass >12 tonne/ha). If water deficit restricts vegetative growth and canopy development from very early on, canopy would be too sparse and would capture less of the incident solar radiation for growth and production. In that case, biomass production could be reduced sufficiently to result in less yield in spite of a high HI. *AquaCrop* has been constructed to account for these rather nuanced effects of water status on HI and yield.

The cases of highest $WP_{lint/ET}$ under drip irrigation, mentioned earlier, are likely the combined effects of reduced soil evaporation and a more controlled deficit. Surface irrigation, generally with a minimum of 30 to 40 mm applied periodically, provides enough water for good vegetative growth at least for a few days, whereas drip irrigation can be managed to keep the plant within a more controlled range of mild water deficit.

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Sunflower

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Sunf ower

GENERAL DESCRIPTION

Sunflower (*Helianthus annuus L.*) is an annual plant that originated in Central and North America and is now widely grown throughout the world. Among oil crops, sunflower is the fifth most cultivated annual crop with 23.7 million ha in 2009, after soybean, rapeseed, cotton and groundnuts (*FAO, 2011*). The sunflower area greatly increased after the introduction of hybrids in the early 1970s, and since then average yield increased moderately (Figure 1). World production of sunflower oil (13 million tonne) represents around 9 percent of total world oil production, ranking fourth after palm (30 percent), soybean (26 percent), and rapeseed (15 percent) oil.

Sunflower is grown in arid and semi-arid climates under irrigation or rainfed, and in temperate zones under rainfed conditions. The main producing countries are the Russian Federation, Ukraine, Argentina, China, France, the United States, and Hungary, in that order (see Figure 2 for harvested areas). Growing sunflower in rotation with other crops is very important for the sustainability of the cropping system. In fact, sunflower fits in well as a scavenger crop following shallow-rooted crops, as its deep root system can recover some of the nitrogen applied to the previous crop that has been leached to below its root zone. Residual water left in the subsoil by previous crops can also be exploited by sunflower (Fereres *et al.*, 1993). In addition, its shorter growing season, compared to many other summer crops makes it an attractive option for double cropping. Because of its high water extraction capacity, sunflower can be important in rotations at locations with high probabilities of annual replenishment of soil water at depth. Sunflower is usually grown in 3-4 year rotations (reducing the likelihood of disease) with cereals (e.g. wheat, maize, sorghum), soybean, and beans.

GROWTH AND DEVELOPMENT

Even though sunflower was originally a summer crop, it can be sown over a wide time period (once soils have warmed to 7-9 °C) because of its fast growth at relatively low temperatures; efficient photosynthetic radiation capture by sun tracking; and the early maturity of most cultivars. In temperate regions with mild winters, highest yields and oil percentages are obtained by sowing quite early, before spring arrives (Gimeno *et al.*, 1989). Normal sowing dates in colder environments range from early to late

FIGURE 1 World sunflower harvested area and average yield over the period 1961-2009 (FAO, 2011).

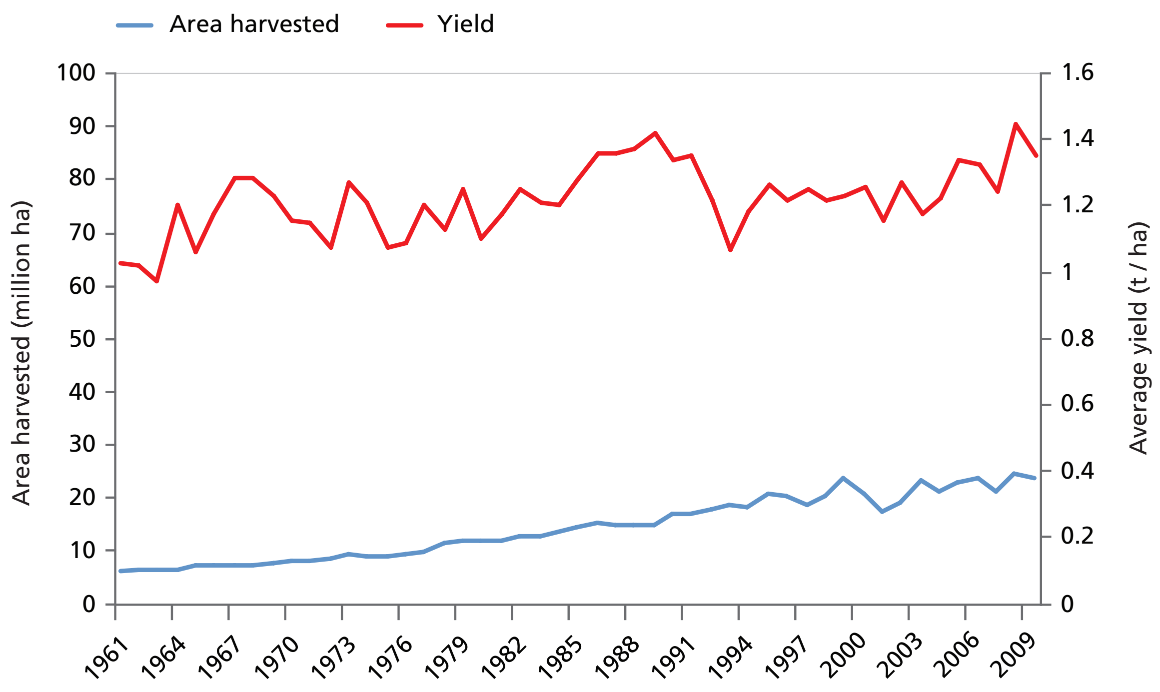
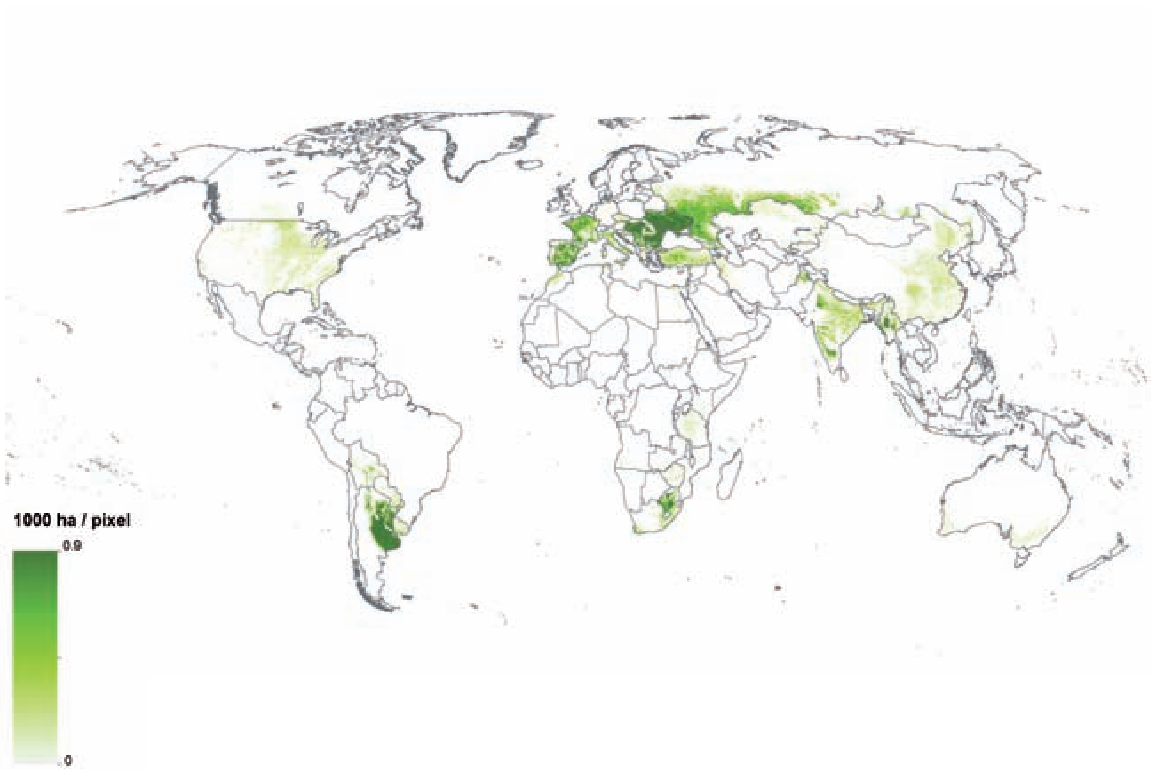


FIGURE 2 Sunflower harvested area (GAEZ, 2011).



Reference year 2000

spring. In double cropping, sowing as soon as possible after harvesting the first crop is always desirable to minimize risks (cold, rains) at the end of the season. With early plantings, more of the growing takes place under low evaporative demand, so water productivity is higher, and high summer temperatures during grain filling are avoided. However, the risk of losing the plant stand increases as planting date is advanced because of cold or frost damage to seedlings, which are quite sensitive up to the sixth-leaf stage (Villalobos and Ritchie, 1992). The cardinal temperatures for crop development are: basal temperature = 4 °C; optimum temperature = 28 °C, and maximum temperature = 40 °C. The tentative setting of T_{upper} for the calculation of growing degree day (GDD) in *AquaCrop* for sunflower is 30 °C, i.e. GDD does not increase further when temperature rises above 30 °C.

Direct sowing is normally practised with a recommended seeding depth of around 5 cm. Plant density depends on rainfall, cultivars, water availability and fertility management. Sunflower is a crop having high plasticity giving similar yields over a wide-range of plant populations. Row spacing for water-limited plantings is customarily wider than under ample water supply (75 -100 cm vs. 50-75 cm). Plant densities between 45 000 and 60 000 plant/ha are common under rainfed conditions, while up to 80 000-100 000 plant/ha can be planted with irrigation. In disease-prone areas, planting densities are in the low range (50 000 to 70 000 plant/ha) even with ample water and nitrogen availability to reduce the incidence of disease and lodging risks. Given the plant's high capacity to intercept radiation, yields are relatively insensitive to variations in plant density provided near full cover is achieved at maximum canopy cover, and similar grain yields are obtained over wide variations in plant spacing above 50 000 plant/ha.

The duration from sowing to emergence varies between 7 and 30 days. Sunflower requires around 4 to 5 days to emerge when shallowly planted in warm soil, while it will take a number of days more in cooler soils or when planted deeper. Minimum temperature for germination can be as low as 3 °C, although it may go up to 5 to 10 °C depending on the various field conditions. The maximum germination percentage is maintained from 6 to 23 °C, declining rapidly above 25 °C (Connor and Sadras, 1992). Seedlings in the cotyledon stage can survive temperatures down to -5 °C. Failure of emergence may result in suboptimal plant populations.

Sunflower grows rapidly, producing large and rough leaves. Leaf appearance rate is affected by temperature and photoperiod (Rawson *et al.*, 1984). Temperature affects the growth pattern and final area of individual leaves, along the cardinal temperatures described above. Thermal time per leaf is between 20 and 25 °C day, calculated with a base temperature of 4 °C (Villalobos and Ritchie, 1992). Maximum canopy cover under standard densities is high, between 90 and 98 percent, and is reached quite quickly. This is because the light extinction coefficient of sunflower canopies is quite high and a leaf area index (LAI) of 2 is sufficient to intercept more than 90 percent of the incoming radiation, while a maize canopy with an LAI of 2 only intercepts around 70 percent of the radiation. Possibly, as the results of canopy growth coefficient (CGC) of sunflower, a C_3 species, is considerably higher than that of most other C_3 crops, about the same as for maize, a C_4 species. Under near optimal temperatures, sunflower maximum canopy cover is reached between 40 and 50 days after planting. For early plantings in cool climates, 60 to 70 days must pass before maximum canopy cover is reached.

Floral initiation occurs early in the growth cycle, 25 to 25 days after sowing, and its timing is predominantly controlled by thermal time and photoperiod. The response of sunflower genotypes to photoperiod is variable, exhibiting a long-day response for floral initiation in most sunflower genotypes. Water and N supply are secondary factors in determining the timing of floral initiation. Cultivar differences for maturity date are usually associated with changes in the length of the vegetative period before the head becomes visible, and longer periods usually are associated with higher leaf numbers per plant. Therefore, the length of the vegetative period depends on the cultivar, temperature and photoperiod (Rawson *et al.*, 1984). As the head enlarges and the two or three leaves subtending the head approach their final size, anthesis begins and lasts 8 to 12 days. The number of grains per head are determined in a period lasting 30 to 40 days centred around anthesis. Post-anthesis effect on grain number is mostly the result of abortion of the youngest developing grains, apparently as determined by the amount of available assimilate to fill them. Canopy senescence starts with the oldest leaves soon after anthesis, but the upper part of the canopy stays green until a couple of weeks before physiological maturity.

Sunflower has a deep and aggressive root system and, as already mentioned, is capable of fully depleting the water present in subsoil layers (Bremner *et al.*, 1986; Sadras *et al.*, 1989). Rooting depth is one of the highest among annual crops, with some studies reporting a rooting depth beyond 3 m in easily penetrable soils. Rooting depth depends on life cycle length of the cultivar; long-season cultivars may reach 3 m while the root system of short-season cultivars in the same soil would not extend beyond 2.3 m (Gimenez and Fereres, 1986). The rate of root deepening of the sunflower is also very high, averaging 3.5 cm/day in the above-mentioned study. In the very open soils of the experimental farm at University of California, Davis, apparent deepening rates of sunflower of about 4.5 cm/day have been observed in a field where maize and sorghum root systems deepened at about 3 cm/day (Berengena, 1976, unpublished).

WATER USE AND PRODUCTIVITY

The combination of season length and different climate generates a wide range of consumptive water use (ET) by sunflower. ET for short-season cultivars may be less than 450 mm, while for long-season cultivars it may exceed 800 mm in some situations (Gimenez and Fereres, 1986). Typical values between 500 and 650 mm are normally found. For a C_3 species sunflower has a high photosynthetic rate, and its efficiency in the use of transpired water for biomass production ($WP_{B/ET}$) is between 2.5 and 3.5 kg/m^3 (25 to 35 kg/ha per mm). $WP_{B/ET}$ decreases after anthesis because of the high energy requirements for the biosynthesis of sunflower seeds high in oil content (Villalobos *et al.*, 1996; Steduto *et al.*, 2007).

RESPONSES TO STRESSES

Sunflower is often reported as a drought-tolerant crop given its high capacity to extract water from the subsoil. Water deficits have differential effects on leaf expansion and stomatal conductance, and hence on transpiration of sunflower genotypes (Connor and Jones, 1985; Connor *et al.*, 1985). No impact has been observed on leaf expansion until the fraction of total available water (TAW) in the root zone declined below 0.85, but it has to decline below 0.4 to induce stomatal closure. The threshold for leaf expansion rate depends on the evaporative demand (Sadras *et al.*, 1993). Prior to anthesis, transpiration is largely dependent on canopy size as affected by soil water deficit, and stomatal control plays a minor role. After anthesis, the leaves are fully grown and consequently the control of transpiration is more dependent upon stomatal closure and the extent of canopy senescence. Periods of water deficit at any growth stage can cause canopy senescence with subsequent reduction in seed yield. There is genetic variability in the response of sunflower genotypes to water deficits. Long-season genotypes have greater canopy cover and produce more biomass under drought conditions, because of their ability to extract more water from the subsoil (Gimenez and Fereres, 1986). Also, it has been observed that sunflower cultivars adapted to an arid climate are less sensitive to water stress than the cultivars developed for humid climates.

Under water stress, the time between planting and flowering remains relatively constant, and inflorescence initiation is also relatively insensitive to water stress. Subsequent development of the inflorescence is, however, affected by water deficits and water stress reduces the number of flowers. The entire flowering period is thus the most sensitive to water deficits as the number of seeds may be negatively affected. Seed filling following flowering is the next most sensitive period to water deficits that reduce both seed weight, seed number (because of abortion) and oil content. Therefore, the reproductive stages (flowering and ripening stages) are more sensitive to water stress than the vegetative stages. Maintenance of green leaf area and photosynthesis after anthesis is key, as seed weight and oil content are mostly influenced by intercepted radiation and carbon assimilation during seed filling. During this phase, both stomatal closure and leaf senescence play a role in the control of plant water status. On the other hand, there is the associated cost of reduced CO_2 assimilation. The contribution that carbon fixed before anthesis makes to grain-filling of sunflower may be important under water stress after anthesis. Nevertheless, the harvest index of sunflower is often negatively affected by water deficits during the reproductive phase.

Genotypes having a gradual response to water stress may be most suited to environments with severe water deficits. In environments with short, frequent and moderate soil water deficits alternating with well-watered periods, maintaining organ expansion and biomass production would result in better agronomic performance. Several studies of sunflower have demonstrated that there is a close relationship between canopy size at flowering and crop seed yield. The plasticity of the crop, in terms of adapting leaf area development to water availability, is well known.

Sunflower is moderately tolerant to salinity, being unaffected by soil salinity up to 4.8 dS/m. It is currently cultivated in dry areas where salinity can be a threat. Thus, it could be adapted to salt-affected soils, provided irrigation management is adequate and salt leaching is practised. In all cases, leaching is important to limit salt accumulation in the root zone, avoiding the reduction of seed and oil yield under salt stress. It would be feasible to use moderately saline water to irrigate sunflower. Nevertheless it is necessary to maintain high soil water content in the root zone all the time, and to minimize salinity built up by leaching.

The nutrient content extracted by a sunflower crop producing around 1 tonne of seed yield per hectare includes around: 50 kg/ha of N, 15 kg/ha of P_2O_5, and 35 kg/ha of K_2O. Fertilizer application depends on the expected yields and the residual nutrients, varying from 20 to 140 kg/ha of N, 15 to 70 kg/ha of P_2O_5, and 15 to 150 kg/ha of K_2O.

IRRIGATION PRACTICE

Sunflower is grown without irrigation in many areas around the world. In subhumid and semiarid regions with limited precipitation, however, irrigation is practised. The ideal schedule under full irrigation must ensure the quick development of a canopy, avoid water deficits at anthesis, and maintain a green canopy throughout the seed-filling period all the way to maturity, thus fully exploiting the genetic potential of the cultivar. This would be achieved by refilling the root zone before damaging water deficits develop at any stage. However, the irrigation schedule should take into account the capacity of this crop to extract subsoil water by conserving irrigation water near the end of the season. Furrow and sprinkler are the most common water application methods for sunflower.

Deficit irrigation is frequently practised. In areas having winter rainfall, the best strategy is to develop the canopy based on stored soil water at planting and concentrate irrigation applications during flowering and seed filling. During these two periods, the ideal schedule should avoid stomatal closure and the hastening of canopy senescence, while the root zone should be fully depleted of soil water at maturity. In situations where water resources are very limited, the best choice for deficit irrigation is to concentrate the irrigation water around flowering and early seed filling. It has been shown that when vegetative growth is manipulated by delayed irrigation, which conserves water for the flowering and seed-filling period, the harvest index can be increased relative to full irrigation regimes.

YIELD

Sunflower yields vary between less than 0.5 tonne/ha in rainfed production on shallow soils or in low rainfall areas to over 5 tonne/ha under ample water and nitrogen supply. Typically, rainfed production between 1.5 to 2.0 tonne/ha is achieved in semiarid areas, reaching 3-3.5 tonne/ha in subhumid areas of good soils. When short season cultivars are grown as a double crop under irrigation, yields of around 3 tonne/ha are obtained. Maximum yields of a single crop under irrigation are around 5-5.5 tonne/ha. Sunflower seeds contain a very high percentage of oil (around 50 percent) and between 15 and 17 percent of protein. Consequently, the harvest index of sunflower (computed on a dry matter basis) is relatively low, from less than 0.3 in long-season cultivars up to 0.4 in short-season hybrids. Sunflower oil is accepted as high quality oil and is in high demand, not only for human consumption, but also for the chemical and cosmetic industries. The oil contains two main unsaturated fatty acids (oleic acid and linoleic acid) and saturated fatty acids (palmitic and stearic). High quality of sunflower oil is associated with higher oleic acid content. Oil concentration is increased when adequate irrigation is provided, especially in the grain-filling stage. However, irrigation does not increase significantly the amount of oleic and linoleic acids. Direct effects of water deficits on oil content of the seed are less than those on seed yield.

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Sugarcane

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Sugarcane

GENERAL DESCRIPTION

Sugarcane is a C_4 carbon-fixing perennial, and commercial cultivars are complex hybrids (spp.) derived from various *Saccharum* species native to Southeast Asia. It is grown in 100 countries (17 countries produced more than 10 million tonne of fresh cane stalks in 2008) in tropical and subtropical regions of the world. The total production of fresh stalks in 2009 was 1 661 million tonne from 24 million ha (Figure 1), resulting in a global average yield of 69.8 tonne of cane/ha per year (FAO, 2011). Brazil produced the most sugarcane (671 million tonne) followed by India (285 million tonne), China (116 million tonne), Thailand (66 million tonne) and Pakistan (50 million tonne). The world harvested areas are shown in Figure 2. Yields vary from region-to-region depending on climatic potential, management level, cropping cycle and whether cane production is irrigated or rainfed. The highest national average yield of countries producing more than 10 million tonne of cane is Egypt with 121 tonne/ha (FAO, 2011). There is a long-term trend of increasing global average cane yield of about 4 tonne/ha per year.

Sugarcane is mostly grown as a monoculture and propagated vegetatively. A crop established by planting cuttings of live cane stalks, is called a plant crop (or plant-cane crop). After the first harvest of the mature stalks, another crop, a ratoon crop, is regenerated from the plant stubbles. Depending on soil and crop health, three to seven ratoon crops can be obtained from one plant crop. Row spacing varies from 1.0 to 2.0 m depending on climate, irrigation practices and mechanization requirements. Rows can be configured as single, evenly spaced rows or as tram lines (double rows spaced around 60 cm apart with tram line centres spaced at intervals of 1.8 or 2.0 m. Burned or green cane is harvested by hand or by machines. Fallow crops are sometimes planted before cane is replanted for a new cycle. The time from crop start to harvest varies from 9 months in areas with limited growing period because of freezing temperatures (e.g. United States) to 12 months (warm climates) and 24 months (cool climate with little or no frost). In irrigated production the normal crop cycle is 12 months.

A sugarcane stalk, after being topped (green immature top of the stalk and green leaves removed) and stripped of dead leaves, typically consists of about 70 percent water, 15 percent fibre, 13 percent sucrose and 2 percent of hexose sugars and other impurities. Sucrose is the main product extracted from sugarcane juice and is used to manufacture sugar. Sugarcane is also used

FIGURE 1 World sugarcane harvested area and average fresh stalk yield over the period 1961-2009 (FAO, 2011).

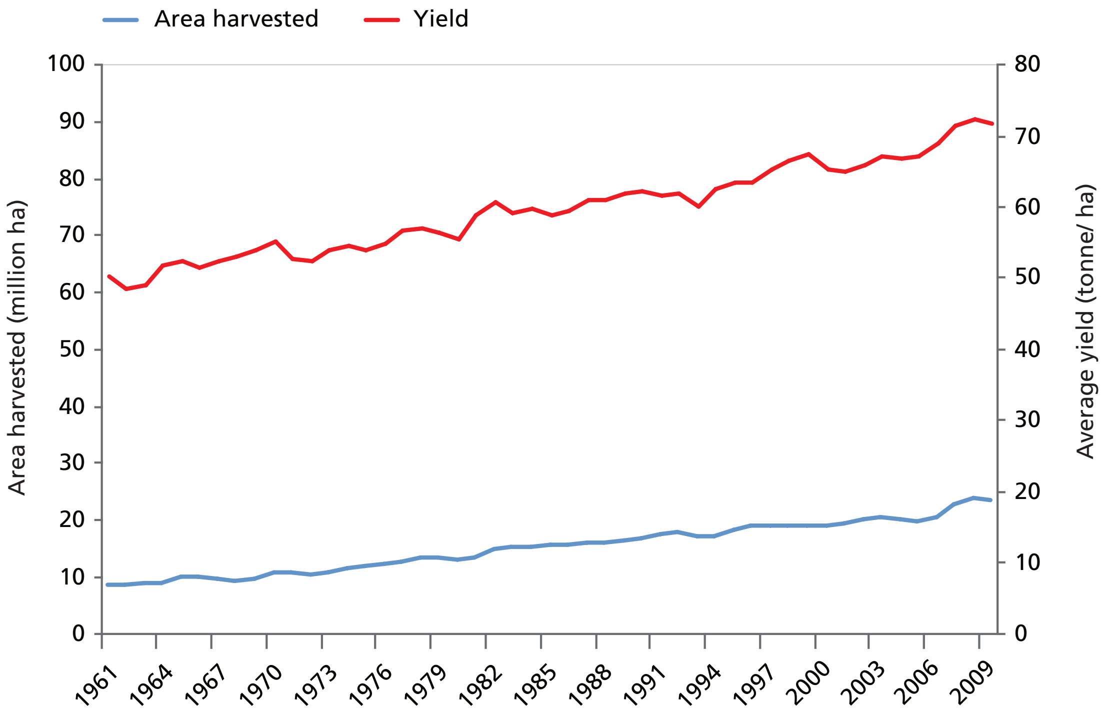
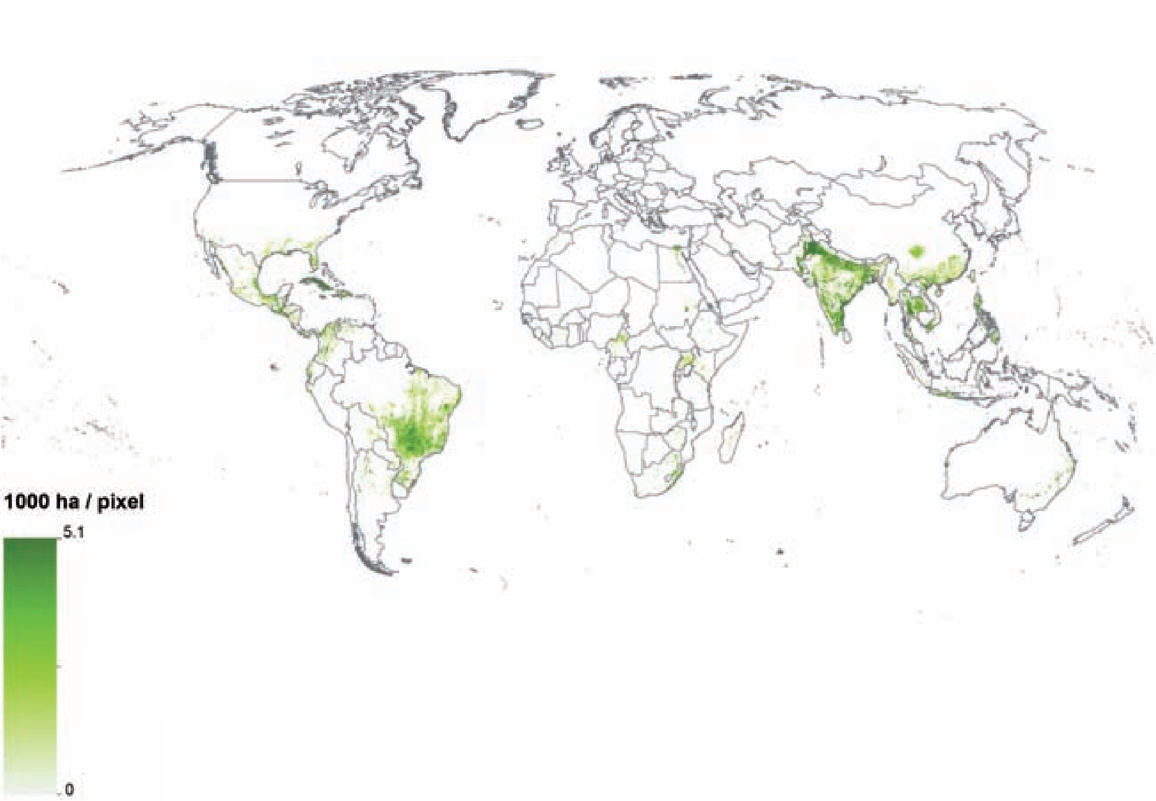


FIGURE 2 Sugarcane harvested area (GAEZ, 2011).



Reference year 2000

to produce energy (electricity from burning stalk fibre and ethanol from fermenting sugars) on a large scale in several countries and this is gaining momentum because it is a renewable source. In Brazil about 40 percent of the cane is used to produce alcohol as auto fuel.

GROWTH AND DEVELOPMENT

The stalk cuttings to establish a plant crop are termed setts and are several internodes long. One primary shoot and many sett roots are produced from each viable node of the sett. These are later followed by roots that grow rapidly (up to 22 mm/day) from shoot nodes and enables deep (up to 4.7 m) exploration of soil profiles (Carr and Knox, 2011). The rate of bud sprouting and primary shoot emergence depends on planting depth, temperature and soil water status (van Dillewijn, 1952). The number of shoots that emerge and the subsequent rate of tillering, depends on the amount of viable buds that were planted (typically 10 to 30 buds/m^2) and row configuration. Sugarcane tillers profusely from the time shortly after primary shoot emergence to canopy closure. At canopy closure, peak tiller population (up to 40/m^2) is reached and the youngest tillers start to senesce, leaving between 4 to 18 tillers/m^2 to develop into stalks that elongate, thicken and accumulate sucrose (Singels *et al.*, 2005; Bell and Garside, 2005). Unless flowering is initiated, stalks will continue to grow and add nodes and internodes as long as water and nutrients are available and temperature is not limiting. Leaves will appear on each new node, expand and senesce at given GGD intervals (Inman-Bamber 1994b).

TABLE 1 Range in duration of different development stages (in calendar days).

Development stage	Plant crop		Ratoon crop	
	Tropical [1]	Subtropical [1]	Tropical	Subtropical
Planting/ratooning to emergence	21-40	28-70	5-10	7 - 21
Planting/ratooning to start of yield formation (coincides roughly with achieving maximum canopy)	110-130	135-175	85-105	105-145
Planting/ratooning to start of maturation [2]	335-395	335-700	335-395	335-700
Planting/ratooning to harvest [3]	365-425	365-730	365-425	365-730
Building harvest index	225-275	200-544	250-300	230-585

[1] Assumed annual range in daily mean temperature: Tropical – 20-28 °C; Subtropical 17 -26 °C
[2] Assumed 30 days before harvest
[3] Harvest at 12 to 14 months in tropical areas, 12 to 24 months in subtropical areas

The stalk is composed of an immature, rapidly growing section at the top with a low sucrose content (top 8 internodes) and a mature, slower growing section with high sucrose content at the bottom. As the stalks become longer (up to 3 m) and older (8 months and older) the mature section forms a large portion of the stalk making it suitable for harvest. The maturation process can be enhanced by withholding irrigation to induce a mild water deficit (Smith and Inman-Bamber, 2005) or by applying chemical ripeners.

Flowering is initiated when minimum temperature exceeds 18 °C and water status is favourable during a 3-week window period of declining photoperiod at about 12.5 hours (Bull and Glasziou, 1976). When a stalk has initiated a flower, it will cease initiating new leaves and internodes and the stalk will mature and, if left long enough, produce side shoots resulting in inferior cane quality. Cultivars differ hugely in their propensity to flower.

The duration of the different development stages are shown in Table 1. With its tropical origin, sugarcane is intolerant to cold temperature. Studies of various growth and related processes of sugarcane have pegged the base temperature in a range of 8 to 18 °C, and the optimum temperature in the range of 30 to 35 °C (Ebrahim *et al.*, 1998; van Dillewijn, 1952; Inman-Bamber, 1994). At the time of this publication, the T_{base} and T_{upper} are set at 9 °C and 32 °C in the preliminary calibration of *AquaCrop* for sugarcane, and may be adjusted slightly as more data become available for calibration and testing.

WATER USE AND IRRIGATION PRACTICES

Although sugarcane develops a canopy relatively slowly (especially for a C_4 species), evapotranspiration of a fully canopied crop is a little higher than that from short grass (Inman-Bamber and McGlinchey, 2003). Depending on climate, peak evapotranspiration rates ranges from 6 to 15 mm/day (Thompson, 1976), and annual ET is between 800 and 2 000 mm of water. At least 850 mm of water per year is required for sustainable rainfed production. For commercial production, full irrigation is practised when annual rainfall is less than 800 mm and supplemental irrigation is applied when annual rainfall is less than 1 000 mm. Irrigation is applied using furrow, sprinkler (portable and centre pivot) and drip systems and scheduled according to soil water status as determined by (1) direct measurements of soil water potential (threshold -40 to -80 kPa) or soil water content (threshold 50 percent of available capacity) or by (2) profit and loss method using weather data (Carr and Knox, 2011). The latter involves estimates of reference evapotranspiration determined from United States Department of Agriculture (USDA) Class A-pan evaporation, evaporation mini-pans or weather data and crop canopy cover (crop factor). Profit and loss methods include simple calculations or complex methods using simulation models.

Adequate irrigation is important during crop establishment and during the stalk growth phase. Irrigations could be reduced during the tiller and maturation phases without significant yield losses (Carr and Knox, 2011). In fact, controlled water deficit during the dry out period near harvest increases sugar content per unit dry stalk biomass and can enhance sugar yield.

RESPONSE TO STRESS

Low temperature

Sugarcane is sensitive to low temperatures. A substantial amount of work has been done to assess the minimum temperature required in the field for various developmental and growth processes. Depending on the process and the particular study, the minimum temperature required was found in the range of 9 °C to 19 °C (Inman-Bamber 1994; Lingle, 1999). Nonetheless, as mentioned, the base temperature for *AquaCrop* is tentatively set at 9 °C at the time of this publication. Frost damage occurs on actively growing parts when they are exposed to freezing temperatures, resulting in the death of the growing points and a subsequent drop in cane quality due to side shooting. In severe cases the entire stalk may die.

Water

Sugarcane can tolerate some drought. Elongation of leaves and stalk are much more sensitive than photosynthesis to water stress. Stalk height and its increase has been used as an indicator of irrigation needs in management. Although growth and cane yield are reduced generally when available soil-water content (TAW) drops below 50 percent, during the maturation phase, periods of mild water deficit (TAW between 80 and 50 percent) actually enhanced sucrose accumulation and sucrose yields (Inman-Bamber *et al.*, 2002; Smith and Inman-Bamber, 2005), by restricting leaf and stalk fibre growth and storing the assimilates as sucrose in the stalk. Largely grown in tropical and subtropical climates with substantial rainfall, sugarcane appears to be exceptionally resistant to waterlogging, withstanding periods of up to 14 days of shallow standing water or saturated soil in a Florida study (Glaz and Morris, 2010).

Fertility

Sugarcane requires appreciable quantities of fertilizer because of its high biomass production. As for other crops, nutrient uptake rates are most rapid during the early phase (tillering and stalk elongation) when biomass accumulation rates are high (Golden and Ricaud, 1963). Sugarcane can grow in a wide range of soils but prefers deep, well-drained soils with an optimum pH of between 6 and 7.5. A sugarcane crop producing 100 tonne of fresh stalks can remove 120-200 kg nitrogen/ha, 20-40 kg phosphorus/ha and 150-300 kg potassium/ha. High levels of nitrogen are undesirable during the maturation phase as nitrogen promotes vegetative growth at the expense of sucrose accumulation.

Salinity

Sugarcane is moderately sensitive to salinity and sensitive to sodicity (Nelson and Ham, 2000). High salinity can induce water stress and symptoms include wilting, scorching of leaves and restricted growth. Soil salinity, measured as saturated paste electrical conductivity, of less than 20 dS/m have little or no effect on crop growth, cane yields decrease between 30-40 dS/m, with 40 dS/m representing the economic production threshold (Rozeff, 1995).

YIELD AND HARVEST INDEX

Commercial yields vary hugely. Under favourable climatic conditions (7 300 MJ/m^2 of radiation over the life cycle, 4 000 GDD using a base temperature of 10 °C) and adequate water supply (1 800 mm net) experimental yield of 200 tonne/ha fresh cane (24 tonne sucrose/ha) per year can be achieved (derived from Inman-Bamber, 1995). Actual commercial yields under irrigation vary from 80 to 150 tonne/ha fresh cane (10 to 17 tonne sucrose/ha) (Waclawovsky *et al*., 2010). Worldwide a yield of 120 tonne/ha (14 tonne sucrose/ha) is considered a good yield under full irrigation. Rainfed cane yields vary from 30 to 90 tonne/ha of fresh cane per year depending on soil and climatic conditions, with a yield of 60 tonne/ha considered as good. Water productivity in terms of above ground biomass and evapotranspiration ($WP_{B/ET}$) ranges from 3.5 to 5.5 kg/m^3, and, in terms of sucrose and evapotranspiration ($WP_{sucrose/ET}$), from 1.3 to 2.2 kg/m^3 (derived from Thompson, 1976; Olivier and Singels, 2003; Carr and Knox, 2011).

The sucrose content of fresh stalk varies in extremes from 5 to 16 percent and from 20 percent to 58 percent on a dry mass basis, depending on genotype, crop age and growth conditions (temperature and water status) during the last four weeks preceding harvest. Typical stalk sucrose content at harvest is around 12.5 percent on a fresh mass basis and around 50 percent on a dry mass basis. Expressed as sucrose mass per unit of aboveground biomass the harvest index varies around 35 percent (derived from Thompson *et al.*, 1976; Inman-Bamber *et al.*, 2002; Carr and Knox, 2011)

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Potato

GENERAL DESCRIPTION

Potato (*Solanum tuberosum*) is a starchy tuberous crop that originated in the Andes, and the two subspecies of the cultivated potato, *S. tuberosum tuberosum* and *S. tuberosum andigena*, account for nearly all of the world's production. Potato ranks as the fourth largest food crop in the world, following rice, wheat, and maize, with a production of 329 million tonne on 18.6 million ha (FAO, 2011) (Figure 1). The largest potato production continents are Asia and Europe with 44 percent and 37 percent of the world's production, respectively. China, India, the Russian Federation, Ukraine and the United States are the largest producers. Rapid expansion of potato production over the past 20 years has occurred in developing countries, particularly in Africa and Asia where production has more than doubled. Potato remains an essential crop in developed countries where per capita production is still the highest in the world (Figure 2).

Potato is particularly suited to a cool climate. It is widely cultivated in the temperate, subtropical, and cool tropical regions where it is grown as a monoculture, in crop rotation, or in multiple cropping. Rotation with other crops is often necessary to ameliorate problems of disease and other pests. In temperate regions, cold temperature and a short frost-free period limit potato production to once a year as a monoculture, or in a three or more year crop rotation with maize, soybean, sorghum, or sugar beet in areas with high rainfall or irrigation; and with wheat, maize, millet, barley, and oats in arid and semi-arid environments. This region includes the water deficit areas of northern China where potato is a rainfed and short season crop (90-110 days); supplementary irrigation is needed but not frequently applied. In northern Europe and North America, potato production is generally carried out with intensive agricultural practices, including high rates of fertilization, pesticide use, and irrigation where necessary. Two- to four-year rotations include oilseeds, cereals and legumes. In the subtropics potato is found in a range of cropping systems. It is in multiple cropping systems with two or even three crops per year in rotation with wheat or maize in the central plains of China, in intercropping systems particularly with maize at lower elevations there, as a single spring crop in higher altitudes of southwest China, or as an irrigated and short season winter crop in rotation with rice or wheat in the Indogangetic plains, lower elevations of southwest China and North Vietnam. In the cool tropics, potato is commonly a once-a-year (in a couple of countries twice-a-year) rainfed crop, a long growing season (180 days) monoculture or is included in rotations with maize, legumes,

FIGURE 1 World potato harvested area and average yield over the period 1961-2009 (FAO, 2011).

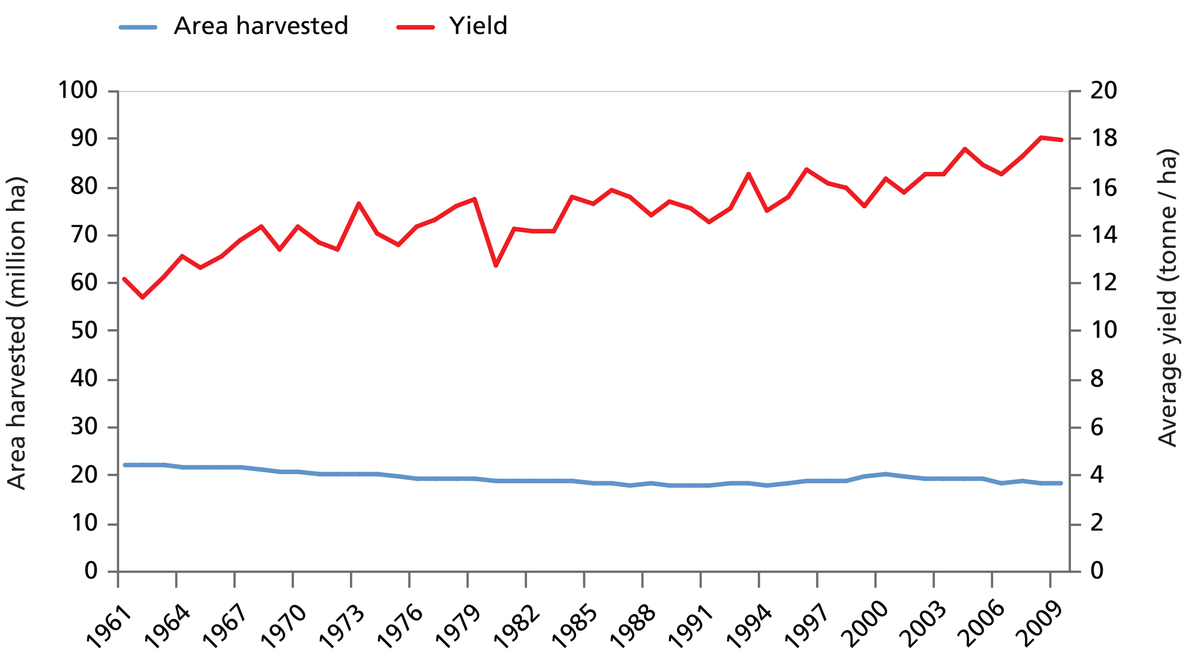
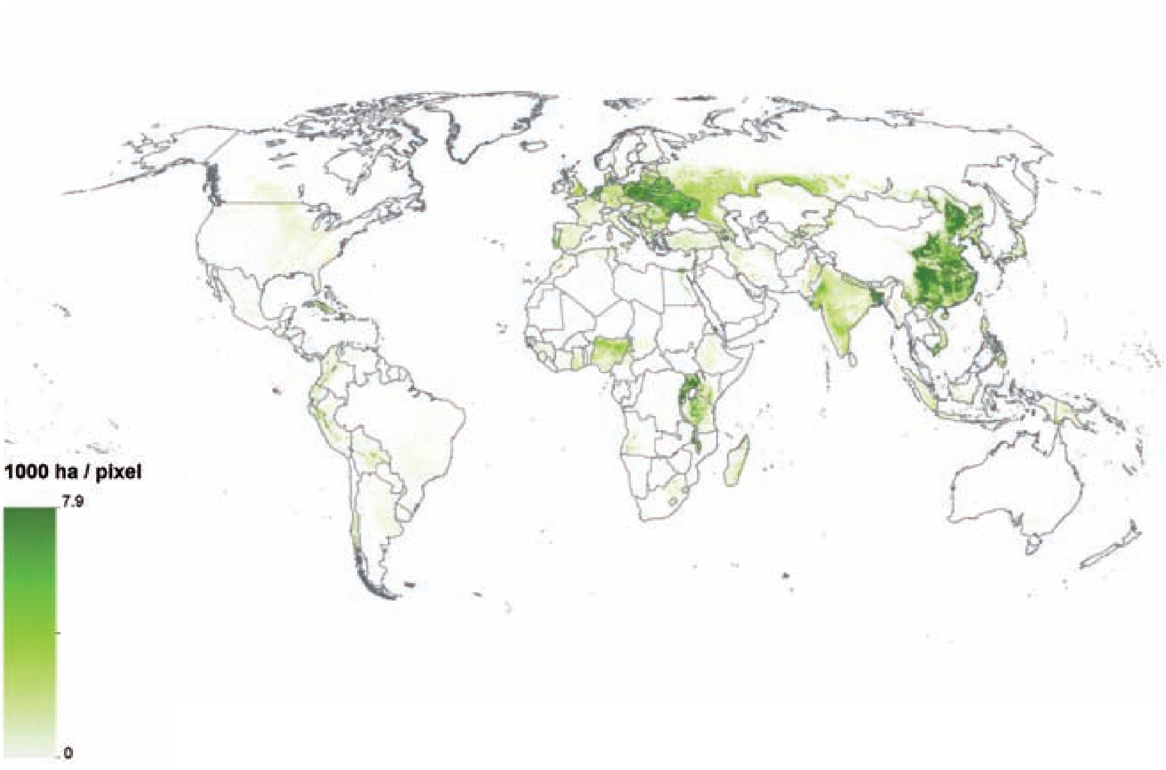


FIGURE 2 Potato harvested area (GAEZ, 2011).



Reference year 2000

quinoa, or vegetables as in the Andean and East Africa highlands. Two crops per year are not uncommon at lower elevations.

GROWTH AND DEVELOPMENT

Potato is grown on ridges or on flat soil. For rainfed production in dry conditions, such as in southwest China and at higher elevations of semi-arid cool tropics, flat planting tends to give higher yields as a result of soil-water conservation. Under irrigation the crop is mainly grown on ridges. Although potato can be planted as botanical seeds, in nearly all cases it is planted as tubers. The tuber seed should have two to three eyes, from which the new buds and shoots sprout. The sowing depth is generally 5 to 10 cm, while deeper planting is preferred in dry areas. Plant density ranges from 30 000 to 60 000 plant/ha and varies depending on seed size, cultivar, and use. Higher plant density is used under irrigation and lower density in rainfed conditions. Cultivation during the growing period must avoid damage to roots and tubers, and often ridges are earthed up to avoid greening of tubers.

The plant emerges about 7 days after planting under good conditions. Emergence may be delayed by lower soil temperature, limited soil moisture, unsprouted or young tubers, and deep planting. Initial canopy cover (CC_o) depends on seed tuber density and the numbers of developing shoots per seed tuber, and whether beds are widely or narrowly spaced. Cultivars may also differ in this regard. The time from planting to maximum canopy cover (CC_x) can be shortened by denser planting, and by practices conducive to earlier plant emergence, warm temperatures, and good water supply. At maximum canopy, the percentage of canopy cover ranges from 45 percent to nearly 100 percent in the cool tropics. At the early vegetative stage, between emergence and tuber initiation, stolon formation begins, followed by tuberization and tuber enlargement. The duration of the growth cycle and total tuber production depends on cultivar, temperature and day length. Tuberization comes before flowering and flowering is not necessary to produce tubers.

As is true for other crops, the rooting depth of potato depends strongly on soil conditions, the absence of impeding layers and soil temperature. Root water extraction has been shown to go deeper than 1.8 m under favourable conditions (Wolfe *et al.*, 1983), although often potato is said to be shallow rooted. Normally, when the upper soil profile is not dry, 70 percent of the total water uptake occurs from the upper 0.30 m and nearly 100 percent from the upper 0.40 to 0.60 m soil depth. The uptake pattern is, however, also dependent on the location of water and nutrients, with water extraction mainly from deeper layers when the upper part of the soil profile is dry.

The subspecies *tuberosum* tuberizes under the 14 to 17 hours photoperiod prevalent in the higher latitude regions but is grown worldwide as it adapts to shorter photoperiods. Some cultivars of *S. tuberosum tuberosum*, when grown under short days may initiate tubers earlier, have a reduced canopy with little or no flowering, and mature earlier but with less tuber yield potential (Condori *et al.*, 2010). *S. tuberosum andigena* and the other seven cultivated Solanum species (other than *Solanum tuberosum*) tuberize under 10 to 12 hours photoperiod prevalent in the tropical region and are grown in the Andes. Hybrids of *tuberosum* and *andigena* are being increasingly grown in developing countries where and when day length is short. *S. tuberosum andigena* and its hybrids, when grown under long days, may have a late tuber initiation, vigorous canopy, profuse flowering, and mature later, but also have a reduced tuber yield potential. Nonetheless, the breeding of long-day adapted *andigena* resulted in large increases in yield (Bradshaw, 2009).

WATER USE & PRODUCTIVITY

Potato requires from 0.35 to 0.8 m^3 of water to produce 1 kg of tuber dry matter. Under field conditions, this translates into a water requirement during the growing period of 350 to 650 mm, which is dependent on climate and cultivar (Sood and Singh, 2003). The water productivity for yield of fresh tuber ($WP_{fresh\ Y/ET}$), which contains about 75 percent moisture, is 4 to 11 kg/m^3. Expressed as dry tuber mass, the yield water productivity ($WP_{Y/ET}$) ranges from 1.3 to 2.8 kg/m^3. Under conditions of limited water supply the available supply should preferably be directed towards maximizing yield per hectare rather than spreading the limited water over a larger area. Savings in water can be made mainly through improved timing and depth of irrigation application.

RESPONSES TO STRESSES

Potato is sensitive to water deficits. Water shortages may result in a reduced tuber yield, number and size, and loss of tuber quality. To optimize yield, generally the total available soil water (TAW) should not be depleted by more than 30 to 50 percent. Water deficit in the early stages, during stolon formation, tuber initiation, and after tuber initiation have the greatest adverse effect on final yield. Although leaf growth is very sensitive to water deficit, if the deficit is moderate and short, leaf growth after the defict is released by rain or irrigation can compensate, and the effect on yield would be minor. The senescence stage is less sensitive, provided the deficit is not severe enough to shorten the duration of green canopy markedly. In general, water deficits in the middle to late part of the growing period tend to reduce yield less than in the early part, but this can vary with cultivar. Some cultivars respond better to irrigation in the earlier tuber formation stage while others show a better response in the latter part of that stage.

Soil and air temperatures affect growth and tuber yield. The temperature for frost or cold stress for potato is considered 1 °C and less, whereas that of heat stress is 35 °C or higher. However, potato cultivars vary in their tolerance to frost, cold and heat stress, and the extent of damage depends on stress intensity and duration. A base temperature of 2 °C has been used in some potato crop models for growing degree days (GDD) computation (Stol *et al.*, 1991). A base temperature of 0 °C can be used for the subspecies *S. tuberosum andigena*. Optimum soil temperature for tuber growth is 15 to 18 °C whereas air temperature requirements for growing potatoes are a diurnal temperature of 25 to 32 °C and night temperature of 12 to 18 °C. As temperature increases from the low end of the optimum, vegetative growth of potato is enhanced, whereas tuber initiation and growth begin to be suppressed as temperature rises further.

Fertilizer requirements of the potato crop are relatively high. The amount of NPK removed by potato plants is estimated at 4 to 6 kg N, 0.6 to 1.1 kg P and 7 to 11 kg K per tonne of fresh tubers produced. Depending on nutrient status of the soil, to obtain high yield recommended fertilization rates range from 100 to 250 kg/ha N, 50 to 100 kg/ha P_2O_5, and 60 to 260 kg/ha K_2O, for soils ranging from highly fertile to highly deficient in the specific nutrient.

The crop is moderately sensitive to soil salinity with a threshold of the electrical conductivity of the saturated soil paste extract (EC_e) of 2-3 dS/m, reaching 100 percent yield loss at 10 dS/m.

IRRIGATION PRACTICE

Most common irrigation methods for potato are furrow and sprinkler. Yield response to frequent irrigation is considerable and very high yields are obtained with the mechanized sprinkler systems where evapotranspiration losses are replenished each or every two days. Frequent and timely irrigation reduces the proportion of malformed tubers at harvest. Where rainfall is low and water supply is restricted, irrigation scheduling should be aimed at avoiding water deficits during the stage of stolon formation, tuber initiation and after tuber initiation. Supply of water can be restricted during the early growth, i.e. before flowering, but canopy growth would be slowed so the restriction must be within bounds. To use up more of the water stored in the soil, irrigation should be cut back toward or at the senescence stage. This practice may also hasten maturity and increase dry matter content of tubers. Correct timing of irrigation may save 1 to 4 irrigation applications, including the last irrigation prior to harvest, depending on the situation.

YIELD

In the temperate region of northern Europe and North America, a good yield, under irrigation where required, is more than 40-50 tonne of fresh tubers per ha. In very humid regions, yield tends to be less as diseases are more difficult to control. Yields of rainfed and even irrigated potato in the subtropics and cool tropics are much lower, ranging from 5 to 25 tonne per ha. Planting low quality seed tubers, less dense planting, lower rates of fertilizer and irrigation, and pest and disease problems led to the low yields. Seed tuber quality is very important for high production, as reflected in the large amount of seed tuber in world trade, amounting to about 1.4 million tonne per year. Dry matter content of fresh tubers normally varies between 20-25 percent of fresh weight.

Economic yield depends strongly on tuber quality, and can be affected by irrigation management. Water deficit in the early part of the tuberization stage increases the occurrence of spindled tubers, which is more noticeable in cultivars of cylindrical tuber compared to those of round tuber. Water deficit during this stage followed by irrigation may result in tuber cracking or tubers with black heart. Water deficit following tuber initiation can reduce the yield of marketable tubers from 90 percent to 70 percent or even 50 percent.

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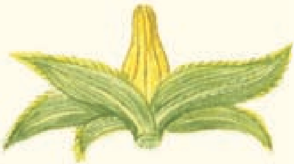

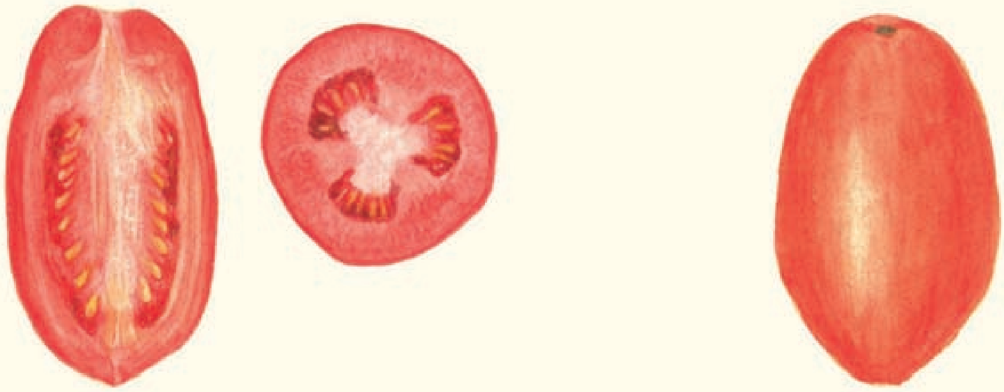

Tomato

Tomato

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GENERAL DESCRIPTION

The tomato *Solanum lycopersicum*, L. (*formerly Lycopersicon esculentum*, Mill.) is a daylength neutral, herbaceous perennial plant usually grown as an annual in temperate regions. There are three types of cultivated tomato, indeterminate, semi-determinate and determinate. Indeterminate plants are tall, frequently more than 2 m high, with vegetative growth continuing much longer after the start of flowering than in the other two types. Fruit ripens gradually, starting from the basal fruit clusters. Semi-determinate plants are less tall than the former reaching a maximum height of 0.9-1.5 m, their characteristic is that the main fruit clusters ripen together, but the plant will also continue to produce additional fruit. Indeterminate and semi-determinate tomatoes need to be staked or trellised, and are grown for the fresh market and harvested by hand. Determinate-types, the so-called bush tomato, mostly rest on the ground and have a relatively concentrated flowering and fruit setting lasting only about three weeks. In this period vegetative growth continues. Most fruit of determinate cultivars matures in a relatively short period and for this reason are suitable for mechanical harvesting. Processing tomato cultivars are bred for firmness and strong skin and are of the determinate type, except for San Marzano type peeled tomatoes which are indeterminate or semi-determinate cultivars. The parameters of the current version of *AquaCrop* are set for processing tomato only, since it considers a single harvest per crop.

Current world production of tomato is about 152 million tonne of fresh fruit from about 4.4 million ha (Figure 1). Tomato is the second most valuable vegetable crop next to potato (FAO, 2011). The cropped area increased 1.4 millions ha (+40 percent) in the period 1997-2007, but total fruit production, including fresh market tomato, increased by only 20 million tonne (15 percent). More than 38 million tonne per year are grown for the processing industry, making tomato the world's leading vegetable for processing. Fruit production for processing increased even more in proportion, by 11 million tonne (+49 percent), while only 0.5 million ha (+10 percent) were cropped with processing tomato (*WPTC, 2011*). Global tomato consumption increased by an average of 4.5 percent per year between 1990 and 2004. Tomato producers are mainly located between subtropical and temperate zones, the main cropping countries being China, the United States, India, Turkey, Egypt, Italy, Iran, Spain, Brazil and Mexico. (See Figure 2 for harvested areas).

FIGURE 1 World tomato harvested area and average yield over the period 1961-2009 (FAO, 2011).

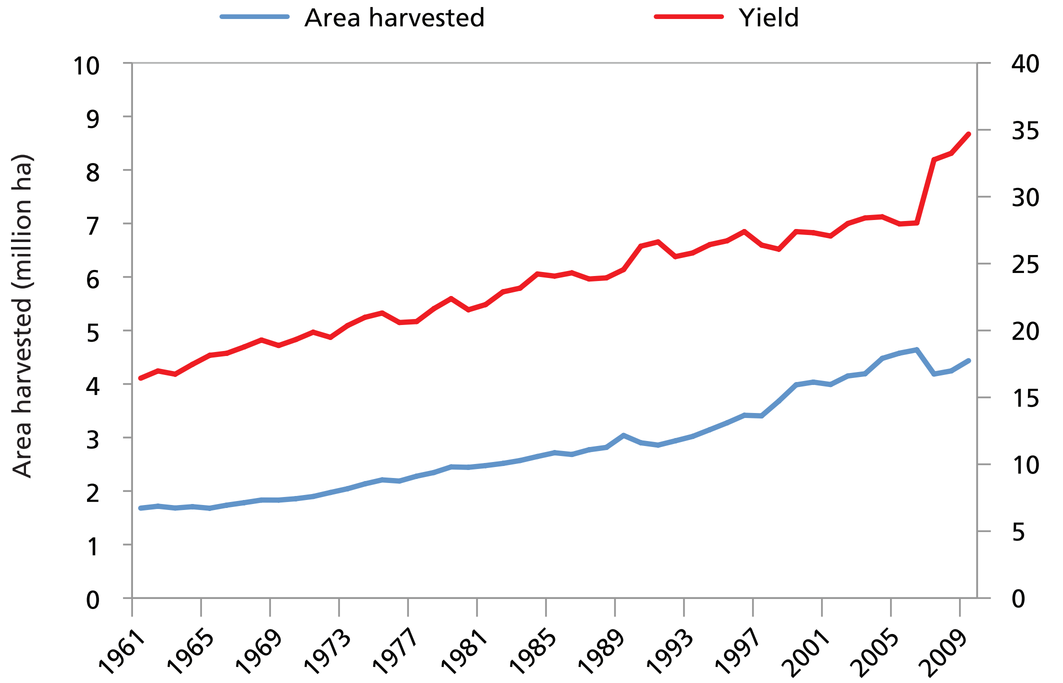
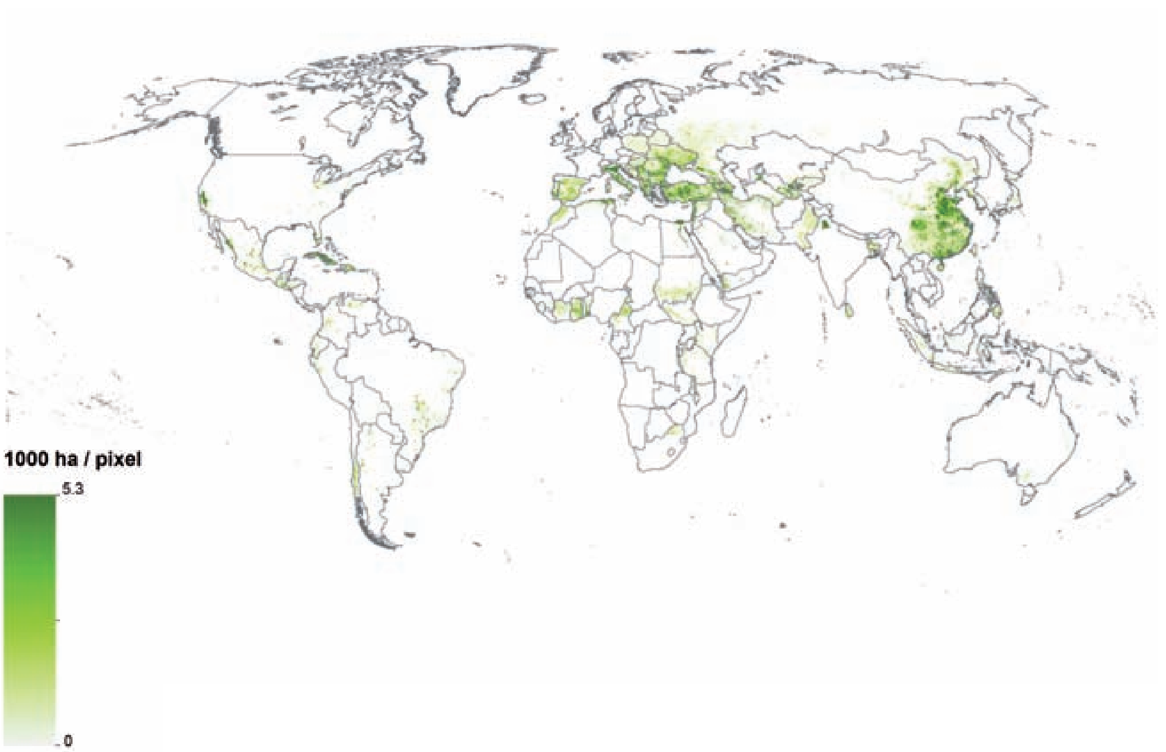


FIGURE 2 Tomato harvested area (SAGE, 2000).



Reference year 2000

Tomato requires soils with proper water-holding capacity and aeration. Well drained, deep, sandy loam soils are preferred, but heavier soils can also be highly productive under proper management. Tomato is intolerant to soil compaction and waterlogging, thus the upper 15-20 cm soil layer needs to be permeable. In clay soils, deep ploughing is sometimes necessary to allows for water drainage and better root penetration. At some locations tomato needs a 3-year rotation, with crops other than solanaceous (e.g. potato, pepper, eggplant, tobacco), to minimize nematodes, virus and bacterial diseases. Generally tomato is grown in rotation, often with only a 2-year cycle.

GROWTH AND DEVELOPMENT

More commonly, tomatoes are transplanted to achieve more uniform plant emergence, density and development. Because of its small seeds it is difficult to attain uniformity and high percentage of emergence when sown in the field. Direct sowing is usually limited to standard cultivars, with hybrids this method is uneconomic because of the high seed cost. Seed beds must be carefully prepared to eliminate soil clogs for direct sowing. The use of precision sowing machines, compared to traditional planters or manual sowing, allows for the use of pelleted seed and avoids the thinning at the fourth leaf or later stage. Tomatoes are best sown when the 7-day average soil temperature of the top 100 mm layer is ≥ 10 °C. Sowing period ranges from end of February to May in the Northern Hemisphere, or from August to mid-December in the Southern Hemisphere. Of course, the season is much less defined in the tropics and subtropics.

The optimal sowing depth is 2-4 cm. The density of sown processing tomatoes is generally higher than those that are transplanted because, up to a point, higher plant densities lead to higher yields and this is counter-balanced by the increasing cost of seedlings for transplanting at higher densities. About 100 000 seeds per hectare (1-1.5 kg/ha) are necessary when traditionally sowing processing tomato. In contrast, 0.3-0.5 kg/ha of seeds are used in case of precision sowing with pelleted seeds. Seedlings for transplanting are sown in a nursery in plug trays (25-35 mm diameter per seedling) at a density of between 750 and 1 000 seedlings/m^2, and transplanted at 25 000-33 000 plant/ha. Seedlings are commonly transplanted at the 4-5 true-leaf stage, 4 to 7 weeks after sowing. Seedlings should be short, 150-200 mm, including the root clod, and less if transplanting is by machine, and should have a thick stem base (diameter ≥ 4 mm). These requirements are met only if the radiation level is high in the nursery. The transplanting period ranges from the end of March to the end of June-early July in the Northern Hemisphere, or from September to mid-December in the Southern Hemisphere.

Plant spacing varies widely depending on conditions, seed or seedling cost, plant type and cultivars and local practices. Density ranges from 2 to 6 plants/m^2 and row spacing ranges from 0.75 m to 1.6 m, with processing tomato often planted more densely than market tomato. in the latter case, wider space is left for picker’s access, so that the ripe fruit can be harvested frequently. On wide beds, processing tomato may be planted in double rows to obtain a slightly higher yield. Generally, tomato starts to flower early, 25-40 days after transplanting or 35-50 days after emergence, depending largely on temperature. The life cycle varies from 95-115 days for processing tomato or up to more than 145 days for undetermined fresh market tomato.

Tomato flowers develop from buds situated in the axis of the angle between the leaf and stem. Consequently, flowers form in sequence as the number of leaves increases on the stem, and flower and fruit initiation overlap vegetative growth for the whole period. This period lasts longer in the indeterminate than the determinate type because of the difference in how long new leaves keep on developing. The first nodes on the stem that can potentially form flowers occur between the fifth and the seventh node, according to cultivar and temperatures in the initial weeks of crop (Dieleman and Heuvelink, 1992); however, there is not much different between the three determinacy types.

Tomato has a strong tendency to drop early flower buds, flowers and young fruit under certain conditions, including low solar radiation level and temperature and high humidity. Nitrogen and water status of the plant are equally influential. High nitrogen and/or high water status stimulates vegetative growth, this apparently competes with the developing flowers and fruit for assimilates, causing abscission of flowers and abortion of young fruit. In addition, restricted water supply can suppress new leaf development, resulting in a shortened yield formation period. Hence, field observation of phenological stages of tomato can be quite variable at times, even for the same cultivar and plant type, making it difficult to generalize. On the other hand, the remarkable adaptability of the tomato plant means cultivation worldwide is possible along with the application of diverse cropping techniques in greenhouses and in the field.

Tomato plants grown from seed develop a strong taproot that reaches a depth > 1.5 m in soils without impeding layers restricting root growth (Battilani *et al.*, 2002). In good and deep soils in California, rooting down to nearly 3 m has been documented. However, most water and nutrient uptake occurs in the 0.2-0.75 m soil layer, where 50-80 percent of the roots concentrate. Lateral roots are normally initiated within 5 cm of the tip of the taproot, increasing in length upward along the taproot to a position about 20 cm from the taproot tip. The taproot of transplant is broken or curved, thus, several large laterals develop in the first 3-4 weeks as main roots and penetrated downward. When soil receives water intermittently as rain or irrigation, the higher root length density is in the top 40 cm soil layer, where the majority of the active roots are concentrated. Drip irrigation alters root development pattern; however, roots grow preferentially in wet soil, irrespective of the areas wetted by surface or subsurface drip (Oliveira *et al.,* 1996).

WATER USE AND PRODUCTIVITY

Processing tomato consumes 400-800 mm of water from emergence/transplanting to harvest, depending on climate, plant type, soil, irrigation and crop management. Tomato plants can tolerate drought to some degree, therefore soil moisture levels can reach 50 percent of total available water (TAW) without significant yield losses after the development of the canopy is completed. It is important to maintain adequate soil moisture levels early in the life cycle, at transplanting, and from the first flower until complete fruit setting (e.g. of the fifth truss on the main axes). Irrigation can stop a few weeks prior to harvest, depending on soil water storage and rainfall expectancy. Over the peak growing period, maximum water use averages 4-7 mm/day in a sub humid climate, but can reach 8-9 mm/day in more arid areas. Tomato water productivity for biomass ($WP_{B/ET}$) ranges from 1.3 to 3.5 kg/m^3, with 3 kg/m^3 being considered as common for favourable conditions and practices (Battilani, 2006). The low end of the range is likely observed in climates of high evaporative demand, as well as where canopy cover is low and there is frequent wetting of exposed soil surface by rain or irrigation. The latter increases the E part of the ET. $WP_{B/ET}$ was found in some studies to be largely independent of nitrogen fertilization and of salinity, but within limits. If nitrogen or salinity is limiting, $WP_{B/ET}$ would be reduced (Heuvelink and Dorais, 2005). *AquaCrop* then requires a local calibration with biomass produced by a treatment of optimal nitrogen (or a non-saline treatment), in order to simulate such cases realistically.

RESPONSE TO STRESSES

Similar to cotton (see Cotton chapter), the vegetative/reproductive ratio of tomato also depends on plant-water status, but to a lesser degree. As already mentioned, high water status stimulates vegetative growth and commonly leads to the dropping of flowers and newly set fruit early in the season. On the other hand, mild to moderate water stress early in the season, if lasting for many days, can result in a markedly smaller canopy, and hence, less biomass production resulting from reduced radiation capture. Photosynthesis per unit leaf area is moderately resistant to water stress. Thus, the crop is fairly resistant to moderate drought once good canopy cover is achieved. Over irrigation causes excessive leaf growth, and plants high in vegetative vigour tend to produce low quality fruit because of reduced content of soluble solids. Moreover, excess water near harvest can cause nitrate accumulation in the fruit. For some cultivars, wide fluctuations in soil moisture levels during fruit maturation can cause fruit cracking, blotchy ripening, blossom-end rot and varied size and shape.

The crop is sensitive to frost. Low temperatures, if persisting for more than a few days, reduces leaf and truss initiation rates, and the plant produces thicker leaves, so they intercept less light; fruit set is reduced as a result of poor pollination. Dropping of flowers and young fruit under cold temperatures has already been noted. Exposure to high temperatures causes a reduction in the number of pollen grains and impairs their viability and germinability, markedly affecting fruit set. High day and night temperatures cause hastening in flowering and marked reduction in number of trusses, flowers per truss and an increase of blossom drop and fruit abortion. High humidity, combined with temperatures above about 27 °C, also affects pollen germination, resulting in reduced yield. Tomato, as with many other crops, can compensate for day and night temperatures, mitigating the stresses already suffered. Nevertheless, differences between day and night temperatures of less than about 12 °C adversely affect yield of many cultivars (Gent and Ma, 1998). Processing tomato cultivars bred for semi-arid warm climates, however, do not respond negatively to maximum temperatures in the range of 35-40 °C.

As is true for other crops, mineral nutrient requirement is high for high production. Fertilizer applications may be up to 220-250 kg N, 40-80 kg P_2O_5, 300 kg K_2O, and 20-50 kg MgO per ha for crops yielding about 100 tonne/ha. Fresh market tomatoes yielding over 150 tonne/ha requires up to 300-600 kg N, 150-300 kg P_2O_5, 600-1000 kg K_2O per ha. Nitrogen is often given in split applications, at planting and one at the early stage of fruit setting. Nitrogen, either in excess or when applied late during the growing season, affects fruit ripening by delaying fruit maturation. Too much nitrogen early in the season induces fruit drop and minimizes fruit set (Adam, 1986; Benton,1999).

The crop is moderately sensitive to salinity. The average root zone salinity threshold (EC_e) is about 2.5 dS/m. Yield decreases as EC_e increases, to about 50 percent at EC_e of 8 dS/m, and nil at EC_e of 13 dS/m in some studies. For practical purposes, the irrigation water salinity threshold for long-term use is about 3.5 dS/m on sandy soils, 2.0 dS/m on loamy soils and 1.2 dS/m on clay soils (Ayers and Westcot, 1985). During fruit ripening, light saline stresses can improve the fruit quality without any detrimental effect on yield. In fact, fruit quality is better with moderate salinity but at the cost of reduced yield, as shown by a number of studies in Israel.

IRRIGATION PRACTICE

Surface irrigation by furrow is still commonly practised. Pressurised irrigation methods (sprinkler, mini-sprinkler and drip irrigation) are now common in many main cropping countries. Large-scale tomato growers have long learned to limit irrigation as the crop approaches maturity. Because of its vegetative vs. reproductive changes in response to water status, irrigation management should focus on water saving while maintaining yield and enhancing fruit quality. In recent years, experiments with deficit irrigation have been directed at these objectives, with either the deficit maintained at a selected level over a long time (often referred to as DI), or with the irrigation being deficit only at selected stages of the crop's life cycle, referred to as regulated deficit irrigation (RDI) (Battilani *et al.*, 2008). In more arid areas preplant irrigation is practised when past rainfall is insufficient to replenish the soil profile. Preplant irrigations are also used to leach more saline soils. Frequently, if soil is well charged initially, one to two irrigations over a 2-4 week period are used for stand establishment after transplant or seeding. During canopy development and much of the flowering period, irrigation needs to be sufficient to ensure fast canopy growth and yet not so much as to cause excessive leaf growth and the associated dropping of flowers and young fruit. Soon after fruit colour change, irrigation should be reduced, but the start of irrigation cutback depends on the water remaining in the root zone of the soil, and the ET rate for that period. These are readily simulated by *AquaCrop*. The cutback over the ripening stage saves water but needs to be optimal to improve fruit quality while allowing last fruits to reach commercial size and maintaining the canopy coverage to protect fruit from sunburn.

YIELD

Yield of processing tomatoes has increased by more than 50 percent over the past 30 years in California and Mediterranean countries. A good commercial fresh fruit yield ranges from 60 to 120 tonne/ha for processing tomatoes and up to more than 150 tonne/ha for fresh market cultivars. Yield can be much higher in greenhouse production for fresh markets. In drier areas, rainfed crop production ranges from 40 to 70 percent of irrigated. Soluble solids content of the juice of most widely used cultivars can vary between 4.2 and 5.5 percent. Factories requires a minimal quality for processing tomatoes: juice acidity must range between 0.34 and 0.40 g/100 ml, reducing sugars between 2.5 and 3.0 g/100 ml and Bostwick consistency between 8 and 12 cm/30 s. Dry matter content of fresh fruit ranges from 4.0 to 7.0 percent (Leoni, 2002). Harvest Index (HI, the ratio of yield measured as dry matter to total above ground biomass) normally ranges from 0.5 to 0.65. HI decreases when plants are over watered or receive excessive nitrogen fertilization because of excessive vegetative growth, but yield may not be affected or even slightly increased, as long as the increased biomass production compensates for the lower HI. On the other hand, yield can be negatively affected when vegetative growth is so excessive that fruit setting is much delayed and HI is reduced sufficiently. *AquaCrop* provides the means to simulate this behaviour and the possibility of optimizing yield by using the appropriate irrigation strategy.

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Sugarbeet

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Sugar Beet

GENERAL DESCRIPTION

Sugar beet (*Beta vulgaris*) is a biennial plant that produces a large storage root as a part of tap root containing 14 to 20 percent sucrose on a fresh mass basis. When cultivated for sugar production, it is harvested in the first season, while for flowering and seed production the cultivation is prolonged to the second year. The first season for autumn planted crop is autumn to early summer of the next year, and for spring planted crop, from spring to autumn of the same year.

Current world production is about 227 million tonne of beets produced on 4.2 million ha (FAO, 2011). The cropped area has been decreasing over the past two decades; total root production, however, remained stable over the same period because of increasing yields (Figure 1). Sugar beet is cropped in the belt from 60° LAT N to 30° LAT S, with the main producing countries being France, United States, Germany, Russian Federation, Turkey, Poland, Ukraine, United Kingdom and China, in that order (FAO, 2011) (Figure 2).

Sugar beet is usually cropped in rotation with cereals (Europe, Russian Federation, Ukraine), maize (Southern Europe, America), beans and soybean (United States, China), in 3-5 year rotations (e.g. wheat – sugar beet – barley – peas). Optimal beet yields are obtained following wheat or barley, while excessive nitrogen availability after maize or soybean reduces sugar yield. At least a 3-year rotation is required to minimize root disease, Cercospora leaf spot, and herbicide carryover.

GROWTH AND DEVELOPMENT

Beet seeds are bulky and light in mass, one seed weighs only about 10 mg. Seeds are planted 1 to 2 cm deep in a single row, seldom in a double row, with rows spaced 0.40 to 0.76 m apart. Monogerm seeds allow precision sowing with 120 000 seeds/ha to obtain 60 000 to 110 000 plant/ha at harvest. In some situations, thinning by hand or by machine is needed to obtain optimal plant density and uniform spacing. Planting should be done when soil temperature is higher than 4 °C and the risks of frost is nil, and also depends on crop management and harvest scheduling. The sowing period ranges from autumn (India, Mediterranean-type climates), to early spring (Western and Eastern Europe, Eastern Europe, United States), to late spring (Russian Federation, United Kingdom, United States). Sowing in

FIGURE 1 World sugar beet harvested area and average yield over the period 1961-2009 (FAO, 2011).

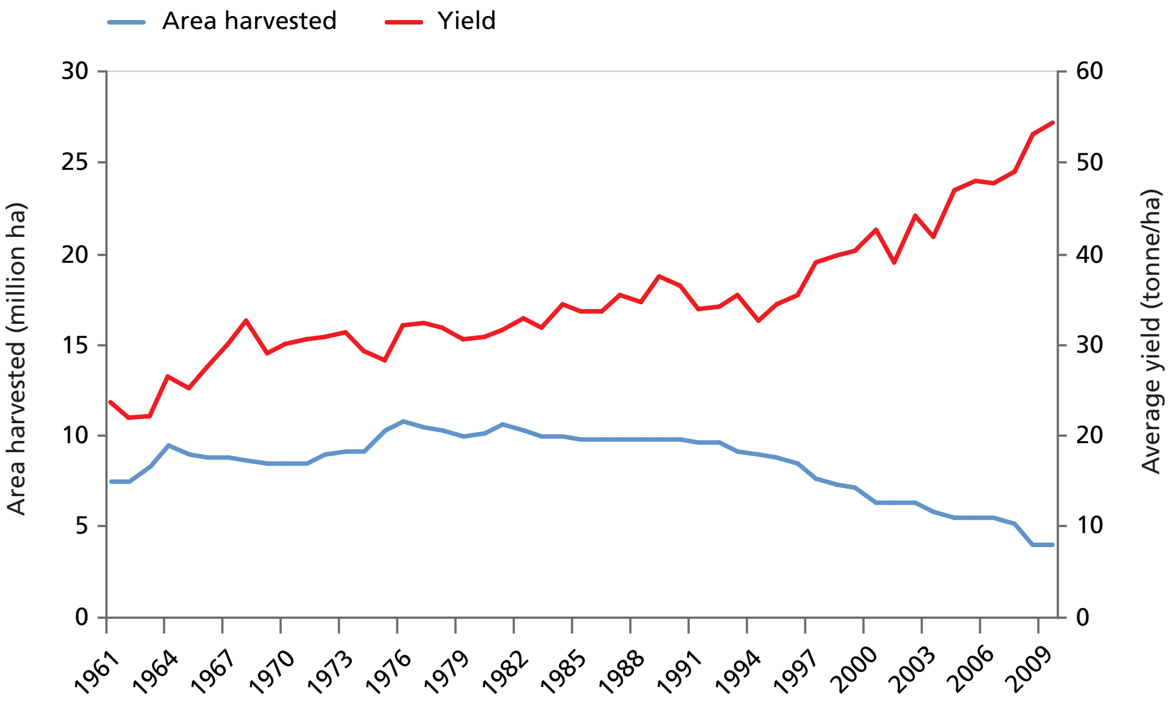
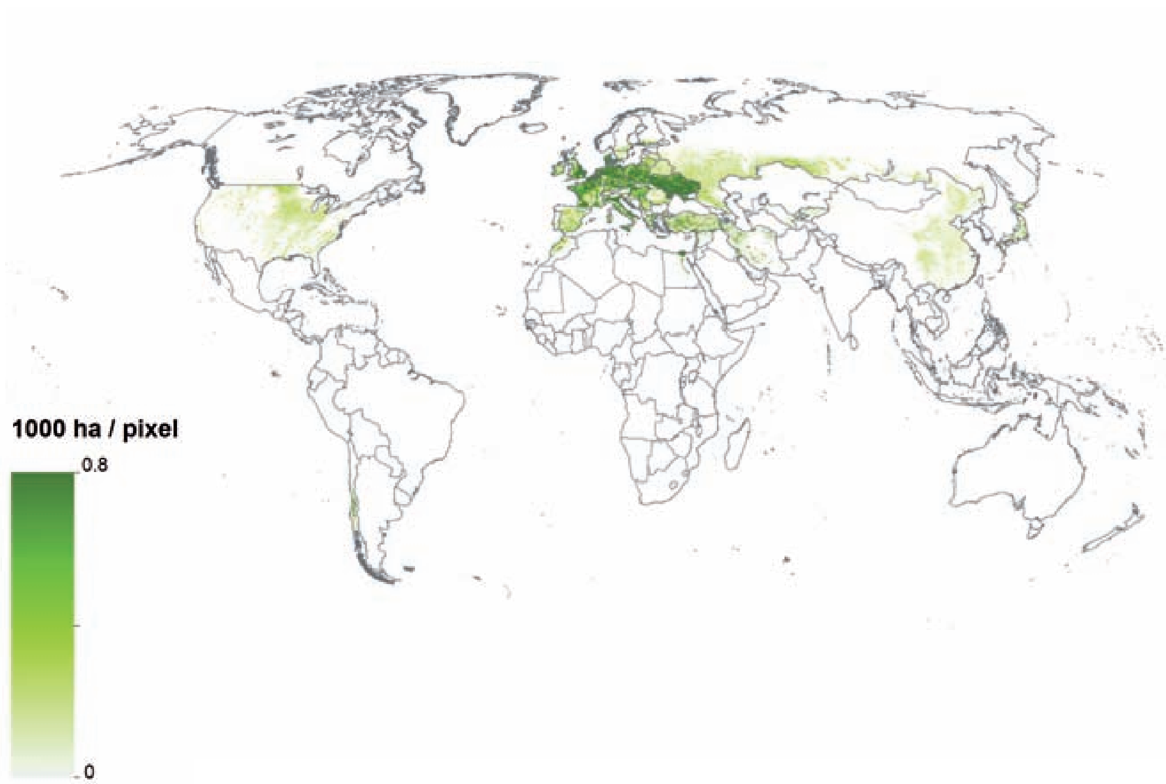


FIGURE 2 Sugar beet harvested area (GAEZ, 2011).



Reference year 2000

North Africa and near East ranges from September to December, depending on the beginning of rainfall. Sowing in India can be in summer, winter and *kharif* period. Extending the sowing time of sugar beet in winter and autumn has been an important breeding goal in the last decades, in order to reduce water requirement by avoiding parts of the summer, while lengthening the crop cycle and thus increasing productivity (Rinaldi and Vonella, 2005).

Minimum soil temperature for germination can be as low as 4 °C. Once established, the seedling enters a period of leaf initiation with virtually no enlargement of the upper portion of tap root for storage. By six weeks the plant has 8-10 leaves but the storage portion of the root is just enlarging (see Table 1 and Figure 3). From this stage onwards, growth of leaves and storage portion of root occur simultaneously with the root making up an increasing proportion of total plant dry weight.

Sugar beets develop an effective root zone of 1.20 m or deeper. In deep soils the crop can develop a deep tap root system. As is the case for other crops, when the soil profile is relatively wet, normally most of the water is extracted from the upper half of the soil of the root zone, although water extraction down to 3 m has been reported for deficit-irrigated sugar beet in very deep, open soils. Since this crop is cultivated for sugar production, the season length influences the root sucrose concentration. The length of time when the crop is in the field is limited by the biennial cycle duration and by the water, light and temperature constraints; in general, a prolonged crop cycle during the summer can modify the source-sink relationship between leaves and root and, consequently, reduce the storage root sucrose content that can flow to the leaves.

The evolution of canopy cover (CC) is mainly temperature dependent, and often maximum CC (CC_x) is reached after about 8 to 10 weeks. The duration in days is merely indicative because temperatures and water availability can influence the length of each phase. How long the leaves (hence the canopy) remain green depends on temperature and water stress. Spring planted crops in western and Eastern Europe and United States are harvested between September and November, while autumn planted crops are harvested at the end of spring or early summer (May to July in the Northern Hemisphere). Lengths of main crop stages are reported in Table 1 with reference to different cropping regions and sowing dates.

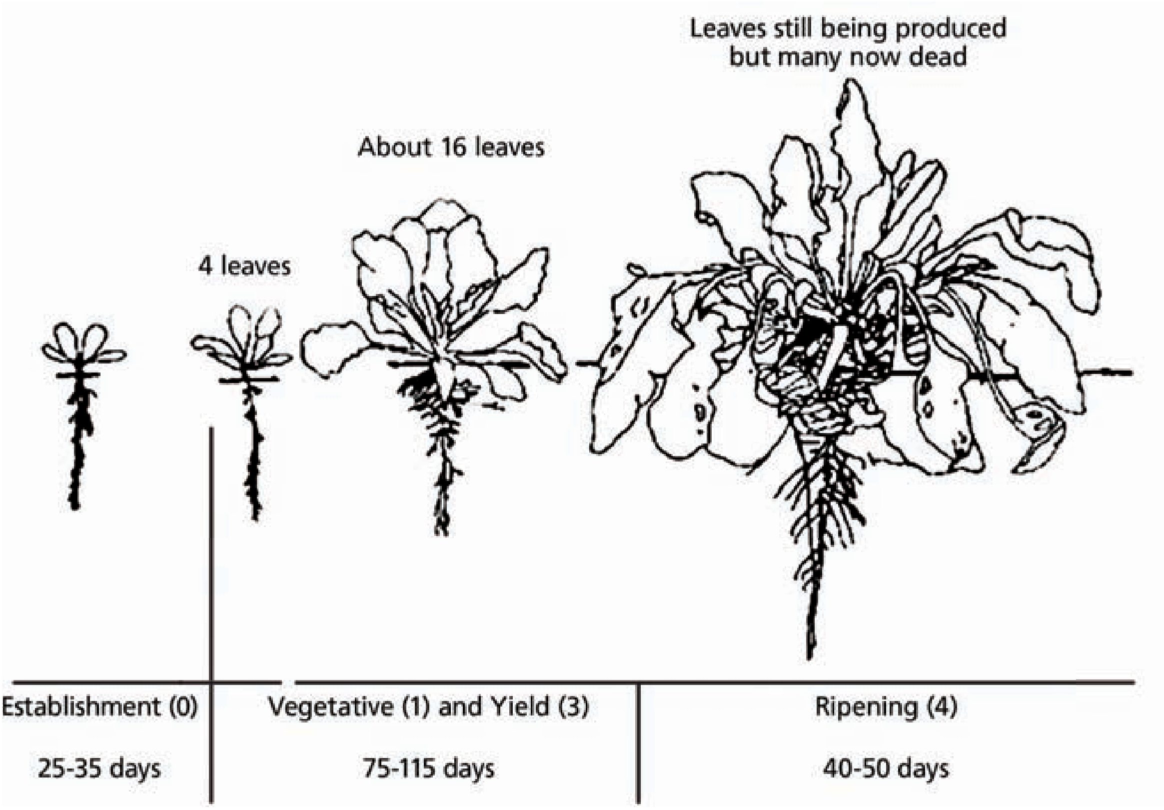
When grown at several constant temperatures (range of 7 to 31 °C, spaced 4 to 7 °C apart), fastest leaf growth was obtained at 24 °C, and fastest tap/storage-root growth was observed a considerably lower temperature, at less than 17 °C (Terry, 1968; Milford and Riley, 1980). Leaf growth is a linear function of temperature above 3 °C, and in the field leaf growth is close to a linear function of growing degree days calculated with a base temperature of 1 °C (Milford *et al.,* 1985).

Modern sugar beet cultivars are almost insensitive to day-length, and bolting (appearance of flowering stalk) and flowering do not take place under normal cropping conditions in the first season. Bolting reduces sucrose yield and is induced by a combination of low winter temperatures (0-10 °C) and long days. Breeders have selected cultivars with very strong flower induction requirements that can now be used for early sowing. The plant only flowers in the second year when seed production is the goal.

TABLE 1 Phenology of sugar beet in several environments (durations are in days).

	Sowing period	Sowing-emergence	Sowing-maximum canopy cover	Sowing-start canopy senescence	Sowing-maturity
Mediterranean countries	November	10-14	100-130	130-160	200-250
	February	16-20	80-100	100-130	150-180
Northern Europe	March	18-22	80-100	100-120	160-190
	April	18-22	70-90	90-120	150-180
India	October	8-12	40-60	60-80	120-140
USA	September	8-20	90-110	110-130	240-270
	March	16-20	80-100	100-120	170-190
	June	7-17	70-80	80-90	130-150

FIGURE 3 Typical developmental stages of sugar beet.



WATER USE & PRODUCTIVITY

Sugar beets consume 500-800 mm of water during the growing season. The seasonal water requirements depend on climate and weather conditions, planting date and density, irrigation, and crop management (Allen *et al.,* 1998). Sugar beets are most sensitive to moisture shortages in the early growing stages but their peak water consumption comes late in the season when maximum canopy cover is reached. Soil moisture levels should be maintained above one-half to one-third of total available water (TAW) to avoid stomatal closure. Over the peak 30-day growing period, maximum water use ranges from 6 to 9 mm/day, depending on climate. Commonly there is a positive relationship between water use, root production, and sugar content. Water stress reduces yield, while overirrigation near harvest reduces root sucrose concentration and increases processing costs, thus reducing profit (Ehlig and LeMert, 1979).

As for water productivity, spring sown beet commonly studied in Northern Europe and America, have reported consumptive water productivity for dry matter production ($WP_{B/ET}$) between 2.1 and 6.8 kg/m^3 (Dunham, 1993). This wide range of values reflect the diversity of climates in terms of evaporative demand and the fact that many $WP_{B/ET}$ values were not normalized for this parameter. It is pertinent to indicate here that the dry matter of concern is mainly composed of storage root dry matter, with shoot dry matter making up only a small portion (e.g. 20 percent). This is in contrast to all non-root crops, for which dry matter of concern is focused on the above–ground portion, neglecting the root portion because it is extremely difficult to extract quantitatively from the soil (Rinaldi *et al.,* 2006).

RESPONSE TO STRESSES

Sugar beet is sensitive to water deficits at the time of crop emergence and for a period of about one month after emergence. Frequent, light irrigations are preferred during this period, and irrigation may also be needed to reduce crust formation on the soil and to reduce salinity of the top soil. Early over-watering may retard leaf development and can encourage flowering during the first year (bolting). Water deficits in the middle of the growing period (vegetative and yield formation periods) tend to affect sugar yields more strongly than when occurring during later periods. Unrestricted water supply near harvest time tends to reduce root sugar concentration although it increases root fresh weight, with the final effect on sucrose yield being small. Moderate water deficits, together with mild nitrogen deficiency towards the end of the growing period, reduce root growth but increase sucrose concentration. In general, top growth toward the end of the growing period tends to be negatively correlated with sugar production, apparently the result of competition for assimilates between vegetative growth and root storage. Normally, the irrigation season ends between 2 to 4 weeks before harvest, depending on the water-holding capacity of the soil, to increase sucrose concentration in the beets. The soil should, however, not be too dry to hamper lifting the beets at harvest. Thus, except during emergence and early growth, it appears that the crop is not very sensitive to moderate water deficits. When plants are under water stress, leaves become dark green in colour and if the stress is severe, the leaves fail to recover from midday wilting in the evening (Hanks *et al.*, 1981).

Adequate soil nitrogen availability is required to ensure a good vegetative growth in spring. Nitrogen is often given in split applications, a small amount at planting and the rest after thinning. As mentioned, excessive nitrogen, especially late in the season, encourages excessive leaf growth and reduces sugar concentration of the beet. Fertilizer applications may be up to 150 kg/ha N, and 50 to 70 kg/ha P_2O_5 and 100 to 160 kg/ha K_2O at planting.

Except for during the early growth stages following stand establishment, the crop is quite tolerant to salinity (Katerji *et al.,* 1997). Yield decrease is 0 percent at an EC_e of 7 dS/m, 50 percent at EC_e of 15 dS/m, and 100 percent at EC_e of 24 dS/m. During early growth EC_e should not exceed 3 dS/m.

IRRIGATION PRACTICE

About one-fourth of the world's 4.2 million ha of sugar beet receives irrigation, but the fraction varies greatly from region-to-region. In the United States, Eastern Mediterranean, Iran and Chile between 80 and 100 percent of the sugar beet area is irrigated; in the western Mediterranean irrigated area amounts to 20-80 percent of total, while in Central and Northern Europe, it is less than 40 percent. In most sugar beet growing areas of the world irrigation is supplemental and typically only 100-200 mm are needed. In other areas (United States, Egypt, Pakistan) irrigation is essential for beet production and 500-1 000 mm are commonly applied. Practically, all irrigation methods are used for sugar beet, mainly sprinkler (pivot, booms), but also surface irrigation, and in rare cases, even drip irrigation.

When water supply is limited but land is not, water should not be used to meet the full water requirement of the crop. Instead irrigation should cutoff earlier and the water saved used to expand the area cropped. This is because the efficiency of water utilization for sucrose yield increases when water is restricted near harvest, for reasons already discussed. Under those conditions, harvest index increases significantly over the value achieved under full irrigation.

YIELD

A good commercial yield of 160 to 200 days sugar beet is 40 to 60 tonne/ha of fresh beet. Under very favourable conditions yields of up to 100 tonne/ha or more have been obtained. Total dry matter production varies from less than 10 tonne/ha to more than 20 tonne/ha. Sucrose content varies, mainly between 14 and 18 percent on a fresh mass basis, corresponding to sucrose yields of 5 up to 15 tonne/ha. $WP_{sucrose/ET}$ varies from 0.9 to 1.7 kg/m^3.

Harvest index (HI) for sugar beet is best defined as the ratio of sucrose produced to biomass of the storage root and shoot. Biomass of fibrous roots is neglected because most studies do not attempt to measure it. Also, shoot biomass is often not measured. On the assumption that storage root biomass is four to eight times the shoot biomass, HI in terms of sucrose produced would commonly fall in the range of 0.4 to 0.55, although values outside of this range are also encountered in the literature. HI tends to decrease when conditions favour luxurious vegetative growth, mainly high nitrogen and high water supply, especially as the harvesting time approaches. Extending the harvesting time to later in the season usually enhances HI, but only up to a point.

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Alfalfa

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Alfalfa

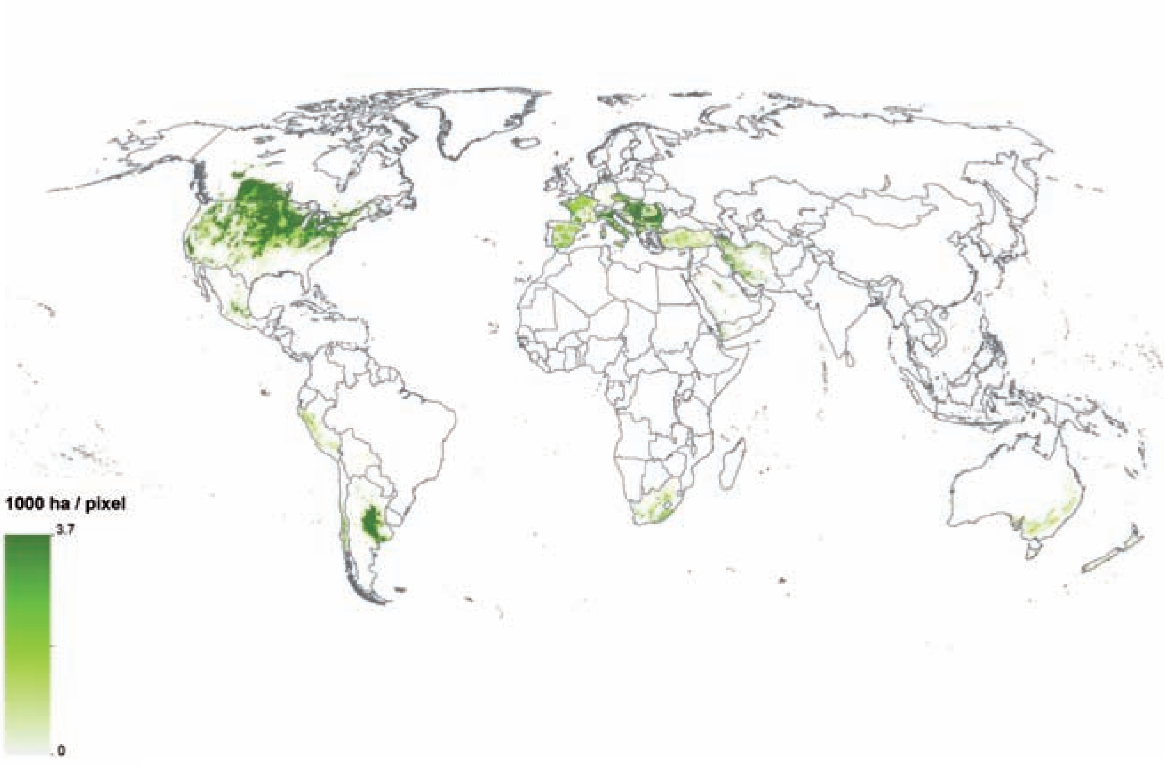
GENERAL DESCRIPTION

Alfalfa (*Medicago sativa* L.) is the oldest and most important forage crop globally (Michaud *et al.*, 1988). It is a perennial legume widely adapted to continental and temperate climates. Alfalfa can be conserved as hay, silage or pellets or grazed in pure stands or in mixtures with grasses. It is an effective source of nitrogen from symbiotic fixation which contributes to its high leaf protein and metabolizable energy content.

Alfalfa originated in the Caucasus region with related species scattered throughout central Asia. It was initially sown across Europe, Mexico and South America by invading armies to feed horses. China has had cultivated alfalfa for over 2 000 years with renewed interest in recent times for its ability to mitigate damage in erosion prone landscapes. In North America, Australia and New Zealand germplasm was introduced from various sources by colonists to support livestock farming. There are now over 30 million ha of alfalfa grown throughout the world as monocultures or in pasture mixes with grasses. (Figure 1 shows the world harvested areas).

The specific agronomic and management requirements of alfalfa are dependent on its intended use and the agro-climatic environment. Alfalfa can be used to dry the soil profile, reduce drainage and nitrogen losses to ground water, and minimize seepage of saline water to the soil surface. It can be established by conventional sowing, after plough, into a fine, firm seed bed or by direct drilling into existing herbage that has been suppressed with a broad spectrum herbicide. Alfalfa seeds are small (~2.0 g/1 000 seeds) so should be sown at depths less than 20 mm when soil moisture conditions are favourable and no deeper that 35 mm in drought prone or semi-arid soils. When spring sown, post emergent alfalfa should be left to grow until plants approach the flowering stage. This enables them to build up root reserves to aid stand establishment. Shoot growth and canopy expansion are slower during the seedling stage because alfalfa preferentially allocates photosynthates below ground. Alfalfa can fix nitrogen (N) once it has formed a symbiotic relationship with rhizobia bacteria, more specifically *Ensifer meliloti. E. meliloti* was formally known as *Rhizobium meliloti* and was also referred to as *Sinorhizobium meliloti* (Willems, 2006).

FIGURE 1 Alfalfa harvested area (SAGE, 2000).



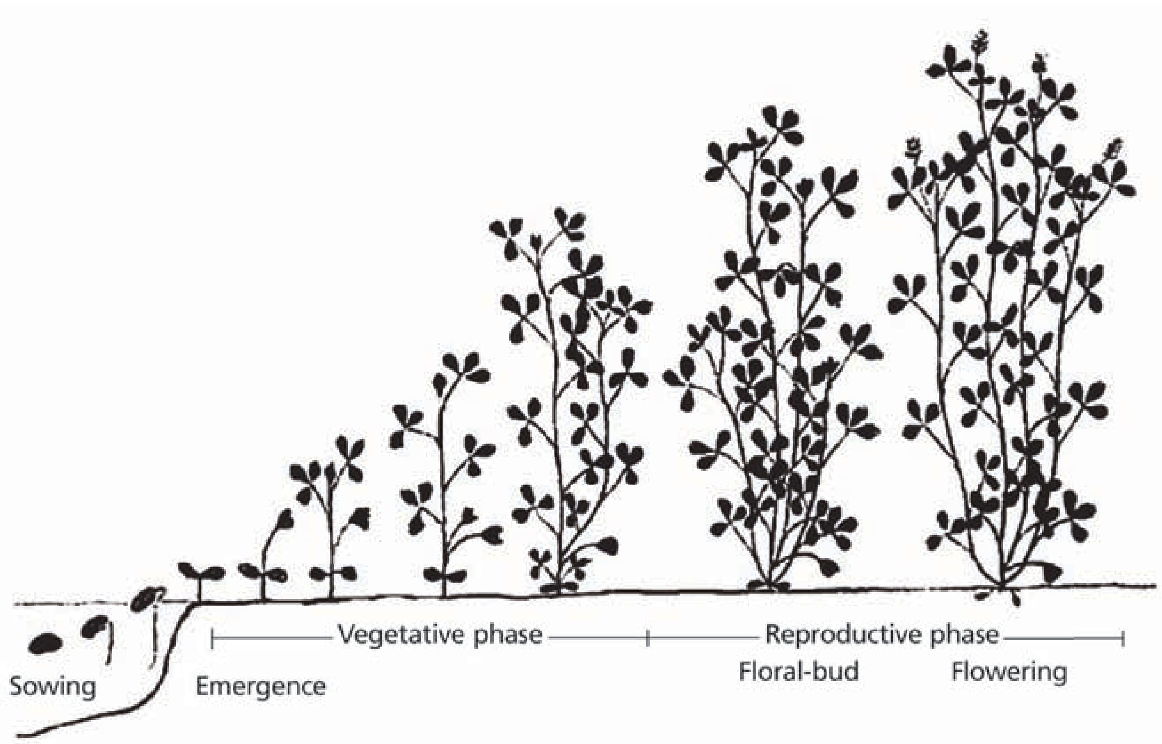
GROWTH AND DEVELOPMENT

Sowing of alfalfa can occur throughout the year depending on environmental conditions such as the availability of soil moisture and the occurrence of frosts. In temperate and continental climates that experience cold winters, stands must be established before the end of summer to enable plants to survive through winter. The earlier the sowing date in spring or summer, the higher the production in the following spring (Justes *et al.,* 2002). The timing and rate of germination are dependent on temperature, moisture conditions, soil salinity and seedling depth. In regions with warm winters, autumn sowing is preferred to ensure adequate weed control and obtain suitable soil moisture and temperature conditions.

Once the crop is established, stand longevity depends largely on plant population, climate and stand management. The initial plant population, determined by sowing and emergence rates, progressively self-thins and consequently the population declines. In most cases this progressive decline does not immediately affect shoot yield. Alfalfa stands have been shown to maintain maximum yields with populations declining from 140 to less than 60 plant/m^2. Yields are maintained over a wide range of populations because the self-thinning is compensated by increases in other yield components namely; (i) the number of shoots per plant (ii) the individual shoot weight, and (iii) the degree of branching. Plant death is mainly caused by competition for light, among alfalfa plants or with other species (e.g. weeds), and accentuated by poor management (e.g. not allowing sufficient regrowth before winter dormancy). Additional stresses such as the occurrence of pests and diseases accelerate plant death. Yield and stand longevity are compromised once plant populations fall below a critical level at which compensation by other yield components is impossible. At this point, re-establishment of the stand is necessary to recover productivity. To maintain high yielding (greater than 10 tonne DM/ha) stands, a plant population of higher than 40 plant/m^2 or about 450 stems/m^2 is required.

The phenological development of alfalfa, from emergence to maturity (Figure 2), is mainly driven by temperature (Fick *et al.,* 1988), quantified by accumulated temperature units (thermal-time in degree-days: °Cd). Development rates are negligible below 5 °C, which defines the base temperature (T_{base}) of alfalfa. Above T_{base}, development rates increase linearly with temperature until an optimum (T_{opt}) of ~30 °C. Above T_{opt}, development rates decline to be zero at greater than 45 °C. Daylength also influences alfalfa development during the vegetative stage. Alfalfa is a long-day plant and reaches reproductive stage (characterized by the appearance of floral buds) faster during summer when daylengths are longest, whereas the vegetative stage is extended when daylength shortens in late summer and autumn. After emergence, in the seedling stage, growth and development is slower than during regrowth. This is because seedlings lack a mature root system, nodulate and preferentially accumulate carbon and nitrogen reserves in perennial organs during this early stage. The seedling crop goes through a 'juvenile' period of vegetative growth when development is insensitive to daylength and flowering is delayed relative to regrowth crops (Teixeira *et al.,* 2011).

FIGURE 2 Typical developmental stages of alfalfa.



The number of times alfalfa can be harvested during a year depends on climatic conditions and management (Teixeira *et al.,* 2007). After each harvest a new cohort of vegetative shoots are generated. The duration from the initiation of new shoots to the reproductive stage may be modified by daylength and temperature. The response to daylength differs with cultivar and is more pronounced at high latitudes. After floral initiation, temperature alone drives development through flowering, seed filling and maturity. Temperatures above 27 °C, water stress or excessive soil moisture conditions can decrease seed yields.

The main factor determining alfalfa growth, i.e. the rate of biomass accumulation, is the amount of carbon assimilated through photosynthesis, which in turn is dependent on the amount of light intercepted by the canopy. Light interception increases with canopy cover as new leaves appear and expand. The rate of leaf appearance is driven by temperature with a new main-stem leaf appearing every 34–37 °Cd under optimal conditions. Daylength can also regulate the rate of leaf appearance with a delay observed during autumn, particularly for dormant cultivars. In summer, alfalfa may expand up to 20 main-stem nodes. It is an indeterminate plant and therefore leaf appearance continues after flowering, although at slower rates. Leaf senescence is a function of leaf age, the canopy light environment, and other environmental stresses. The canopy architecture of alfalfa enables efficient light capture as a result of the distribution of flat leaves in the lower canopy and vertical leaves in the top. This is characterized by its high light extinction coefficient per unit of leaf area of 0.8–0.9, which is high and stable in different commercial alfalfa cultivars. The rate of leaf area expansion is higher in spring and summer than autumn, in response to higher temperatures and longer daylengths.

Alfalfa radiation use efficiency for total biomass (shoots, crowns and roots), a proxy for net canopy photosynthesis, is ~1.8 g/MJ (total solar radiation). Once carbon is assimilated though photosynthesis, biomass can be partitioned to above (leaves and stems) or perennial below-ground organs (crowns and roots). Alfalfa survives during winter by storing carbon and nitrogen compounds as reserves in its perennial organs. These reserves are then used to resume growth during the following spring and after each harvest (Avice *et al.,* 1997). Nitrogen and carbon are mobilized to form new leaves and stems while carbon is also respired to supply energy to sustain root metabolic activities. The partitioning of assimilated carbon to crowns and taproots is seasonal.

During spring, most biomass is retained in shoots and less than 5–15 percent is partitioned below ground. From mid-summer to late-autumn more than 50–60 percent of total assimilated carbon may be partitioned to perennial organs below ground to sustain future spring growth and stand persistence (Teixeira *et al.,* 2008). These seasonal patterns of biomass partitioning differ with alfalfa cultivar, according to their Mediterranean or northern origin. High latitude cultivars have a more evident seasonality with higher biomass partitioning to roots in late-summer/autumn in response to lower temperatures and shorter daylength. The extent of cultivar response to decreasing temperatures and daylengths is defined by its dormancy rating which range from 1 to 11. More dormant cultivars (rating 1-5) have reduced growth rates, shoot production and higher underground partitioning in autumn than non dormant (winter active) cultivars.

WATER USE & PRODUCTIVITY

As a perennial crop, alfalfa can produce dry matter throughout the year if environmental conditions are favourable. During the most active growth period from spring to autumn, daily values of evapotranspiration (ET) are driven by the interaction of environment and defoliation (cutting) management. The removal of leaf area reduces transpiration so ET values less than 1 mm/day occur immediately after defoliation, mainly through soil evaporation, and in cool winter conditions. When the crop reaches full canopy, ET can rise to over 8 mm/day. As the canopy recovers and leaf area index increases the daily ET can be estimated from potential ET multiplied by the fraction of canopy cover (French and Legg, 1979). During this phase the proportion of soil evaporation in relation to ET declines and transpiration increases. The ratio of actual to reference ET peaks at around 1.1-1.15 at full canopy and declines when senescence occurs as a result of self-shading (i.e. at high leaf area indices), the onset of flowering or frost events. Total cumulative ET ranges from less than 200 mm in arid conditions to over 1 000 mm in well watered conditions.

The slope of the relationship between cumulative herbage yield against cumulative water use gives an indication of water productivity ($WP_{Y/ET}$). The average $WP_{Y/ET}$ is typically around 1.0–2.6 kg/m^3 (Grimes *et al.,* 1992) but has been reported as high as 2.9 kg/m^3 (Brown *et al.,* 2005). In one study, $WP_{Y/ET}$ dropped from 2.1 kg/m^3 to 0.4 kg/m^3 immediately after defoliation (Asseng and Hsiao, 2000). In temperate climates, the highest water productivities are recorded in the spring and values decrease through summer and autumn. The high spring time water productivity results from low vapour pressure deficits in the atmosphere and the highest proportions of total biomass production being partitioned to the harvested shoot (leaf and stem) fraction. Water productivity is lower in the summer because of the high evaporative demand and concomitant higher vapour pressure deficits. Water productivity declines in the autumn because of changes in crop partitioning to roots and cold temperatures. This reduces shoot production per unit of water use. The linear relationship between dry matter production and ET appears stable across cultivars of different fall dormancy ratings.

The annual water requirement of an alfalfa crop can be estimated for any location by the sum of daily estimate of ET for the period that the crop is actively growing. The irrigation requirement can then be estimated by subtraction of effective rainfall during the growth period plus the amount of readily available soil water at the start of the growing season from the total crop water demand. If complete recharge of soil water is achieved prior to the start of the growing season a value of 50 percent of the soils available water capacity (field capacity minus lower limit to a depth of 1.5 m) is commonly taken to represent the readily available water. If incomplete recharge occurs, a simple water balance can be used to estimate soil water content at the start of the season and 50 percent of this value used to represent readily available water.

RESPONSE TO WATER STRESS

Alfalfa has a strategy of drought avoidance by accessing water through its deep root system but has poor drought resistance and is rapidly affected by water shortage (Sheaffer *et al.*, 1988). Water shortage occurs when water supply is insufficient to meet water demand. When soil moisture is near field capacity the water use of alfalfa is limited by the requirement set by transpiration demand for the crop canopy which is driven by atmospheric conditions.

When crop water requirements are greater than total soil water available in the root zone, it restricts the major plant processes of canopy expansion, transpiration and photosynthesis or radiation use efficiency, and accelerates leaf senescence. Relative leaf area expansion rates decrease from their maximum at a threshold between 15-20 percent below field capacity, to be negligible as the total available soil water decreases from field capacity down to about 30 percent or more of the total available water capacity of the soil. Radiation use efficiency is less sensitive to water stress than canopy expansion and declines in a 1:1 response to the decrease in available soil water (Brown *et al.*, 2009). If water supply is only half of crop demand, production will only be half of potential.

The amount of water extraction can be calculated for different layers of soil (Brown *et al.* 2009). Starting in the top layer, extraction is the minimum of potential supply from that layer and demand from the atmosphere. Water extraction from underlying layers depends on the remaining demand after extraction by overlying layers. Effectively, alfalfa has a top-down water extraction pattern throughout the growing season for seedling and regrowth crops. Reductions in water extraction rates are observed in situations of water shortage. In the absence of other measurements, it can be assumed that alfalfa can extract about 3 percent of the plant available water from the soil on any day. Effectively the potential daily water supply can be estimated from the available water capacity of the soil and the rooting depth of the alfalfa crop. The extraction rate coefficients of alfalfa are low compared with other crops (Dardanelli *et al.*, 1997) so alfalfa will prolong the use of the soil water it has access to, mainly because its deep rooting enlarging the supply reservoir.

Alfalfa is less tolerant of waterlogging (saturated soils) than other forage (grass) species. Anaerobic conditions for more than 7-14 days lead to root death and secondary disease infection, particularly from *Phytophthora* species.

SOIL FERTILITY

Successful alfalfa stands are grown on deep (>1.0 m) free-draining soils, to take advantage of its taproot, with a pH of 6.0–8.0. Adequate phosphorous (P), Sulphur (S), Boron (B) and Molybdenum (Mo) are usually required depending on soil nutrient status. Potassium (K) based fertilizers are recommended, particularly under intensive cutting, because leaves of alfalfa, a natrophobe, have a higher potassium and lower sodium (Na) content than many other forage species.

TEMPERATURE

At temperatures less than 5 °C or greater than 45 °C, alfalfa development is negligible. Between these thresholds, alfalfa development rates increase linearly to reach a maximum at ~30 °C. Low temperatures also limit net canopy photosynthesis rates. Radiation use efficiency was shown to increase linearly from 0.6 g/MJ at 6 °C to 1.6 g/MJ at 18 °C (Brown *et al.* 2006).

SALINITY

Alfalfa is tolerant to relatively high salinity in the lower root zone provided the upper zone is saline free. It is more sensitive to Na^+ than Cl^- so that sodium accumulation is the dominant reason for yield decreases when irrigating with saline water. Irrigation, even with moderately saline water, can cause salts to accumulate deeper into the soil profile which enables roots to proliferate in regions of relatively low salinity. At salt concentrations above 10 dS/m significant yield reductions are expected. In these conditions, the absolute yield of alfalfa may still be greater more than 'salt-tolerant' grasses.

YIELD AND QUALITY

The diversity of climate and soil types used to grow alfalfa means reported yields range from less than 1 tonne DM/ha in rainfed systems, on soils of low water holding capacity combined with low annual rainfall (<300 mm/year) to over 28 tonne DM/ha per year in well watered deep silt loam soils in New Zealand (Brown *et al.,* 2005). A similar maximum yield has been reported in Africa, with yields of 10 to 20 tonne DM/ha commonly produced in Europe, China and North America under irrigated conditions. Under rainfed conditions with 500-800 mm of annual rainfall, yields of 5 to 17 tonne DM/ha have been reported. The productivity and persistence of alfalfa stands are affected by management and location with a decline in plant population expected over the first 4–5 years. Stands can persist for over 20 years in low rainfall climates that have a distinct winter dormant period, provided soils do not freeze and cause plant death.

For alfalfa, the quality of herbage is directly related to the fraction of leaf and palatable stem compared with lower quality lignified stem. During vegetative crop growth, the first 2 tonne DM/ha is predominantly high quality forage with a crude protein content of at least 25 percent. As alfalfa matures beyond this stage the proportion of lower quality stem material increases and the overall leaf to stem ratio declines (Marten *et al.,* 1988). So for high quality hay, alfalfa is cut normally at the early flowering stage or sooner. When alfalfa is grazed in a rotational system it is recommended that each paddock is rested for 35–42 days before re-entry of livestock (Moot *et al.* 2003). Continuous grazing (or set stocking) contributes to a decline in root reserves and consequent death of weakened plants. Allowing a period of extended autumn regrowth is beneficial to replenish root reserves and aids persistence of the stand.

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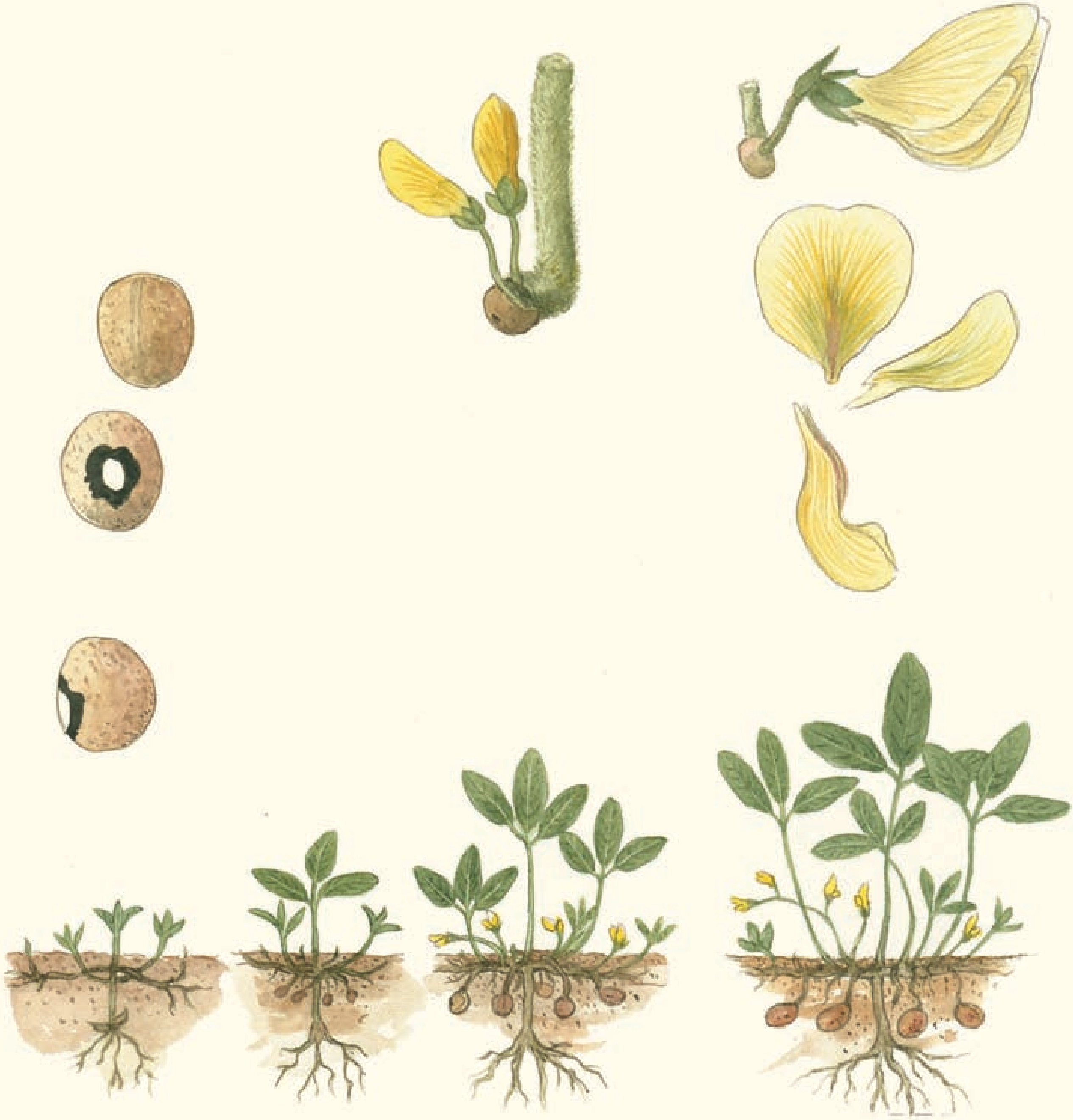

Bambara Groundnut

Bambara Groundnut

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GENERAL DESCRIPTION

Bambara groundnut (*Vigna subterranea*) is an indigenous food legume crop that originated in the regions between the Jos Plateau in northern Nigeria and Garu in Cameroon. The variety *subterranea* is the cultivated form with wild forms belonging to variety *spontanea* (Pasquet *et al.*, 1999). No established varieties exist and, to date, there have been no coordinated programmes of crop improvement, resulting in high genetic variability within cropped fields. Marginal and subsistence farmers in Africa grow locally selected 'landraces', which are often grown from seeds stored from previous harvests or from unregulated supplies of seeds bought from local markets.

Bambara groundnut has been grown widely in Africa for many centuries and now plays a significant role in cropping systems in semi-arid sub-Saharan Africa. It is mainly grown by women farmers for the subsistence of their families, often intercropped with cereals, tuber crops, vegetables, and other legumes (Linnemann, 1991). Bambara groundnut has been introduced through historical migrations to Indonesia, Thailand and Malaysia. More recently, the crop has been experimentally evaluated in India. (See Figure 1 for area harvested and yield).

GROWTH AND DEVELOPMENT

Because pod formation occurs at or just below the soil surface, this crop benefits from a well-prepared seedbed. The planting density is variable and there seems to be significant plasticity in response to planting density. In Swaziland, five plant densities between 33 000 to 267 000 plant/ha were investigated (Edje *et al.*, 2003). Across this range, the number of pods per plant varied between 40.5 and 5.8. However, there was no effect of these planting densities on seed yield.

FIGURE 1 World bambara groundnut harvested area and average yield over the period 1961-2009 (FAO, 2011).

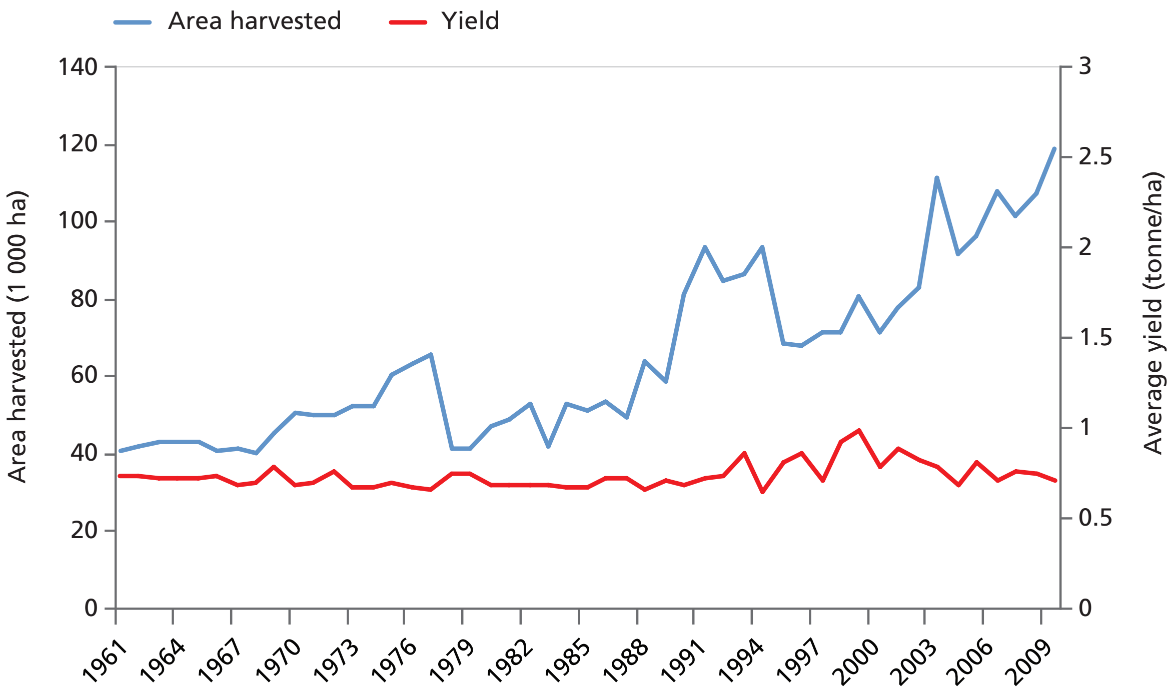

TABLE 1 Duration of developmental stages in bambara groundnut landrace-UniswaRed with different sowing dates in Botswana and Swaziland.

Region	**Notwane, Botswana**			**Malkerns, Swaziland**
Landrace	**Uniswa Red**			**Uniswa Red**
	Sowing date			**Sowing date**
	21 Dec 2006	**18 Jan 2007**	**1 Feb 2007**	**26 Nov 2002**
Days after sowing to:				
Emergence	7	7	7	11
Flowering	55	55	57	74
Max rooting depth	58	58	60	79
Max canopy	68	69	72	93
Canopy senescence	77	80	84	105
Maturity	127	130	135	130
Duration of yield formation	40	48	66	58
Duration of flowering	23	25	28	31

Generally, the growing season begins in December in most of the Southern African region whereas in parts of Eastern African farmers may plant in two seasons around December and June. When water supply is unlimited, the rate of germination is dependent on temperature, genetic variability, and seed size and age. Germination generally takes 7 to 15 days and the maximum rate of seed germination occurs around 30 °C, with no germination below 9 °C or above 45 °C (Massawe *et al.*, 2003). The length of the main growth stages is reported in Table 1. Once established, the seedling enters a period of leaf initiation with very little root growth. By about 35 days, the plant has 6-10 leaves with a shallow root system. From this stage onward leaf and root growth occur simultaneously with the above ground parts making up an increasing proportion of total plant dry weight. The evolution of canopy cover (CC) is temperature dependent and, at optimal temperature, maximum CC (CC_x) is reached after about 60 days in field conditions. Onset of flowering ranges between about 45 and 70 days after sowing. Bambara groundnut is an indeterminate crop, with overlapping of vegetative and reproductive phases, as leaf production continues alongside flowering and podding. The total growing period ranges from 120 to 140 days. Across landraces, stands of bambara groundnut effectively extract water down to at least 0.90 m under drought whilst when water is unlimited most extraction occurs in the top 0.50 m of the soil profile.

A major labour requirement is the practice of earthing up, also known as ridging, which involves covering the developing pods with soil. Different reasons are given for this practice, including better pod development, protection of the pods against pests and disease and avoidance of waterlogging where rainfall intensities are high. However, there is no clear quantitative evidence for the benefits of earthing up across different environments.

WATER USE & PRODUCTIVITY

Seasonal transpiration under adequate water supply varies between 500 to more than 600 mm, depending on land races and environment. There is little information on the transpiration of water-limited crops. Water productivity ($WP_{Y/ET}$) varies with landrace and possibly ranges from 2-3 kg/m^3.

RESPONSE TO STRESSES

Bambara groundnut tolerates a wide range of agroecological conditions and poor soils and this resilience to variable and low-input systems makes it popular among farmers with limited resources. In particular, it exhibits a number of drought tolerance traits that confer agronomic advantages over other legumes in low and variable rainfall areas. Nevertheless, severe drought during the vegetative phase affects leaf and dry matter production. Water availability influences the allocation of dry matter to reproductive yield with harvest index (HI) reduced by up to 16 percent under water limitation.

There are reports of significant effect of heat stress on pod formation in some landraces (e.g. Uniswa Red from Swaziland). Experimental evidence from controlled environment glasshouses at Nottingham, United Kingdom showed that, whilst Uniswa Red produced a massive vegetative canopy through unrestricted leaf production and expansion, it exhibited a 45 percent reduction in HI when exposed to temperatures above 33 °C. Whilst high temperatures clearly influence reproductive performance disproportionately more than vegetative performance, it is not known how temperature stress reduces pod formation. Whether the maintenance of leaf production and expansion at high temperatures may be a cause or a consequence of poor pod formation, it results in the major proportion of biomass being allocated to vegetative development. The reduction in pollen viability due to heat stress may be associated with poor pod set.

Bambara groundnut is a short-day species. While flowering is generally set by thermal time, very unusually, the onset of pod growth is affected by photoperiod (Harris and Azam-Ali, 1993). At daylengths longer than 12 hours, the crop will take longer to initiate pod filling, delaying maturity.

IRRIGATION PRACTICE

Generally, bambara groundnut is grown as a rainfed crop in semi-arid Africa. Where available, irrigation practices enhance the total productivity of the crop. However, even when water is not limiting yield is still subjected to the daylength control of pod growth. This has important implications both for rainfed and irrigated production as sowing date needs to be set by the optimal daylength for pod filling and seasonal rainfall and/or irrigation need to fit within this production interval. When water resources are limited and daylength is not a constraint, any available water should be applied during the late vegetative period (up to flowering) to ensure that the maximum numbers of pods are set, provided that water is not so restricted as to shorten the crop life cycle markedly.

YIELD

Yields under favourable conditions may range from 3.0 to 3.8 tonne/ha (Collinson *et al.*, 2000). However, as a result of genetic variability and because the environments in which bambara groundnut is grown are characterized by various biotic and abiotic stresses, typical yields are extremely low and vary between 0.65 and 0.85 tonne/ha for most of the semi-arid tropics (Hampson *et al.*, 2000). In practice, there are large differences in reported yields between and within countries, with yields as low as 0.06 to 0.11 tonne/ha (Zambia), 0.05 to 0.66 tonne/ha (Swaziland), and 0.07 to 0.86 tonne/ha (Zimbabwe). At harvest, the ratio of pods to total dry matter (Harvest Index, HI) is in the range of 0.30 to 0.45. The HI decreases under drought, temperature stress and longer day lengths, and is maximal when applied water is sufficient for maximum canopy cover to be achieved and daylength and temperatures are optimal. The nutritional composition of bambara groundnut (protein content is 16-25 percent) is comparable or superior to other legumes (Linnemann and Azam-Ali, 1993), providing an important supplement to cereal-based diets.

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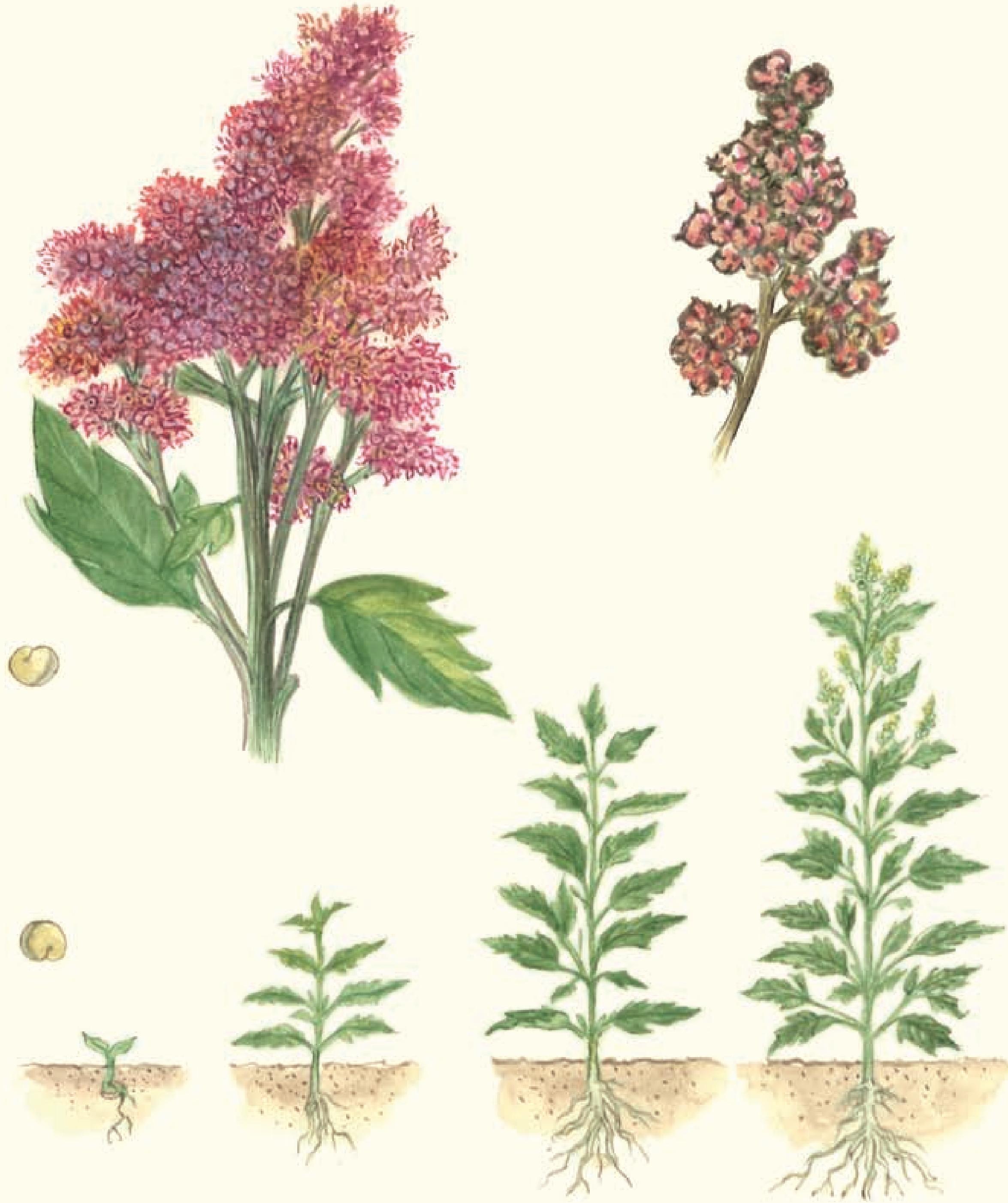

Quinoa*

**Flower and grain colour presented in the figure are only an example. Depending on the quantity of anthocyans, this colour varies from green-yellowish to deep purple and even black throughout quinoa varieties.*

Quinoa

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GENERAL DESCRIPTION

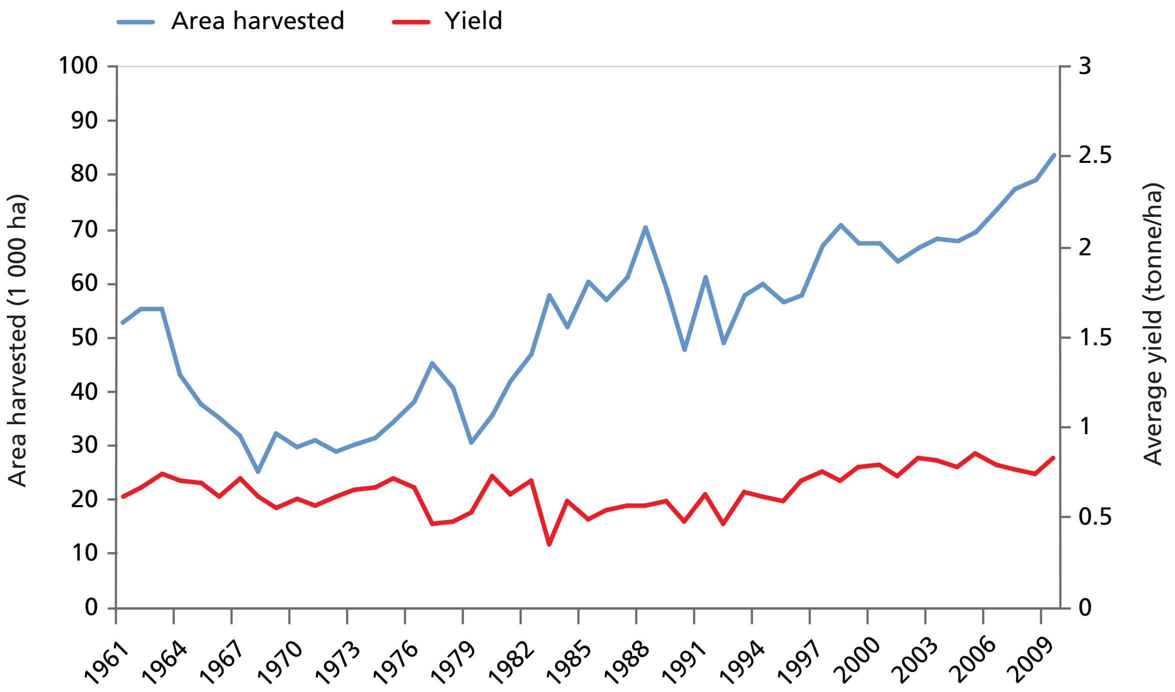
Quinoa (*Chenopodium quinoa* Willd.), a species of the goosefoot (*Chenopodium*) genus of the family of sugar beet, beetroot, mangold and spinach, is a grain-like crop grown primarily for its edible seeds. It is a seed crop, rather than a true cereal, or a grain, as it is not a member of the grass family. It is native to the Andean mountains where this traditional seed crop has been cultivated in the Peruvian and Bolivian Andes for more than 7 000 years. Although the production declined significantly during the Spanish conquest, popularity of quinoa rose again in the last century. Production is now widespread in the Andes, covering Bolivia, Peru, Ecuador, Colombia and the north of Argentina and Chile. As a crop with a large food utilization potential, it is rapidly gaining interest globally, being already fairly known in North and Central America, Brazil, Europe and Asia (Schulte auf'm Erley *et al.*, 2005). First results also indicate the potential of quinoa in Africa. In 2009, 83 thousand hectares were sown to quinoa, producing 69 000 tonne of grain at an average grain yield of 0.8 tonne/ha (FAO, 2011). The worldwide trend for cropping area and production over the last 50 years is shown in Figure 1.

Quinoa is characterized by an enormous intra-species variety and plasticity that allows the crop to grow under highly diverse climatic and agronomic conditions. It is well adapted to arid and semi-arid locations and grows from sea-level to high altitudes, up to Andean Altiplano at around 4 000 m above sea level, where its cultivation is of special importance. Quinoa is cultivated as a mono-culture (e.g. Southern Bolivian Altiplano) or in rotation with potato and barley, and sometimes with wheat and maize at the low altitudes. When cultivated as mono-culture, fields are left fallow for 1 to 3 years and sometimes even longer (up to 10-12 years) for pest control, soil fertility regeneration and build up of the soil water reserve. Traditionally, a range of quinoa landraces is cultivated in the same vicinity, though for export purposes a few local cultivars sown in monoculture are generally preferred (e.g. quinoa var. Real Blanca). Daylength neutral cultivars of quinoa can be grown under the long day conditions of northern Europe (Christiansen *et al.*, 2010).

GROWTH AND DEVELOPMENT

Quinoa is a C_3 annual dicot of 0.5 to 2 m height, terminating in a panicle consisting of small flowers, and with only one seed of around 2 mm

FIGURE 1 World quinoa harvested area and average yield over the period 1961-2009 (FAO, 2011).



produced per flower. In the Andean highlands, quinoa is grown from September to May, and normally without any fertilizer or pesticide. In the Bolivian Altiplano, the sowing date varies between the beginning of September and the end of November, according to the crop cycle length of the different cultivars and local climate, particularly when the soil is moist enough for germination. Sowing practice is the key for the success of quinoa. Superficial sowing runs the risk of seed dehydration or sunburn whereas deep sowing can prevent emergence; in both cases, a poor stand and uneven canopy cover occurs with detrimental effects on final yield. Common practice is to sow between 8 to 15 kg of seeds per hectare in rows 0.4 to 0.8 m apart, either on top of the bed or in the furrow, with plants spaced about 10 cm apart within the row after thinning. Another practice, adapted to arid environments where commercial production is widespread, is to group several plants each in pits spaced about 1 m apart. Less common are transplanting (Inter-Andean valleys) or broadcasting of the seeds. As nutrients are often scarce in the Altiplano, early weeding (± about 30 days after sowing) and thinning of excessive plants are important activities in the areas where rain is sufficient to allow for rapid plant growth. In arid areas, instead, weeding and thinning are not practised, even in commercial production.

Phenological development is highly variable among varieties. Additionally, phenology is highly flexible in response to water stress, with differences in time to maturity of as much as 30 days for the same cultivar (Geerts *et al.*, 2008c). Under no stress conditions, time from sowing to emergence is 3 to 10 days. The time to maximum canopy cover (CC_x) depends on plant density and temperature regime. Phenology is further complicated by a response to photoperiod — a short day response for duration of emergence to flowering, and for the duration of all developmental phases in some cultivars (Bertero, 2003). The time from emergence to physiological maturity varies between 100 and 230 days, again because of wide variation among cultivars. Flowering starts between 60 to 120 days, and lasts around 20 days. Canopy senescence starts generally about one month before physiological maturity, and progresses relatively fast. It is important to note that these indicative values are given for cultivars cultivated at high elevations, and could be biased because growing conditions (temperature, fertility, water supply) are not optimal. Roots, often with numerous ramifications, can deepen to 1.80 m depth in cases of drought stress in light soils.

In the southern Andes, quinoa is harvested in April-May, mainly by pulling out or cutting the plants and leaving them in stacks on the field to dry. Harvest can take up to 1.5 months because of asynchronous flowering and ripening. In principle, realistic simulation of such production practice with *AquaCrop* would entail simulations runs for each maturity group, and then summing up the yields of all groups in proportion to their population density or land area occupied (Figure 2. Example of quinoa).

WATER USE & PRODUCTIVITY

In midseason, quinoa reaches maximum canopy cover (CC_x), shortly after first anthesis. CC_x is largely dependent on the management conditions and, to a large extent, determines quinoa transpiration. For a complete canopy cover of the ground and under non-limiting nutrient conditions, quinoa transpires at a rate similar to the reference evapotranspiration (ET_o). Seasonal ET values for quinoa with a normal season length of 150-170 days are around 500 mm under non-stressed conditions. As a C_3 crop, normalized crop water productivity (WP*) is low,

FIGURE 2 Flower and grain colour presented in the figure are only an example. Depending on the quantity of anthocyanins, this colour varies from green-yellowish to deep purple and even black throughout quinoa cultivars.

with typical values around 10.5 g/m^2 under the low, natural fertility in the Bolivian Altiplano (Geerts *et al.*, 2009). Still-under poor fertility conditions, a decrease of the reference biomass water productivity (WP*) value only occurs at higher total transpiration sums, and only by 10 percent. The C_3 pathway is well adapted to the prevailing low average temperatures in the Altiplano. Reported values of seed yield per unit of water consumed ($WP_{Y/ET}$) are rather low and lie between 0.3 and 0.6 kg/m³ because of the generally prevailing low fertility conditions (Geerts *et al.*, 2009). On the other hand, it is a crop with a large nitrogen-sink thus causing an increased metabolic cost or higher glucose-equivalent per unit dry matter produced. To our knowledge, no research has been conducted on the response of quinoa to increases in atmospheric CO_2.

RESPONSE TO STRESSES

Quinoa is highly resistant to a number of abiotic stresses (Jacobsen *et al.*, 2003). Several drought resistant mechanisms are present in quinoa. Drought in early vegetative stages may prolong its life cycle, allowing the plant to make up for growth lost during the early drought if water is available later. Also, the availability of cultivars with different season length makes it possible to match the water requirement of the quinoa crop to the available rainfall or the stored soil water at a given location. Quinoa tissue is relatively high in osmotic solutes and undergoessubstantial osmotic adjustment under drought, which enable stomata to remain somewhatopen down to a leaf water potential range of -1.5 MPa. During soil drying the plants are able to maintain leaf water potential and photosynthesis due to the complex stomatal response, resulting in an increase of leaf water use efficiency. Root originated ABA plays a role in stomata performance during soil drying. ABA regulation seems to be one of the mechanisms utilized by quinoa when facing drought inducing decrease of turgor of stomata guard cells (Jacobsen *et al.,* 2009). The plant also avoids negative effects of drought through fast and deep rooting particularly in dry soils. Quinoa also reduces its leaf area by controlled leaf senescense under drought.

Quinoa is a facultative halophyte (Bosque-Sanchez *et al.,* 2003) and can grow in non-saline to extremely saline conditions, depending on the cultivar. Seed production is enhanced by moderate salinity (EC in the 5-15 dS/m range) and may not be drastically reduced even at EC of 40 to 50 dS/m in some cultivars (Jacobsen *et al.,* 2003). Osmotic adjustment by the accumulation of salt ions in tissues enables the plant to maintain cell turgor and transpiration under saline conditions.

Apart from drought, frost and cold are the other major growth limiting factors in the Altiplano. Quinoa is tolerant to frost, partly because of the protection provided by its heterogeneous canopy (Winkel *et al.,* 2009), although the tolerance varies with cultivar and appears to diminish at the late phenological stages (Jacobsen *et al.,* 2005). Leaf freezing of quinoa occurred only between -5 and -6 °C, and is delayed in case of mild water stress (Bois *et al.,* 2006). The resistance to frost is associated with super cooling of tissue water and tolerance of extracellular ice formation (in the cell wall), as is common for most winter crops.

Linked to frost resistance is a low base temperature (T_{base}) for plant processes. In a study of the leaf appearance rate of different quinoa cultivars originating from various altitudes and latitudes, T_{base} averaged 2 °C and the temperature at which maximum rate was reached averaged 22 °C. Other studies found a T_{base} of 3 °C, T_{opt} of 30-35 °C and T_{max} estimated to 50 °C

(Bertero *et al.*, 2000; Jacobsen and Bach, 1998).Temperature sensitivity of quinoa was highest in cultivars originating in cold and dry climates and lower in cultivars from warmer and humid climates (Bertero *et al.,* 2000).

Because soil fertility is generally poor in its centre of origin, cases of quinoa cultivation under non-limiting soil fertility are very rare. Research into nitrogen and phosphorus requirements conducted in Colorado, United States, found that maximum yields over 4.5 tonne per ha are possible when 170 to 200 kg N/ha were applied (Oelke *et al.,* 1992). If these results are confirmed in other studies, the WP* of quinoa under non-limiting fertility would be much higher than the value of 10.5 g/m^2 reported earlier for the low fertility natural conditions of the Andean Altiplano. No effect on yield was observed when 34 kg of phosphorus (as phosphoric acid) per ha was applied, in comparison to an untreated field plot (Oelke *et al.,* 1992). In areas of traditional cultivation, some sheep or lama dung is applied when available; but mostly, quinoa is sown in unfertilized fields. If sown after potato, nutrient supply is generally better because of the nutrients left over from the potato fertilization.

IRRIGATION PRACTICE

As quinoa is drought resistant, it is traditionally cultivated under rainfed conditions, even in semi-arid locations. Researchers, though, started to study the impact of additional water on quinoa production and found that deficit irrigation (DI) was highly beneficial in various experimental locations. DI is already practised for the reintroduction of quinoa in arid regions of Chile. On the other hand, currently quinoa is rarely cultivated under full irrigation, as research of quinoa under full irrigation gave only slightly better results than quinoa cultivated under deficit irrigation (Geerts *et al.*, 2008a and b), besides the issue that sufficient water for full irrigation is mostly unavailable.

YIELD

Quinoa produces nutritious seeds (Alvarez-Jubete *et al.,* 2009) with high protein content (from 12 up to 20 percent), as compared to maize, rice or even wheat. The balanced amino acids composition makes the protein quality comparable to that of milk, making it an effective meat and milk substitute. Additionally, quinoa is gluten free, which is advantageous for commercial food manufacturing for celiac consumption. On the other hand, the seeds also contain the anti-nutritional component saponin (Mastebroek *et al.,* 2000), that the plant produces as an inherent protection against pests. Saponin is removed by washing or dry polishing before consumption.

Although high yields (up to 4.5 tonne/ha and more) have been occasionally reported for some quinoa cultivars under non-limiting fertility and water conditions, rainfed yields in the Peruvian and Bolivian Altiplano do not exceed 0.85 tonne/ha as an average. Pests, including birds and rodents, and diseases are major causes of yield loss, in addition to low fertility and water deficits. Harvest index (HI) of quinoa in the field ranges between 0.3 and 0.5. Building up of HI takes a short time for the short season cultivars, and up from 80 to 100 days for the long season cultivars. Individual grain size is quite variable among cultivars, with 1 000 grain weight ranging from 1.2 to 6.0 g in non-stress conditions (Rojas, 2003).

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Tef

GENERAL DESCRIPTION

Tef (*Eragrostis tef* [Zucc.] Trotter) is a C_4 annual grass (Holden, 1973; Hirut *et al.,* 1989) also known as bunch grass, which originated and diversified in Ethiopia (Vavilov, 1951). It is one of the most important cereal crops in that country, ranks first in cultivated area among all annual crops and occupies about 29 percent of the land devoted to cereals. Tef yield is quite low (averages around 1 tonne/ha or less), but accounts for about 20 percent of the total cereal production (in most cases second to maize) in Ethiopia. The trend there over the last decade is an increase in cultivated area (about 25 percent) and a 45 percent increase in yield per hectare. Outside Ethiopia, tef is also traditionally grown in Eritrea, and to a lesser extent in India.

Tef is predominantly grown alone, though it is intercropped occasionally with oil crops such as rapeseed, safflower and sunflower or relay-cropped with maize and sorghum (Seyfu, 1997). In Ethiopia, tef is often rotated with pulses, such as field pea, faba bean, chickpea, or oil crops like linseed depending on location and the type of soil. In most cases a 4 or 5-year rotation is common, with pulse/tef/tef, wheat or barley/pulse, and pulse/tef/tef/other cereal/pulse.

Tef is predominantly produced as a staple food for local consumption and an important cash crop for farm households. The grain is grounded into flour to make a pancake-like local bread called *Injera*. It provides about two-thirds of the daily dietary protein intake for most Ethiopians (NRC, 1996). The protein content of the grain is about 9-11 percent, slightly higher than sorghum, maize or oats, but lower than wheat or barley. Tef is also appreciated as a fodder crop, with nutritious straw preferentially given to lactating cows and oxen used for traction. Moreover, its straw is the preferred binding material in Ethiopia for walls, bricks and household containers made of clay.

Tef grain contains gluten lacking the gliadin fraction that causes coeliac disease; therefore it can be consumed by gluten intolerant people. The amino acids of protein in tef grain are fairly balanced. These properties make tef an attractive potential crop for cultivation outside its traditional areas. Countries like the United States, Canada, Australia, South Africa, and Kenya began production of tef for different purposes, as a forage crop, as a component of porridges and pancakes, and as a thickener for soup and gravy, probably because tef flour imparts the product a short, stiff texture and a slight molasses-like sweetness.

GROWTH AND DEVELOPMENT

The common method of sowing tef is hand broadcasting. The tef seeds are extremely small, weighing 250 to 350 mg per 1 000 seeds (*NRC, 1996*). Hence, special care is necessary to prepare a fine and smooth seed bed. This entails ploughing the field between 3 to 6 times (Aune *et al.*, 2001) to pulverize the soil and cover the seeds lightly after sowing. A seeding rate of 25-30 kg/ha is recommended for broadcast sowing (Fufa, *et al.*, 2000 and Seyfu, 1997). Sowing period in Ethiopia ranges between mid-July to early August, depending on local climate, soil type and life cycle length of the cultivar, and usually when the soil water is near field capacity.

Emergence takes a few days or longer (between four and 11 days), depending on soil moisture and temperature. Soil temperature below 19 °C slows the rate of emergence. Vegetative growth and canopy development (Alemtsehay *et al.*, 2011) follows the common pattern for other crops, as does biomass accumulation. Because tef is usually planted at high density (e.g. 2 000 plant/m^2), full canopy cover (CC_x) is reached early. Final height of the plant ranges from 0.6 m to just above 1 m.

Tef is self-pollinating, with very small inconspicuous flowers typical of grasses borne on panicles (Figure 1), which can range from loose to compact (Seyfu, 1997). It is photoperiod sensitive and its time to flowering is accelerated by short days. Under certain conditions, flowering can start as early as 40 days after sowing or even earlier. Since the stem terminates at the panicle, the earlier the flowering, the fewer the leaves produced on the stem. Time to flowering ranges from about 35 to 65 days, as observed in various studies. Canopy senescence starts

FIGURE 1 Tef showing panicle type of inflorescence on the left and panicles bearing seeds on the right.

about 55 days or more after planting, depending on genotype and environmental conditions. Rooting depth of tef grown in plastic tubes differs with genotype and ranges from 0.6 to 1.0 m at heading (Mulu *et al.*, 2001).

As tef grain fills and approaches maturity, lodging is often a problem, especially if the grain is bountiful and there is strong wind and heavy rain. Tef is harvested when the vegetative part turns yellow or brown. Depending on the maturity group of the cultivar and photoperiod, tef may be harvested between 60 and 150 days after sowing (Fufa *et al.*, 2001).

WATER USE & PRODUCTIVITY

In Ethiopia, tef performs well with annual rainfall of 750-850 mm and 450-550 mm during its growing season, but reasonable yield can be obtained with 300 mm of rainfall in its growing season (Seyfu, 1997). There is very little reported research on its water productivity (WP) other than the first attempts to estimate normalized WP (WP*) of tef for use in *AquaCrop* simulations. The values arrived at in two studies (Araya *et al.*, 2010; Alemtsehay *et al.*, 2011) fell in the range of 14 to 20 g/m^2, similar to values common for C_3 species but much lower than the 30 g/m^2 found for other C_4 species. The low WP* of tef is attributable at least partly to low N fertilization, as the crop was fertilized with only 60 kg/ha of N, in both studies. The general WP* values noted above for C_3 and C_4 species are for crops grown with optimal mineral nutrition (receiving 150 to 250 kg N/ha). Additional and more definitive study of tef WP is much needed.

RESPONSE TO STRESSES

Tef is genetically diverse, grown at elevations of 1 000 to 2 500 m and a mean temperature range of 10°C to 27°C (Seyfu, 1997). The crop is considered to be tolerant to both drought and waterlogging (Mulu *et al.,* 2001). This feature is valuable to poor farmers in locations with highly variable environmental conditions.

With regard to water stress, at least one of the coping mechanisms is apparently osmotic adjustment. In a study (Mulu *et al.,* 2001) with many genotypes, it was found that most of the tef lines osmotically adjusted by more than 0.4 MPa to slowly developing drought. However, under water stress canopy senescence is accelerated (Araya *et al.,* 2010) as in most crops. Many cultivars require 200 to 300 mm of water during their early growth (NRC, 1996). Seyfu (1997) mentioned that 300 to 500 mm of rainfall is adequate in a growing season and even less than 300 mm seasonal rainfall may be sufficient for early-maturing cultivars. This is the reason why tef is often planted after a cereal fails because of early drought, as a rescue crop in the same season, taking advantage of later rains to yield some grain and straw. Seasonal ET of early maturing tef estimated using *AquaCrop* or other simulation models for Ethiopian high lands would fall in the range of 280 to 300 mm. Hence, a short life-cycle tef may not even experience water stress in such a situation, albeit the yield would be less compared to longer cycle cultivars.

Tef grows on a wide range of soil types. To improve the yield where nutrients are limiting, one recommendation is to apply phosphorus at the rate of 60 kg P_2O_5/ha at sowing to both light and heavy soils, and 40 kg and 60 kg of nitrogen per hectare, respectively, to light and heavy soils (EARO, 2002). Tef has some tolerance to frost and flooding, and to high temperatures up to 35 °C, but cannot survive a prolonged freeze (NRC, 1996).

IRRIGATION PRACTICE

Irrigation is not commonly practised in the traditional culture areas, though water scarcity is the major limiting factor for tef growth in arid and semi-arid regions of Ethiopia because of inadequate and erratic rainfall. Research shows clearly that tef benefits from supplementary irrigation in locations prone to terminal drought by maintaining the green canopy longer (Araya *et al.,* 2010).

YIELD

The national average yield under rainfed condition in Ethiopia is around 1 tonne/ha, although yields more than 2 tonne/ha may be attainable with good agronomy. One reason for the low yield is the nitrogen limitation. In one study (Tulema *et al.,* 2005) on two soil types and three locations in Central Ethiopia, a late-maturing cultivar of tef yielded 0.77, 1.6 and 1.9 tonne/ha, and the measured N (grain plus straw) totaled 58, 103 and 126 kg/ha, at the three locations. 64 kg/ha of N was applied to the soil in all cases. For the highest yield, the amount of N applied was only about half of the N removed by 1.9 tonne/ha crop. These results indicate that N may be a major factor limiting current yields. Nevertheless, increasing N fertilization may increase lodging, and another likely reason for low yield is tef's tendency to lodge while the canopy is still green. The potential for yield increase by minimizing lodging was shown in a study (Teklu and Tefera, 2005) where many cultivars were optimally grown in the field through fixed nettings to provide support for the stems and prevent lodging. The yields varied from 2.9 to 4.6 tonne/ha, with a mean of 3.8 tonne/ha. Efforts are apparently underway to breed for lodging resistance (van Delden *et al.,* 2010).

Still another reason for the low yield of tef is its low harvest index (HI). As a national average for Ethiopia, an HI of 0.24 is reported by Seyfu (1997). Teklu and Tefera (2005) found HI to be in a similar range for their many tef cultivars. On the other hand, Temesgen *et al.* (2005) reported mean HI ranging from 0.33 to 0.38 for different clusters of germplasm accessions, but did not specify the plant density. In contrast, HI of modern cultivars of other cereal crops fall around 0.45 to 0.50.

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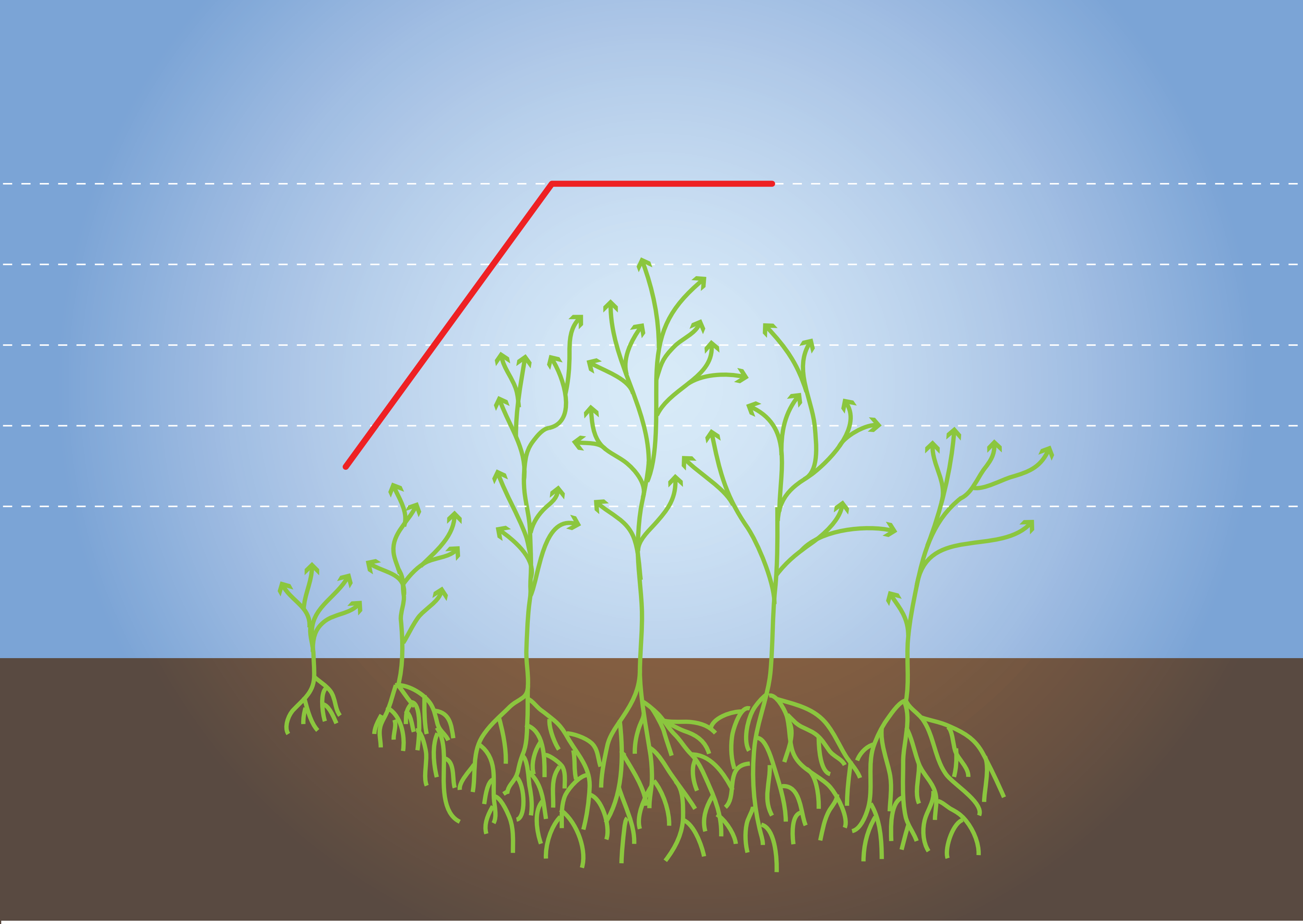

Yield response to water of fruit trees and vines: guidelines

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4. Yield response to water of fruit trees and vines: guidelines

INTRODUCTION AND BACKGROUND

Orchards and vineyards are long-term, costly investments. The development of plantations must avoid two critical issues: a) poor soil conditions (e.g. too shallow, poor drainage, high salinity); and b) uncertainty in irrigation water supply. Limiting soil conditions are a threat to the long-term viability of plantations, and the severe water deficits imposed by lack of irrigation water not only would reduce current year yields but could negatively affect production in subsequent years, enhance alternate bearing and damage or kill trees, either directly or indirectly. In perennial plantations, growers need to keep the risks to the minimum, thus orchards and vineyards traditionally have been developed under good environmental conditions. However, due to water scarcity, orchards and vineyards are subjected to periodic droughts and, more recently, many orchards and vineyards have been planted in situations where the soil and/or the water may be limiting. This is why it is important to understand the responses of orchards and vineyards to variations in water supply so as to manage water judiciously.

Tree crops and vines have more complex behaviour and have been less studied than the major annual crops. Therefore, it is not possible at this time to build a simple and robust dynamic simulation model of the yield response to water, as *AquaCrop* is for the herbaceous crops in Chapter 3. Alternatively, we provide first an overview of the generalized responses to water supply of tree crops and vines, followed by Sections on each crop that delineate the specific responses of each major tree and vine crop, for which there is sufficient information, grown primarily in temperate and subtropical climates. The material presented focuses on the relevant issues related to orchard and vineyard development in relation to: a) water requirements; b) responses to water deficits; c) irrigation scheduling techniques; d) relations between yield and water use; and e) water management strategies suggested under limited water supply.

World trends in fruit tree and vine production

The rapid rate of world economic development in recent decades has been accompanied by many transformations; an important one is the change in human diet, such as the increase in demand for animal products in many emerging economies. In most countries, health-related concerns have led to a renewed interest and increased consumption of fruit and vegetables. Strong consumer demand has resulted in the production of high-quality horticultural products; a very high priority of both public and private institutions worldwide. This increased demand for fruit is expected to continue and presents an incentive for growers to develop efficient horticultural industries, which in most areas will be dependent on irrigation.

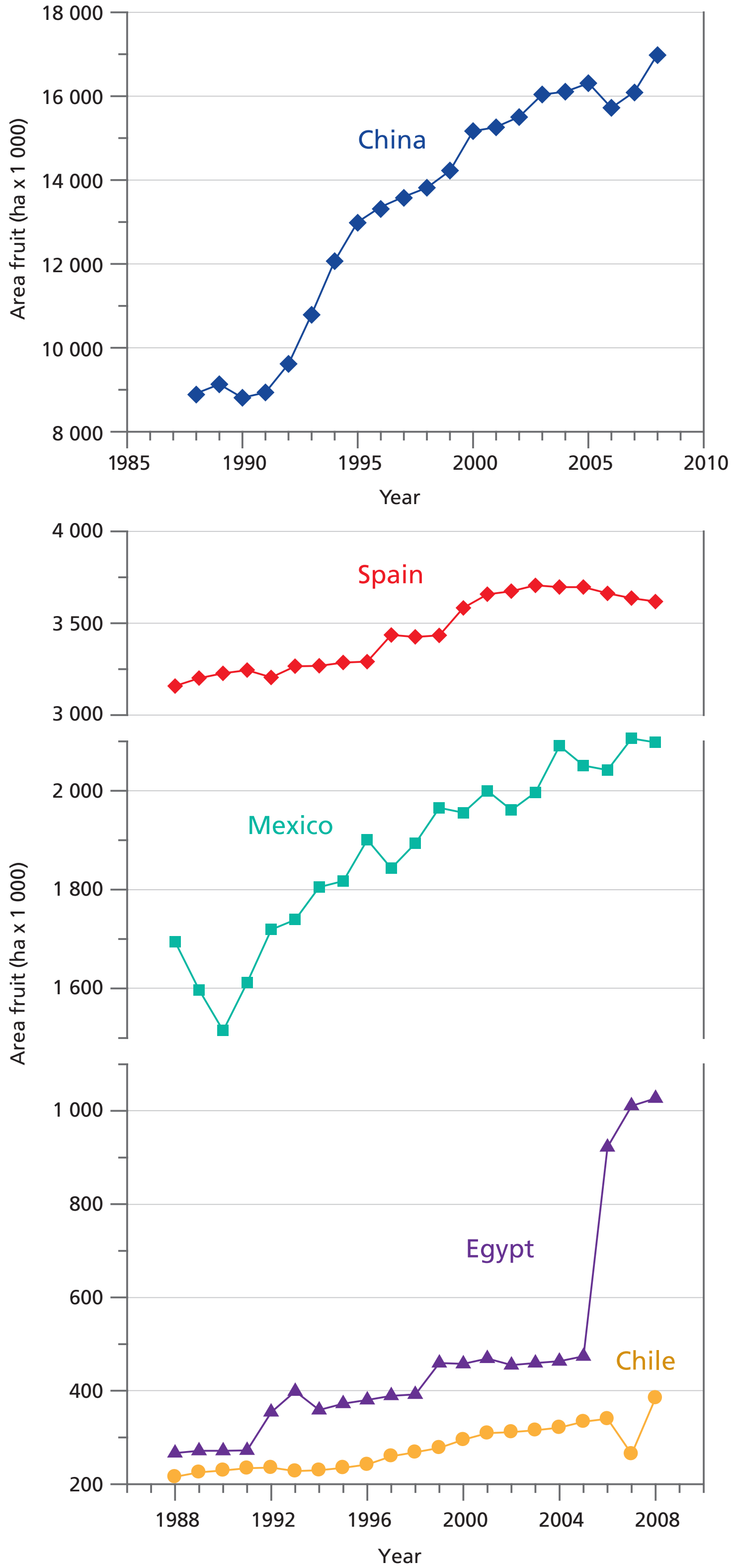
Current water demands by other sectors of society require that the agricultural sector reduces water use for irrigation; the world primary user of diverted (developed) water. Indeed, current agricultural water use is considered by some competing interests simply another 'source' of water, since the development of additional water supplies has been limited, especially in developed countries. In many parts of the world, one result of reduced water supply for agriculture has been a shift in cropping patterns to economically more viable crops; from annual field crops to horticultural crops, such as fruit trees and vegetables. Figure 1 shows that the areas devoted to growing fruit and vines in a number of countries have increased significantly over the last 20 years, indicating that this is a general trend in irrigated agriculture in most parts of the world.

Recent improvement of irrigation and management methods have reduced irrigation-related water losses, thus decreasing the amount of applied water per unit of irrigated land. Both the shifts towards high-value crops and towards higher application efficiency suggest that more water should be available for irrigation of trees and vines. However, these improvements have coincided with an expansion of irrigated land, to the extent that most of the water saved has generally been used to irrigate additional land or crops that have higher water requirements. In many cases, the water requirements of tree crops exceed those of the major field crops that were previously grown in these areas. Therefore, the availability of water for tree and vine irrigation most likely will continue to decline. This will be more so in areas where the supplies have been stretched to the limit and where environmental water needs are considered high priority by society and are in direct competition with irrigation needs.

Towards intensification in fruit and vine production

The general trend in fruit-tree production over the last decades, as in other forms of agriculture, has been towards intensification. This trend is manifested as an increase in tree or vine density, often coupled with the use of dwarfing rootstocks to reduce tree vigour. There are many reasons for the success of these intensive plantations, relative to those that are traditional low density. Greater radiation interception results in increased carbon assimilation and productivity and lower vigour reduces pruning needs and often harvesting costs; both of which are significant expenses in orchard production. Since access to the orchard is improved because the drive rows (areas between the tree rows) are not usually wetted by microirrigation, pest control applications are easier and on time. In short, high-intensity orchards are more manageable. Their major limitation is the higher capital

FIGURE 1 Trends between 1988 and 2008 of the area devoted to fruit trees and vines in China (top), Spain, Mexico, Egypt and Chile (FAO, 2011).



requirements per unit land area for orchard establishment, but smaller orchards can be economically sustainable if they are adequately designed for intensive production. Another drawback is the higher water requirements associated with greater radiation interception, especially during the first years of the orchards (Box 1).

Methods of irrigation

Irrigation has both scientific and technological components and recent improvements of tree and vine crops have involved primarily the latter; the adoption of improved irrigation systems. The traditional method used in the past was surface irrigation, primarily with furrows or small basins, as is still practised today in many areas (Figures 2 and 3). The introduction of sprinkler irrigation in the 1950s had limited impact on tree crops, although it was useful to develop new plantations on steep land that was not amenable to surface irrigation (Figure 4). In the mid-1960s, drip and other forms of microirrigation were invented, which portended a drastic change in tree and vine irrigation. For the first time, growers had not only control of how much water was applied but could fully overcome the limitations of harsh topography. Furthermore, it was possible to apply water only to the areas near trees planted on uneven land, thus avoiding conveyance and evaporation losses from the zones not explored by tree roots. This was particularly important in the first years of the orchard when significant water savings could be achieved by using microirrigation. This benefit diminishes with time and as orchards approach maturity, and more ground area is shaded, evaporation losses become only a small component of consumptive water use. Nevertheless, if trees are widely spaced and the wetted soil areas are extensive and sunlit, surface evaporation can still be a significant part of orchard water use, as in the photograph in Figure 5.

Another significant advantage of microirrigation is its adaptability to large and small growers, and the simplicity of its management. The success of the drip method for orchard irrigation

BOX 1 Investment costs (US$/ha) of conventional and intensive irrigated orchards: an example.

Conventional Tree Spacing: 8 x 6 m equivalent to 208 tree/ha
Intensive Tree Spacing: 5 x 2 m, equivalent to 1 000 tree/ha

	208 tree/ha Costs (US$/ha)	1 000 tree/ha Costs (US$/ha)
Trees	505	2 438
Tutoring	169	810
Holes	1 685	8 100
Microirrigation system	3 650	13 740
Total	**6 009**	**25 078**

Costs (determined in Spain in 2010) are around four times higher for the intensive orchard in this case; however, benefits will also differ and it is possible that, in certain situations, the greater production in the first years and the higher productivity of intensive orchards may outweigh the costs.

FIGURE 2 Surface irrigation of pistachio trees.

FIGURE 3 Flood irrigation of citrus.

FIGURE 4 Vineyard on steep land under sprinkler irrigation.

FIGURE 5 Young avocado orchard planted on steep land under drip irrigation.

has been such that wherever farmers can afford to purchase such systems, they are very much preferred for use in new plantations worldwide. As with other permanent irrigation systems, the most important management issue is to determine the amount of water to apply, while the frequency of application is much less important. While irrigation is applied to meet the sum of transpiration loss from the leaves and evaporation from the soil surface, some losses normally take place in the process of irrigation, even though these should be relatively small with well-designed and managed microirrigation systems.

Efficient use of water in orchard irrigation

The key to efficient use of water for irrigation is to quantify the disposition of the water applied to a field. A schematic water balance for an orchard under microirrigation is shown in Figure 6, in which the various losses that occur during and after irrigation are shown. Efficient irrigation is achieved when most of the water applied is consumed as Tr and the losses in E, runoff and percolation are kept to a minimum. Traditionally, irrigation efficiency under surface irrigation was low and less than 50 percent of the applied water was used in ET. Precise land levelling and adequate management can raise efficiency values to 70 percent or more. Efficiency of microirrigation systems that are well designed, operated and maintained may reach 90 percent.

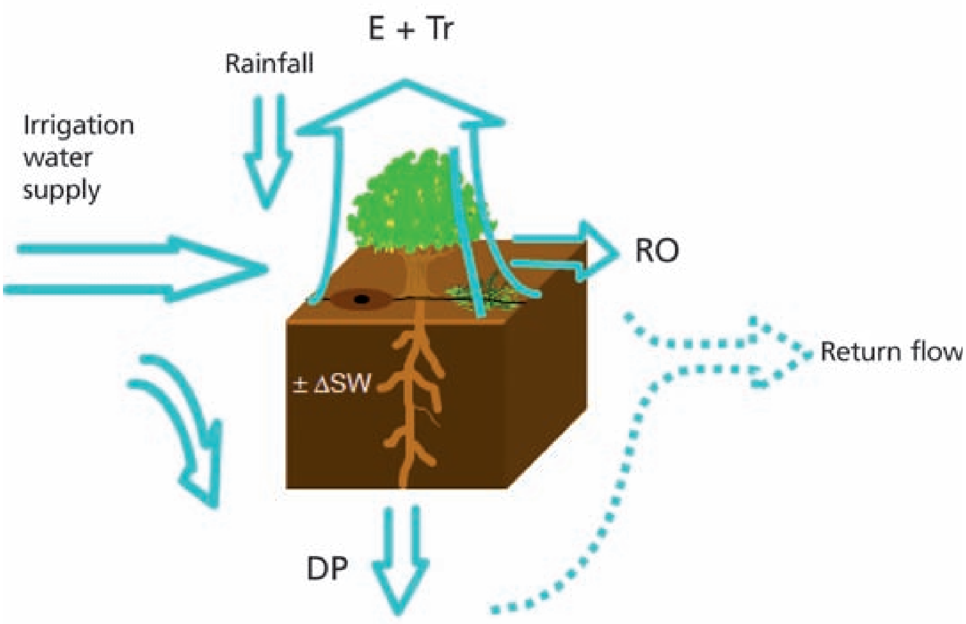
An important contribution of research to improving water management has been the establishment of the consumptive use requirements of crops. In the case of tree crops, because in many areas trees and vines were grown rainfed, the amount of irrigation traditionally used was insufficient to achieve maximum yields. As the accuracy of crop-water use estimates for tree crops improved and, with production intensification, the water requirements of tree crops have been increased. This change has led to greater irrigation water use but to increased production as well.

Worldwide, irrigation management decisions are based primarily on local experience, with very limited technical input. The main reason for the lack of adoption of the many technical procedures that now exist is the growers' perception that there is no need to improve on current practices. As irrigation methods improve and water becomes scarcer, this perception is changing and growers are beginning to see the need to be much more precise in the management of irrigation for orchards and vineyards. Increased governmental regulation, and even some legal decisions, can force the issue of improved irrigation management. The challenges that fruit tree and vine producers face to maximize their sustained productivity require: i) knowledge of the irrigation requirements to meet the full tree needs; ii) determining the irrigation schedule that will be best in terms of net profits, which may include a moderate reduction in applied water relative to the maximum needs determined in i) ; iii) tailoring that schedule to their own conditions and monitoring the tree response to the water applied, and iv) knowledge of the orchard response to a reduction in irrigation water below that needed for maximum net profits, which may be caused by regional droughts or other restrictions.

Water management under scarcity

Farmers that face irrigation supply restrictions must make decisions at the farm level by allocating the available supply to the various crops. The initial response to water scarcity is normally focused on *reducing irrigation system losses* thus improving irrigation efficiency (see Figure 6). This is achieved by improving existing or installing newer systems, such as

FIGURE 6 The water balance of an orchard showing the disposition of irrigation water. E: Evaporation from soil; Tr: Transpiration; RO: Runoff; DP: Deep percolation, and, ±SW: Changes in water content of the root zone. Note that irrigation system losses in RO and DP may be recovered if the return flows are used elsewhere.



microirrigation, that have high potential application efficiency. Also, *technical irrigation scheduling* procedures that match water applications close to the water-use rates, are used more often when irrigation water is scarce. However, there are practical limits to reducing water losses associated with irrigation. Once these losses are nearly eliminated, further reductions in water supply will unavoidably result in crop-water deficits. When this occurs, it is important to understand the species-specific physiological responses to water deficits.

Water deficits that reduce plant transpiration also decrease the production of biomass in all crops. If the crop is being grown for its biomass, such as alfalfa or corn silage, there will be a reduction in farmers' income. For the main annual crops such as wheat, maize, and rice, a reduction in transpiration also decreases grain yield and gross income. However, for many tree crops and vines (and for some annual crops, such as cotton) where the fruit is the economic product, a reduction in biomass production does not always result in a parallel reduction in fruit production. Nevertheless, some quality parameters, such as fruit size or appearance, may be negatively affected.

The other distinctive feature of the response of perennial crops to water deficits is the carryover effects of water deficits that affect production in subsequent years. It is not known if the longevity of plantations may be affected by long-term water deficits; in some species, such as peach or some citrus, shorter longevity may not be too important, as new cultivars with better market opportunities are replacing older ones well ahead of full orchard maturity. In other species, however, it may have important economic consequences that must be considered.

Further, there may be cases of water deficits having beneficial effects on the production of trees and vines. It has long been known that fruit from trees grown under water deficits tasted better than those from fully irrigated trees. Much research in recent years has shown that water deficits affect many fruit quality features, and that they can also positively impact on the quality of products derived from fruit juices, such as wine. Therefore, in addition to saving water, there may be other incentives to applying and managing water stress in perennial crops in terms of improving product quality and growers' revenues.

EVAPOTRANSPIRATION AND IRRIGATION REQUIREMENTS OF FRUIT TREES AND VINES

Background

Water evaporates from soils (E) and from inside plant leaves, a process that is called transpiration (Tr). The sum of evaporation from soil and plant transpiration (Box 2) from a field is termed evapotranspiration (ET; Figure 6) and is equivalent to the consumptive water use of that field. Evaporation of water requires energy that is provided by solar radiation, the primary energy source and the driving force for the ET process. The ET is the result of the interception of solar radiation by the wet soil surfaces and by the vegetation. Other meteorological factors that influence the rate of ET are temperature, humidity and wind.

Because the ET process is complex, very dynamic and is affected by local environmental conditions, researchers have developed equations to estimate ET using meteorological parameters. The FAO Penman-Monteith equation, currently accepted worldwide as the standard method, calculates the water loss from a theoretical grass surface that fully shades the ground and is never short of water, providing the reference ET (ET_o). The procedures to calculate ET_o from radiation, wind, humidity and temperature data are presented in the FAO *I&D No. 56*. The ET_o is a measure of the evaporative demand of a given environment. There are many other methods to calculate ET_o, some of them use temperature data only and are useful in locations where other climatic data are not available. In any case, they should not be used unless there is insufficient information to calculate ET_o with the FAO Penman-Monteith equation.

The ET_o provides a reference that is useful for calculating the maximum ET (ET_c) from any given crop. Past research has generated information on the ratio between ET and ET_o, defined as a crop coefficient, K_c. Thus, if K_c is known, the ET_c is calculated as:

$$ET_c = K_c \, ET_o \tag{1}$$

This is the standard procedure for estimating the crop consumptive use requirements as shown in FAO *I&D No. 56*, where a list of K_c values for each crop and developmental stage is provided. This K_c approach may also be used to obtain the ET_c for the various tree crops and vines, as shown below.

The FAO *I&D No. 56* publication also offers the option of differentiating E from Tr by using a dual crop coefficient approach, according to the equation:

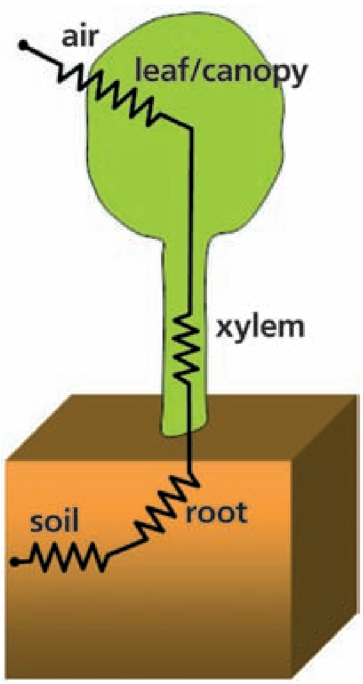
$$ET_c = (K_{cb} + K_e) \, ET_o \tag{2}$$

Where K_{cb} is a transpiration coefficient and K_e is an evaporation coefficient.

BOX 2 Understanding the transpiration process.

Water loss from plant leaves takes place primarily through pores called stomata that are opened during daylight hours and close at night. Stomata are also the path for the entrance of carbon dioxide into the leaves, the necessary input for photosynthesis. Transpiration losses from leaves trigger a sequence of events in the soil tree system; water moves from the shoots into the leaves to compensate for leaf losses, drawing water from the trunk into the shoots; this in turn, draws water from the roots to the trunk, and finally, from the soil to the roots. Thus, liquid water flows from the soil to the sites in the leaves where it evaporates before diffusing through the stomata to the atmosphere. Water moves passively through this path following a gradient in potential energy, from the soil to the leaves. In any location along this path, such energy level may be determined and is called water potential. Furthermore, the water flow encounters resistance all along the pathway from the soil to the atmosphere (see diagram). The tree exerts some control on this water flow, which is needed to match the transpirational loss to the evaporative demand of the environment. When there are imbalances between supply and demand, the tree controls its water loss through the adjustment of the degree of stomatal opening and by other means.

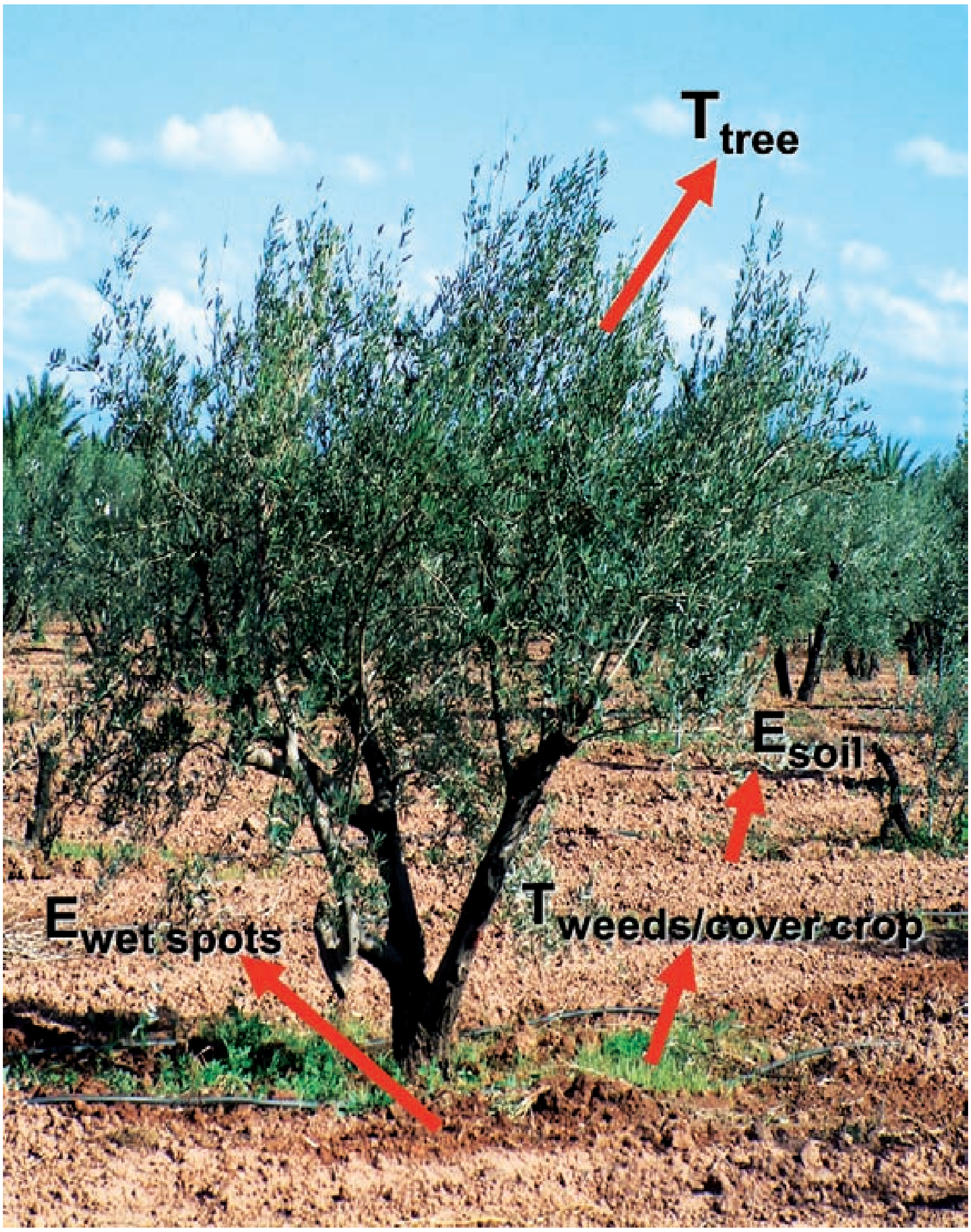
The water flow from soil through tree to the atmosphere.



The orchard ET process

The ET_c from an orchard is more complex than from a uniform herbaceous crop because there are different components that contribute to the water loss from an orchard. In addition to tree Tr, there could be Tr losses from a cover crop or from weeds, and there are E losses from the soil. In the case of microirrigation, there are two E components that may differ in their rates: one is the E from the soil areas wetted by the emitters, and the other is the E from the rest of the soil surface which is only wetted by rainfall. Figure 7 shows the four different components of water vapour that contribute to orchard ET and are further explained below.

FIGURE 7 The evapotranspiration process from an orchard under microirrigation.

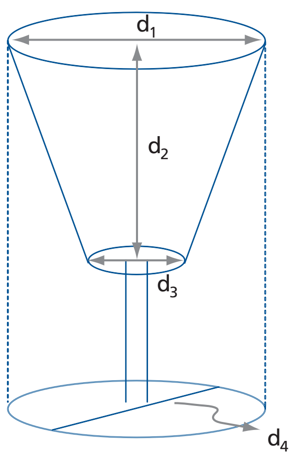


Orchard transpiration

Tree Tr is determined by the amount of radiation intercepted by the tree canopy and by the behaviour of stomata. The degree of stomatal aperture is influenced by the climate drivers mentioned before: radiation, temperature, humidity and wind. The stomatal behaviour of tree leaves is complex; it reflects a trade-off between maximizing the uptake of carbon dioxide and minimizing Tr loss, and is affected not only by environmental, but by internal tree factors as well. While individual leaf Tr depends on its stomatal conductance and on the environment around it, tree Tr depends on the number and behaviour of all individual leaves and on their disposition in relation to the incoming radiation. The integration of the conductance of individual leaves over the whole tree canopy, yields the canopy conductance, a useful concept to understand the Tr process. In herbaceous crops, the canopy may be considered as a 'big leaf'; for trees and vines, while the canopies are more complex because of their three dimensional nature and the gaps between individual trees, the concept of canopy conductance is also valid to represent the behaviour of the whole tree. It is important to characterize canopy size because it determines the amount of solar radiation that is intercepted, which is directly related to Tr. Box 3 shows how to estimate some parameters that relate to canopy size.

BOX 3 How to characterize the size of tree canopies.

Tree canopies may be characterized using two parameters: canopy volume (m^3 of tree volume/m^2 of ground surface) and leaf area density (m^2 of leaf area /m^3 of tree volume). The first one may be estimated easily with a measuring rod once the tree shape has been approximated as a sphere, an ellipsoid, or a truncated inverted cone. However, the second parameter is much more difficult to assess and requires specialized instruments. As an alternative to the measurements or calculations of the radiation actually intercepted by the tree, a simple parameter that is easy to determine is the degree of ground cover. The ground cover (normally expressed in percentage) is obtained by measuring the shaded area outlined from the horizontal projection of the tree canopy (See Figure below).



Percent Ground Cover

$$\text{Shaded area} = A = \frac{\pi d_4^2}{4}\ (m^2)$$

$$\text{Percent Ground Cover} = \frac{A}{\text{tree spacing}}$$

Example:

Shaded area diameter = d_4 = 1.5 m

Tree spacing= 5 x 2 m

A = 1.77 m^2

Percent Ground cover = A x 10 = 17.7%

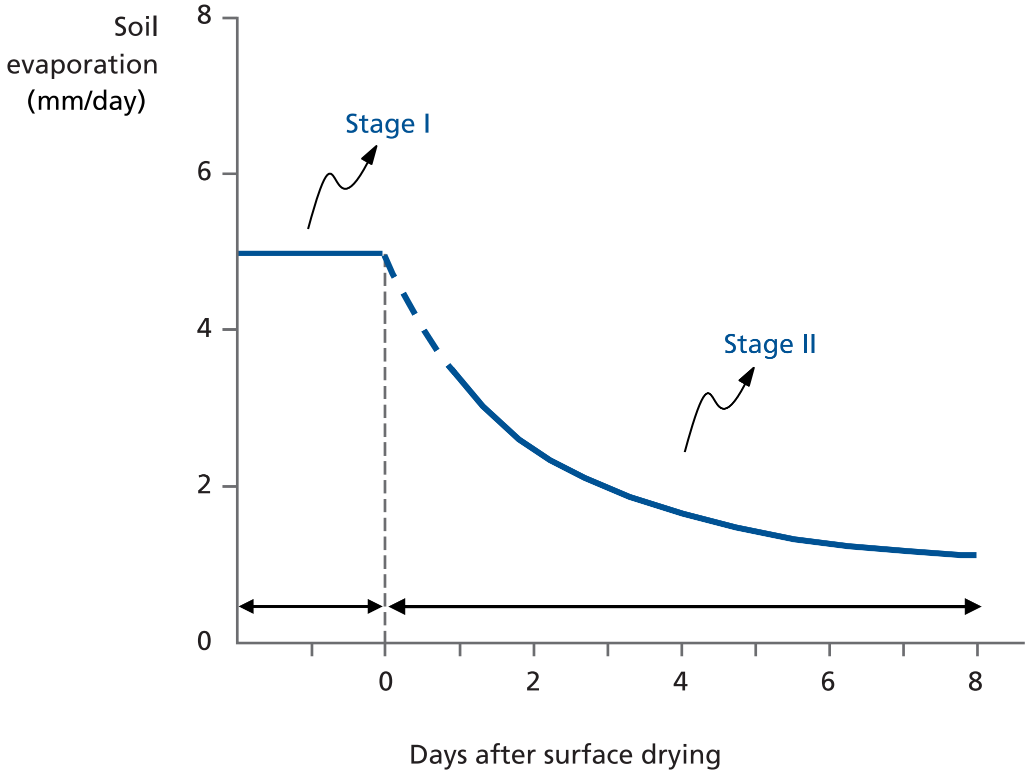
$$\textbf{Canopy Volume:}\ \frac{1}{3}\,\pi\, d_2\left(\frac{d_1^2}{4}+\frac{d_3^2}{4}+d_1 d_3\right)$$

Canopy size and stomatal conductance are the two main parameters determining tree Tr. When orchards and vineyards approach maturity, they intercept much of the incoming radiation, although for most species the horizontal projection of their canopies seldom covers more than 70-75 percent of the ground. This is because their growth is often controlled by pruning to allow mechanization and to achieve a more even distribution of direct solar radiation to fruiting branches. For the same level of intercepted radiation, tree Tr differs among species depending on their growth habit (evergreen vs. deciduous), canopy size and architecture, developmental stage, and on their stomatal behaviour. Therefore, the models needed for calculating Tr in different orchards as a function of the size and conductance of the tree canopy must be specific for each tree species.

Orchard evaporation

The process of evaporation from soil comprises two stages, as presented in detail in Chapter 3 of the *Aquacrop Reference Manual*. First, after the soil is wetted by rain or irrigation, E from soil takes place at a constant rate and is limited only by the incoming radiation (Figure 8). The first stage continues until the surface dries to a level such that the soil surface layers restrict the E loss. This point marks the beginning of the second stage when E declines more or less exponentially with time. A certain amount of water must be evaporated before E starts to decline (Stage II), and this amount is constant for a given soil, varying from about 5 mm in sandy soils up to 10 mm in clay loam soils. In the declining E rate period, cumulative E can be expressed as a function of the square root of time or as a function of soil-water content in the uppermost soil layers.

FIGURE 8 The process of evaporation from the soil.



The model *AquaCrop* computes E for the two stages according to the equations:

(3)

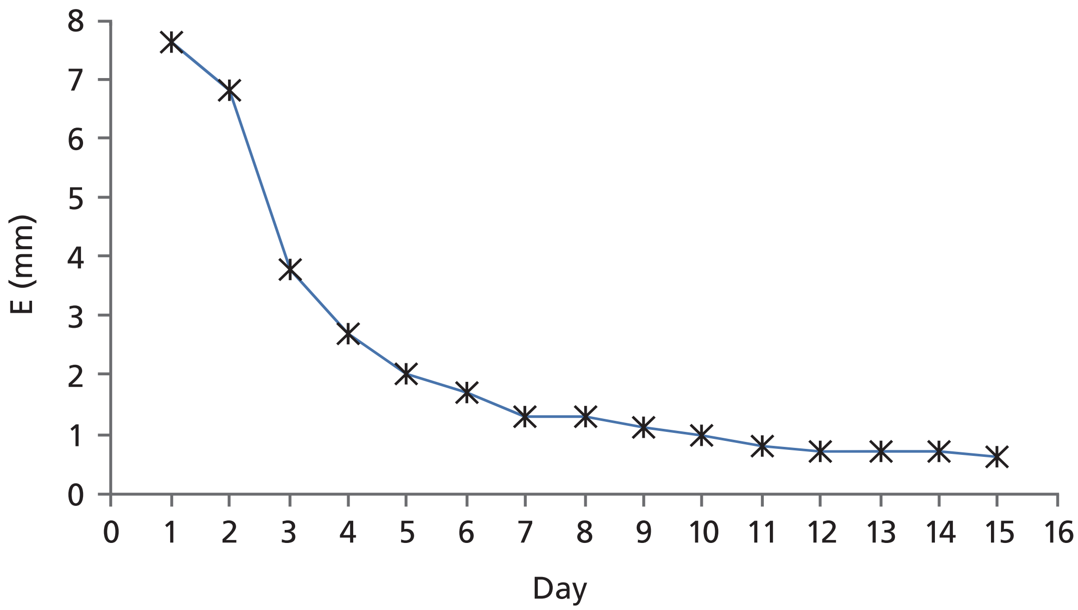
$$E_{Stage\ I}=(1\text{-}CC^{*})Ke_{x}ET_{o}$$

$$E_{Stage\ II}=Kr(1\text{-}CC^{*})Ke_{x}ET_{o}$$

Where, CC is canopy cover, (1-CC*) is the non-shaded, exposed soil from which evaporation takes place, corrected with an advection coefficient; Ke_x is a coefficient set at 1.1, and Kr is a reduction coefficient, which is calculated as a function of the soil-water content of the upper soil surface layers.

Figure 9 shows a calculation of bare soil evaporation using the *AquaCrop* model for a period of 15 days after a thorough irrigation.

FIGURE 9 Evaporation from bare soil in midsummer calculated with the *AquaCrop* model following 60 mm irrigation.



The major complication in computing E from an orchard or vineyard is that the soil is partially and dynamically shaded by the crop canopy, and even if the surface is wet, E is limited by the incoming energy.

The spatial variation of incoming energy within the orchard floor depends on tree spacing, canopy size and architecture and on the leaf area density. Some models have been developed to compute E under orchards and they can be used to compute E from soil that is wetted by either rainfall or by full coverage irrigation.

With microirrigation, there are spatial variations in the degree of wetting within the orchard, as some areas are frequently wetted by the emitters while the rest of the soil surface remains dry in the absence of rainfall. Because the drip lines are placed near the trees, the wet areas are generally shaded by the crop canopy, although they are wetted frequently enough to be considered to have radiation-limited E. Measurements and models suggest that the E from the soil areas in orchards, which are wetted frequently (every 1-2 days) by the emitters is equivalent to about 60 percent of the ET_o from the wet areas, as a first approximation. More accurate quantification of the E from the wetted spots in a drip-irrigated orchard is available using a semi-empirical model (Bonachela, 2001).

Orchard evapotranspiration

Gross irrigation requirements have two components: orchard ET, which is considered the net irrigation requirement, and inefficiency losses, as discussed in the next section. In well-managed irrigation, ET is the major component of the irrigation requirements and losses are small. Orchard ET may be calculated using crop coefficients and ET_o, or by estimating its individual components, namely transpiration and evaporation from soil. Crop coefficients are used when lack of data, particularly tree transpiration, precludes the application of the component approach.

(A) CALCULATING ET_c FROM ITS COMPONENTS

Based on Figure 7, orchard or vineyard ET may be calculated as the sum of four components:

$$ET_c = Tr + Tr_{cc} + E_{wz} + E_{dz} \quad (4)$$

Where:

Tr is tree transpiration

Tr_{cc} is cover crop (or actively growing weeds) transpiration

E_{wz} is surface evaporation from the soil wetted by the emitters, and

E_{dz} is surface evaporation from the rest of the soil surface outside the emitter wetting pattern.

This method needs to estimate the four ET_c components and is not yet widely used. However, as there are now methods available to measure tree Tr independently of ET_c, it will become the standard method in the future when the models used for estimation of the ET_c components, such as the one presented here (Testi *et al.*, 2006) will be thoroughly tested. (See Box 4 for sample calculations).

Calculation of E_{dz} using an empirical model

The following equation, derived from research on an olive orchard ET (Testi *et al.*, 2006; Orgaz *et al.*, 2006), for estimating the average monthly value is proposed:

$$E_{dz} = K_{s,e}\, ET_o \text{ (mm/day)} \quad (5)$$

$$K_{s,e} = [0.28-0.18\, G -0.03\, ET_o + (3.8\, F\, (1-F))/ET_o)]\, (1-wz) \quad (6)$$

Where, G is the ground cover fraction of the tree canopy, F is the monthly frequency of rainy days, and wz is the fraction of the soil surface wetted by the emitters.

BOX 4 Sample calculation of E_{dz}, E_{wz}, and Tr_{cc}.

Assume an olive orchard with a tree ground cover, G, of 0.33; the average monthly ET_o in April is 3.5 mm/day; the emitters wet 7 percent of the ground (wz=0.07), and there are 7 rainy days per month (F=7/30 = 0.23).

a) Calculation of E from soil not wetted by emitters, E_{dz},

Using Equation 5 and 6, the average E_{dz} for the month of April is:

$K_{s,e}$ = 0.31 x (1-0.07) = 0.29
E_{dz} = 0. 29 x 3.5 = 1.01 mm/day or 30.4 mm/month

b) Calculation of E from wet spots E_{wz}
Equation 8 yields:

E_{wz} = 0.6 x 3.5 x 0.07 = 0.147 mm/day or 4.4 mm/month

c) Calculation of cover crop Tr_{cc},
If the olive orchard with 8 x 6 m tree spacing, has a cover crop that covers a strip 4 m wide every tree row (f_{cc} = 4/8), and is fairly dense and kept cut about 5-8 cm height, the water use of the cover crop would be estimated as:

Tr_{cc} = 0.45 x 3.5 mm/day x 0.5 = 0.79 mm/day or 23.6 mm for the month of April

Calculation of E_{wz}
Here, as a first approximation, E_{wz} is calculated as

$$E_{wz} = 0.6\ ET_o\ wz \qquad (7)$$

Where 0.6 is an empirical factor described above and wz is the fraction of the soil surface that is kept wet by the emitters.

Calculation of transpiration from the cover crop, Tr_{cc}
Orchards with cover crops have higher ET rates than orchards that are clean cultivated. The water-use rate of cover crops in orchards is difficult to measure and has not been thoroughly investigated. Either cover crops are planted in strips of variable width between tree rows or, sometimes, weeds are allowed to grow in these areas and are controlled periodically by cutting or with herbicides. Cover crops are shaded at least part of the day, and it is difficult to measure their ET independently of the other ET_c components. The Tr_{cc} will vary widely, depending on the cutting frequency, plant density, degree of shading by the tree canopies, and whether it has sufficient water available, i.e. whether the cover crop is fully wetted by the irrigation applications. Thus, the estimation of Tr_{cc} is site specific. The approach to calculate it uses a coefficient, K_{cc} and the ET_o as follows:

(8) $$Tr_{cc} = K_{cc}\ ET_o\ f_{cc}$$

Where, f_{cc} is the fraction of the orchard ground surface occupied by the cover crop, and K_{cc} is a cover crop coefficient that varies from 0.25-0.35 for sparse vegetation, to 0.4-0.5 for fairly dense, short (less than 10 cm) cover crops, up to 0.6-0.8 for dense cover crops.

Calculation of tree transpiration Tr

The approach here is to use a transpiration coefficient ($K_{c,Tr}$) which multiplied by the ET_o would yield the Tr.

$$Tr = K_{c,Tr}\ ET_o$$

The different crop sections offer information that could be used to derive the $K_{c,Tr}$ values; although for many species the information that exists is not sufficiently accurate to generalize the values. There are several factors that affect the seasonal $K_{c,Tr}$ values of mature orchards or vineyards well supplied with water. In addition to the level of intercepted radiation, whether the species is deciduous or evergreen, the stomatal responses to the environment, the presence or absence of fruit, are factors that influence the $K_{c,Tr}$, and even some cultivar differences within a species have been described.

The $K_{c,Tr}$ values of mature deciduous orchards vary from nearly zero at bud break to a maximum value after leaf growth is sufficient to intercept all incoming radiation. The maximum value (which varies between 0.75 and 1.0) is maintained throughout the rest of the season until leaf senescence starts, provided the tree is supplied with sufficient water. Fruit harvest decreases temporarily the value of the maximum transpiration coefficient ($K_{c,Trx}$), down to a level that is species dependent, but the $K_{c,Tr}$ usually recovers two to three weeks after harvest. Figure 10 shows a typical seasonal pattern of the crop coefficient for apple (obtained in a drip-irrigated lysimeter, thus including the E component of ET_c), and similar information for other crops may be found in the various specific sections.

In the case of evergreen fruit trees, the two major evergreen tree crop species are citrus and olive. Citrus trees have $K_{c,Trx}$ values that depend on air humidity levels; in dry climates mature orchard $K_{c,Tr}$ values vary within the season between 0.6 and 0.7, while in humid areas it oscillates between 0.7-0.85. Olive $K_{c,Tr}$ values also vary within the season and are affected by climatic conditions. In temperate, semi-arid climates, it has a minimum of about 0.4 in spring, about 0.5 in the summer and may reach 0.6-0.65 in the autumn. A model to compute $K_{c,Tr}$ and Tr for olive trees has been developed (Testi *et al.*, 2006 and Orgaz *et al.*, 2006), and is briefly described in Box 5. Similar models are now being developed for other fruit tree species and will be available soon.

BOX 5 Computing olive tree transpiration independently of the other ET components.

After E is calculated following the methods described above in Box 4, tree transpiration, Tr (mm), may be calculated as the product of the intercepted radiation by the tree and two factors (F_1 and F_2) which are related to canopy conductance. These factors were calibrated and tested for olive in a Mediterranean environment (Testi *et al.*, 2006 and Orgaz *et al.*, 2006). The method has also been tested in an arid environment in Argentina and in other Mediterranean-type environments.

$$Tr = ET_o \, K_{c,Tr}$$

Where, $K_{c,Tr}$ is a transpiration coefficient calculated as:

$$K_{c,Tr} = (Q_d \, F_1) \, F_2$$

Where, Q_d is the intercepted radiation by the tree (fraction), calculated as:

$$Q_d = 1 - e^{-K_{ext} \, V_u}$$

Where,

$$K_{ext} = 0.52 + 0.00079 \, d_p - 0.76 \, e - 1.25 \, DAF,$$

$$DAF = 2 - 0.53 \, (Vu - 0.5); \text{ (Note: DAF must be} < 2),$$

$$V_u = V_o \, (d_p/10\,000), \text{ and,}$$

$$V_o = 1/6 \, \pi \, D^2 \, H$$

Symbols:

Tr : Tree Transpiration (mm)
ET_o: Reference evapotranspiration (mm)
$K_{c,Tr}$: Transpiration coefficient
F_1 : Depends on tree density; $F_1 = 0.72$ for tree densities of < 250 tree/ha and $F_1 = 0.66$ for tree densities > 250 tree/ha.
F_2 : Monthly coefficient from Table below
K_{ext}: Radiation extinction coefficient
d_p : Tree density (tree/ha)
DAF: Leaf area density
V_u : Canopy volume per unit ground surface (m^3/m^2)
V_o : Canopy volume (m^3/tree)
D : Canopy average diameter (m)
H : Canopy height (m)
e: Exponent (2.718)

BOX 5 (CONTINUED)

F_2 VALUES (Northern Hemisphere)

Month	F_2
January	0.70
February	0.75
March	0.80
April	0.90
May	1.05
June	1.25
July	1.25
August	1.20
September	1.10
October	1.20
November	1.10
December	0.70

(B) CALCULATING EVAPOTRANSPIRATION WITH THE K_c METHOD

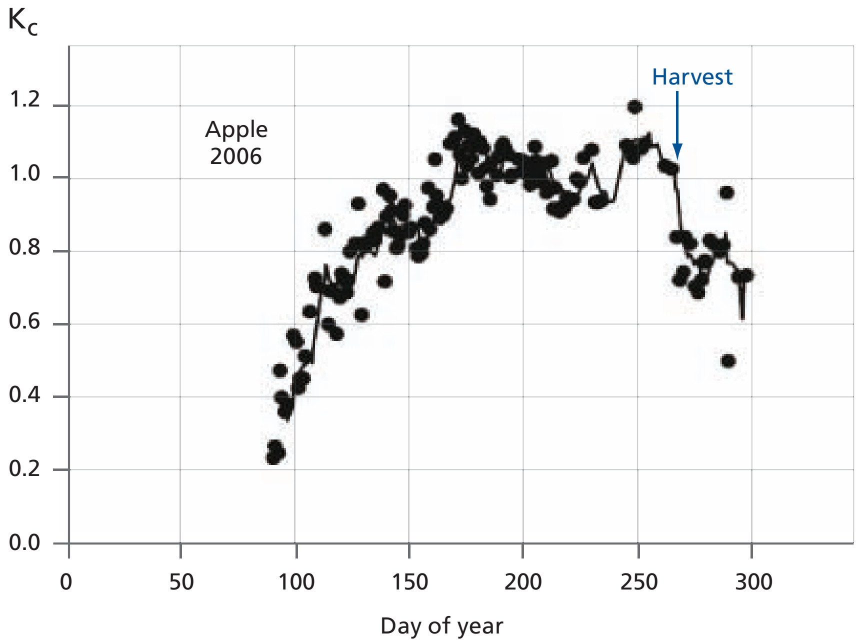
If it is not possible to calculate Tr separately, what is needed is an overall crop coefficient (K_c) that embodies all the components of ET_c. The FAO *I&D No. 56* provides the K_c values for tree crops and vines, derived from the original values published in FAO *I&D No. 24*. The different crop sections in this publication provide sets of K_c values for the different tree crops and vines, which are an update of those published earlier in FAO *I&D No. 56*.

As shown in Figure 10, the crop coefficient (K_c) for deciduous orchards on bare soil, increases sharply in spring in response to bud break and leafout until it reaches a maximum in early summer. The peak K_c value is maintained until harvest, after which it declines temporarily for some tree crops. In others, the maximum K_c stays more or less the same until the beginning of senescence, when it starts to decline until leaf fall is complete. For evergreen trees, there may be variations in K_c within the season, caused by changes in leaf area, and by responses either to environmental changes or to internal tree signals. It should be emphasized that the standard K_c values include an average E component but do not include the Tr_{cc} from cover crops, unless specifically stated.

Determining the ET of partial tree canopies

When information exists to compute ET_c as the sum of its components (Equation 4), the same procedure may be applied to non-mature, developing orchards where trees have not yet achieved their mature size. It suffices to measure the canopy parameters that characterize the radiation intercepted by the young trees and to compute the Tr, using a method such as the one in Box 5. The standard K_c procedure described above specifically applies to

FIGURE 10 Crop coefficient (K_c) curve determined for a mature, drip-irrigated, apple orchard with a weighing lysimeter in 2006, at Lleida, Spain. Note that the decline in K_c after harvest occurs close to the onset of leaf senescence in apple trees.



mature trees that have reached their maximum size. In intensive production systems, this is equivalent to attaining a percent ground cover (horizontal projection) of no more than 70-80 percent; maximum ground cover values are generally dictated by harvesting and other orchard mechanized operations. Mature traditional orchards and vineyards generally have lower ground cover values, although such values can be over 80 percent in a few species, such as walnuts or table grapes.

To schedule irrigation for developing plantations or in sparsely planted orchards, as is the case in traditional plantations under limited water supply, it is necessary to relate the ET of a young orchard to that of a mature orchard, for which the K_c values were developed. If the K_c approach is used, a new coefficient is needed to compute ET as:

(9)
$$ET_c = ET_o \, K_c \, K_{r,t}$$

Where, $K_{r,t}$ is an empirical coefficient relating the ET of an orchard of incomplete cover to that of a mature orchard. Here, the $K_{r,t}$ is related to the horizontal projection of the tree shade (ground cover).

Figure 11 shows the relation between percent ground cover and percent ET of a mature orchard, based on an original one obtained experimentally for almond trees (Fereres *et al.*, 1982) and adjusted with data from experiments on several tree species. Box 6 shows two examples on how to calculate the ET of immature tree canopies of different sizes. The tree canopy parameter used in the equation in Figure 11, is the horizontal projection of the canopy, without correcting for differences in leaf area density that could leave gaps within the tree shade. Note that this relationship has been developed for tree canopies of various shapes but all of them formed as isolated trees, with some sort of spherical or conical shape.

BOX 6 Examples for determining ET of canopies with partial cover.

The relationship shown in Figure 11 may be approximated between 0 and 70 percent ground cover (G%) using the equation:

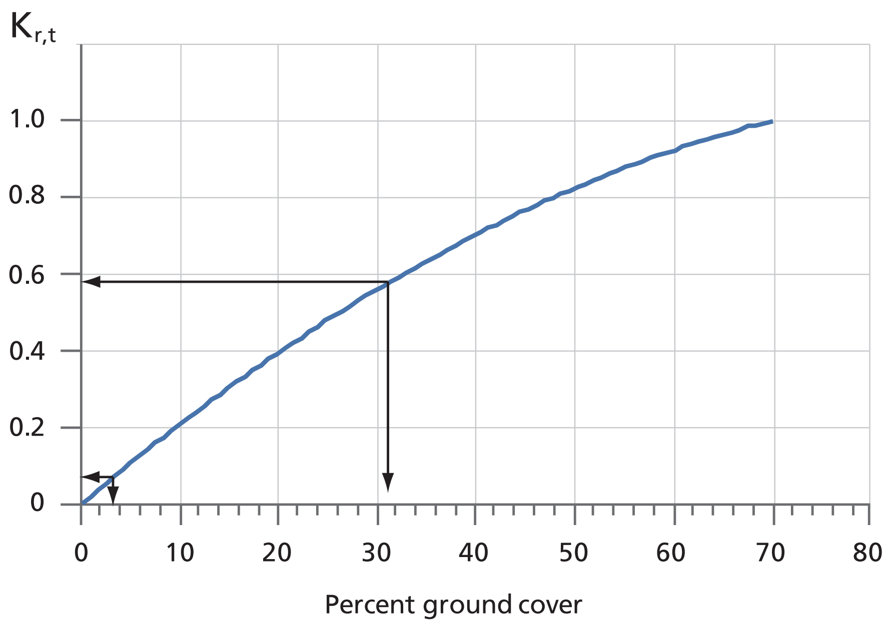
$$K_{r,t} = -0.00012\ (G\%)^2 + 0.0226\ (G\%) \qquad (10)$$

The two examples below refer to citrus and almond trees where the average horizontal projection of the tree canopy has diameters of 2.8 and 1.2 m, respectively.

	Diameter (m)	Tree spacing (m)	% Ground cover	$K_{r,t}$	ET_o (mm/day)	K_c	ET_c[1] (mm/day)
Example citrus	2.8	5 x 4	30.8	0.58	5.0	0.70	2.03
Example almond	1.2	7 x 6	2.7	0.06	7.4	1.05	0.47

[1] $ET_c = ET_o\ K_c\ K_{r,t}$

FIGURE 11 Relationship between tree horizontal projection at midday (Percent ground cover) and the reduction coefficient, $K_{r,t}$, relating the ET of orchards with partial cover to that of mature, full cover plantations formed by isolated trees (for hedgerows, see Apple Section).



For training systems on a vertical plane, such as many trellis systems used for winegrapes, pears and apples, a different relation from that of Figure 11 between percent ground cover or intercepted radiation at noon and percent of ET would apply. This is because, as these canopies expand, they grow vertically with little increase in percent ground cover or noon intercepted radiation but their Tr increases nevertheless. This is because of the vertical growth (wall) intercepting more radiation in the morning and afternoon and also to more advective energy transfer to the trellis rows. The apple and pear Sections describe specific relations between intercepted radiation and percent mature ET for such crops, which should be used for hedgerows and other types of canopies.

Another aspect specific to young plantations is that their canopies grow and expand as time advances until close to leaf fall. Therefore, the seasonal evolution of K_c is different in young orchards than in mature orchards. Thus, estimates of ground cover should be updated on a monthly or bimonthly basis in young orchards/vineyards to adjust the estimation of ET and the resulting irrigation rates.

Variations in the E and Tr of orchards and vineyards

Site specificity affects the ET_c of orchards and vineyards more than that of herbaceous crops. In perennial crops, tree or vine canopy size and leaf area density determine the Tr rate, while rainfall and irrigation frequency determine the E rate. In arboriculture, canopy size may be manipulated by pruning, and hence Tr can vary depending on pruning practices. In intensive production systems, however, pruning is kept to a minimum and Tr is not subjected to wide year-to-year variations, other than those caused by changes in evaporative demand or by internal tree controls, often related to crop load.

The E losses from an orchard or vineyard are somewhat easier to manipulate. Evaporation from soil is minimized when irrigation applications are as infrequent as possible (without causing tree-water deficits). If trees have small canopies and a significant fraction of the soil is exposed to direct solar radiation, E can be an important ET component, in particular if the irrigation method wets a significant portion of the soil surface. In these cases, irrigation frequency should be managed to minimize E loss. Under microirrigation, E losses are comparatively much less, because the wetted areas of soil are smaller and normally located under the canopy shade. Nevertheless, high (daily) irrigation frequency is common for drip systems, and the areas wetted by the emitters always stay wet. If the number of emitters per tree is high and the wetted areas are exposed, significant E losses may occur from these spots. In situations where water is in short supply, microirrigation frequency should be decreased to the longest interval compatible with having an optimal soil water regime, such as a week or even more in extreme cases of very low supply. In these cases, subsurface drip systems that eliminate E from irrigation applications should be considered.

Since Tr and E, do not occur independently, it is important to understand their interactions that are related to the energy balance of the orchard. Adjective energy transfer from the hot, dry soil surfaces in the rows towards the trees will increase Tr. On the other hand, Tr will decrease when E is high following an irrigation or rain. These interactions have not been fully documented, and thus, cannot be included in current procedures for calculating orchard or vineyard ET. However, they need to be considered at least qualitatively.

Determining irrigation requirements

There are a number of losses from irrigated agriculture, often unavoidable, associated with the application of irrigation water that the grower must consider when determining the actual water requirements of an orchard or vineyard. It should be noted that in this context, the term 'losses' does not apply to E and Tr, which are consumptive uses of water rather than losses.

Until now, when determining the ET_c, a situation has been considered in which the calculation applies to an ideal, uniform orchard with all the trees having the same ET_c. However, the uniformity of irrigation water application over a field is not perfect and some areas get more water than others. To adequately irrigate areas that get less, the system must apply more water than required to meet the overall needs of the field. Thus, some areas of the field will receive water in excess of ET and this can result in the deep percolation (loss) of water below the root zone. Additionally, some irrigation water may inadvertently run off the field and this is also considered a loss, at least for that particular field.

Whether deep percolation and runoff are true losses depend on the scale under consideration (field, farm, district, basin), and whether any or all of these losses can be recovered. For example, if runoff from one field is collected and then applied to the same or an adjacent field, it is not a true loss. The same applies to deep percolation that enters a groundwater table and is eventually pumped and reused, although its quality may be degraded. If water enters a saline sink, such as a perched saline water table or the ultimate saline sink, the ocean, it is a true loss.

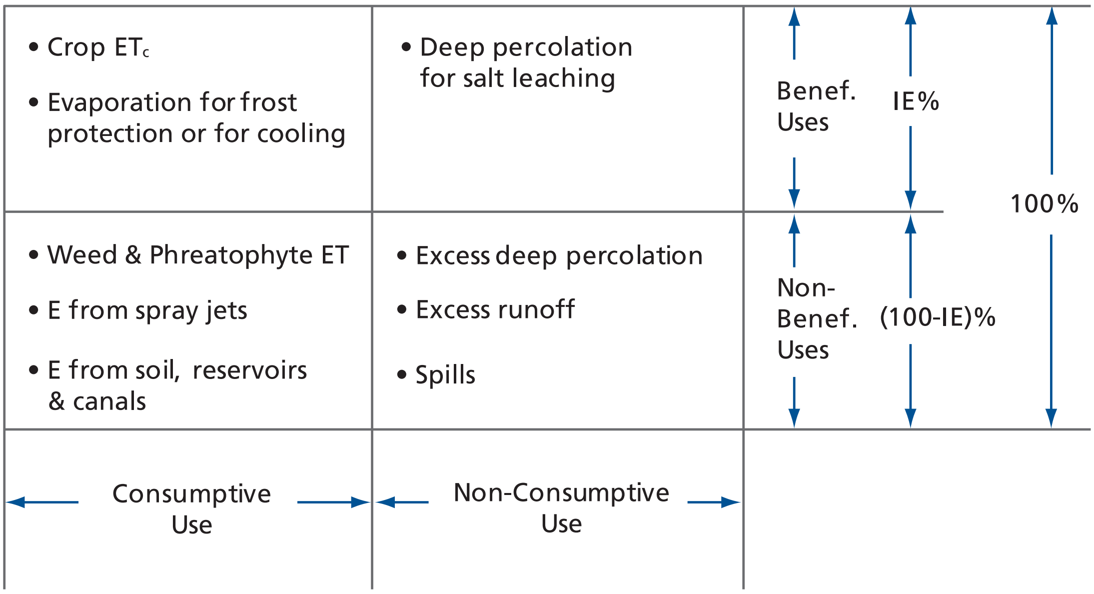
To maintain a favourable salt balance, some deep percolation of water is needed to transport the salt introduced by the irrigation water out of the root zone. The amount of deep percolation required is referred to as the 'leaching fraction' and depends on irrigation water quality as well as the crop sensitivity to salinity. Methods have been established to estimate appropriate leaching fractions and can be obtained in FAO *I&D No. 29*. Leaching of excess salts is a requisite for the sustainabiliy of irrigated agriculture.

Application efficiency is used to express irrigation efficacy and is described as the percentage of applied water that is available for tree use. Variations depend on the irrigation system and skill of the irrigator and on whether an individual field, series of fields, entire farm or region is considered. The chart in Box 7 indicates the disposition of irrigation water into consumptive and non-consumptive uses, and into beneficial and non-beneficial uses. It is important for the grower to understand that some irrigation losses are unavoidable, but that they should be minimized.

For the grower, it is important to have high application efficiency and as good distribution uniformity of applied water as possible. Distribution uniformity (DU) for surface and sprinkler irrigation methods applied to systems operating with trees and vines can be determined using farm-system evaluation techniques. With microirrigation systems, it is relatively easy to measure DU by checking either emitter flow rates or operating pressures throughout the system. In orchards or vineyards under microirrigation, it is possible to attain DU values of 80 to 90 percent and thus, equally high application efficiencies if the systems are well designed, maintained and managed.

BOX 7 Consumptive and non-consumptive uses of water.

Water may be used beneficially for irrigation if used considering ET_c for salt leaching or for frost protection. Irrigation efficiency (IE) is the ratio of beneficial to non-beneficial uses of water. Also shown are the various consumptive and non-consumptive uses of water.



Box 8 illustrates how the distribution of irrigation water varies in different parts of the field; in some, it exceeds the required depth, while in others it is less than required. The shaded area indicates the degree of deficit in the field. This deficit could be reduced or even eliminated by applying a gross irrigation depth in excess of that required, leading to more deep percolation losses. Systems with high DU have water distribution lines in the Figure of Box 8 that are close to horizontal, with little water excess and deficit, while lower DU values cause the line to be steeper (more variation among sites within the field) and hence there will be greater losses and deficits in the field.

In order to calculate the gross irrigation requirement (GIR) of an orchard or vineyard, the computed ET_c, which is considered as the net irrigation requirement (NIR), should be divided by the application efficiency (AE), as:

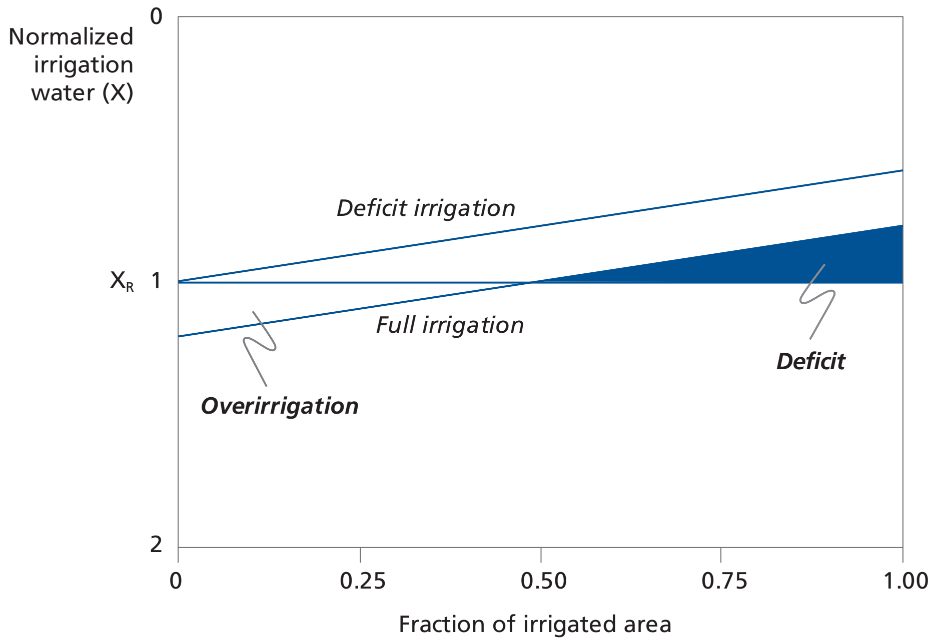
$$GIR = NIR / AE \quad (11)$$

Where AE is expressed as a fraction.

This effectively increases the net irrigation amount by an amount determined by the application efficiency. For example, an application efficiency of 80 percent requires that 20 percent more water than the ET_c is applied to the field. Knowing the system application efficiency is just as important as knowing the ET_c when calculating irrigation requirements. It would be useless to devote effort to calculate precisely calculating the ET_c and then not pay attention to the actual delivery process to the field and the degree of uniformity of the irrigation system.

BOX 8 Spatial relation between the distribution of water over a field and its area.

The Figure shows a simplified diagram of the spatial distribution of irrigation depth, X, as a function of fractional irrigated area. The two straight lines represent the hypothetical relationships between the depth of water applied (X, normalized with respect to the required depth to refill the soil water deficit prior to irrigation) as a function of the fraction of the irrigated area. The two inclined lines represent the distribution of water for full and for deficit irrigation. Note that under full irrigation, 50 percent of the area receives water in excess of the required depth, X_R, needed to refill the root zone. The slope of the line represents the degree of uniformity; the steeper the slope, the less uniform the irrigation application would be.



Periodic monitoring of irrigation uniformity is an important component of a good irrigation maintenance programme.

IRRIGATION SCHEDULING

Background

The goal of irrigation scheduling is to determine how to supply the tree or vine with the correct amount of water at the appropriate time. Irrigation is applied to avoid tree water deficits that are not compatible with management objectives. The usual objective of the manager is to maximize net economic benefit, which does not always coincide with maximum yields, as when deficit irrigation can improve fruit quality and thus crop value. Most growers make irrigation decisions based on their practical experience and consider the practical limitations of their systems. Research has developed technical scheduling procedures to optimize orchard water management. Technical procedures are adopted by growers who are seeking more precision in their irrigation management towards their primary objective of greater revenues (net profits). Conserving water reduces grower input that, by itself, increases revenue by a magnitude that depends on the water cost. However, reducing the consumptive use of water also conserves a resource considered quite valuable by the rest of society. Demonstrating that they are good stewards of their water resources should serve growers well in the ever-increasing competition for existing water supplies.

Three technical approaches may be used for making scheduling decisions. They are based on: a) monitoring soil water status; b) monitoring plant water status; and c) computing a water budget of the tree root zone. It is possible, and often convenient, to combine more than one of these approaches to arrive at the desired procedure. Despite the huge amount of scientific literature on the many methods developed using the different approaches, only comparatively few have proven practical and are being used for irrigation scheduling of tree crops and vines. Even the methods that have proven useful are used by a limited number of growers.

There are many reasons for the limited adoption of technical procedures; the one most frequently mentioned by growers is the lack of perceived benefits relative to their current practices, which they considered adequate. However, as water scarcity becomes more common, and when the crop value is high, as is the case for tree crops and vines, more and more growers are attempting to improve their conventional irrigation practices by adopting new technical procedures for irrigation management. The choice of procedure is primarily determined by the degree of precision required by the manager, which would normally increase in deficit irrigation situations, and/or where water supply is limited or expensive. Ease of use and the expenses involved are also important grower considerations. In some countries, irrigation scheduling services are offered to growers either by public agencies or private consultants in the form of software packages and sensor installation and monitoring.

Monitoring soil water status

Instruments to determine either the soil water content or the soil water tension were developed long ago; although in the last decade techniques have become more sophisticated with the improvements in electronics. The usual approach has been to monitor soil water at one or more depths until a threshold that indicates the need for irrigation is reached. Lately, continuous records of soil water status can be obtained and decisions are made based on the water extraction trends rather than on setting an absolute threshold point.

Traditional soil-based sensors include the tensiometer, which measures soil water tension, and the gypsum block, which measures electrical resistance. Both of these devices and others developed more recently, such as the granular matrix sensors, use porous media where water enters and is in energy equilibrium with the surrounding soil. More recently developed sensors are based on measuring the dielectric properties of the soil or the heat dissipation. There are two approaches based on the dielectric constant of the soil media: time domain reflectometry (TDR) and frequency domain reflectometry (FDR). So far the sensors based on heat dissipation are primarily research tools.

There are advantages to knowing the volumetric water content of soils in that it allows the manager to determine quantitatively the amount of water in the soil. In order to accurately determine volumetric soil water content, all the previously-mentioned sensors must be calibrated for a particular soil, with the exception of TDR. Soil water content may be measured gravimetrically or with the neutron probe. A recent study comparing the neutron probe, against many other devices developed more recently, revealed that there is no suitable replacement technology for the neutron probe for measuring volumetric soil water content. The main advantage of the new sensors is that they provide continuous soil water records that can be useful for adjusting the irrigation schedule and they lend themselves to automated irrigation control. One limitation of many of the newer sensors is the very small soil volume that they explore, leading to large variability among replications.

Use of soil water sensors for irrigation scheduling

The two critical issues with this method are where to place the sensors in the field and how many observation locations (sensors) are needed to adequately characterize a field. It is instructive to conduct a soil survey in terms of soil depth and texture to find a location that is representative of a given field. The decision concerning placement will depend on whether the grower wants to irrigate the field according to the areas where the plants exhibit water deficits first (shallower and/or lighter-textured soils), to an average location, or based on any other management criteria. The number of sensors that should be installed depends on their cost and on the degree of precision demanded by the manager. Two sensors placed in the same location at two different depths provide more useful information than if they are installed separately in two different spots because they can detect the direction of soil water movement (Box 9). The sensor at the shallow depth is installed at 20-30 cm deep, while the deeper sensor is placed at 50-60 cm or even deeper, depending on root system depth. More sophisticated instruments can give continuous records of soil moisture at several depths in any one location.

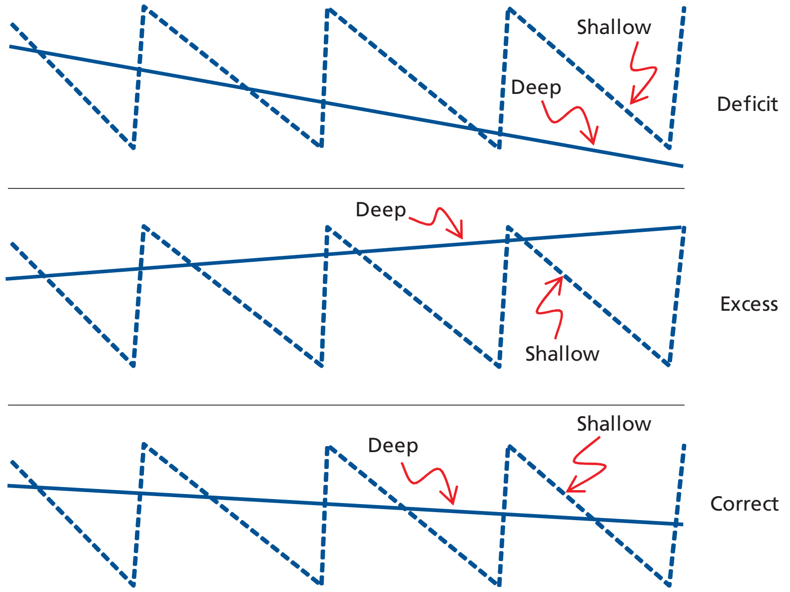
Plant water monitoring

While soil-based instruments give information of soil moisture levels in the plant root zone, the plant itself is the best indicator of its water status. There has been extensive research in measuring plant water status and its impact on plant physiological processes; however, much less work has been conducted on developing specific protocols for using plant-based measurements for irrigation scheduling. The main difficulty is related to the dynamic nature of tree water status, which is affected by both the soil water status and the atmospheric environment. Tree water status changes diurnally and over the season; thus it is not easy to define thresholds for practical use. Tree water status measurements need to be benchmarked against equivalent measurements representing fully irrigated plants in the same environment. This can be accomplished by developing 'references' or 'baselines', representing the behaviour of plants under non-limiting soil water conditions, which can be used to normalize plant water measurements.

Plant water potential

The parameter used for characterizing the state of water in plants is the water potential. This is commonly measured with a pressure chamber. The measurement requires that a leaf be excised, placed and sealed in a chamber with the cut petiole end sticking out, and then pressurizing the chamber with nitrogen gas until the xylem sap just appears at the cut end of the petiole (Box 10). This pressure balances the leaf water potential under certain assumptions. The established method used to assess water status of trees is the stem-water potential (SWP). To measure SWP, an interior, shaded leaf close to a main branch is covered (a small plastic bag

BOX 9 Examples of soil water monitoring in different situations

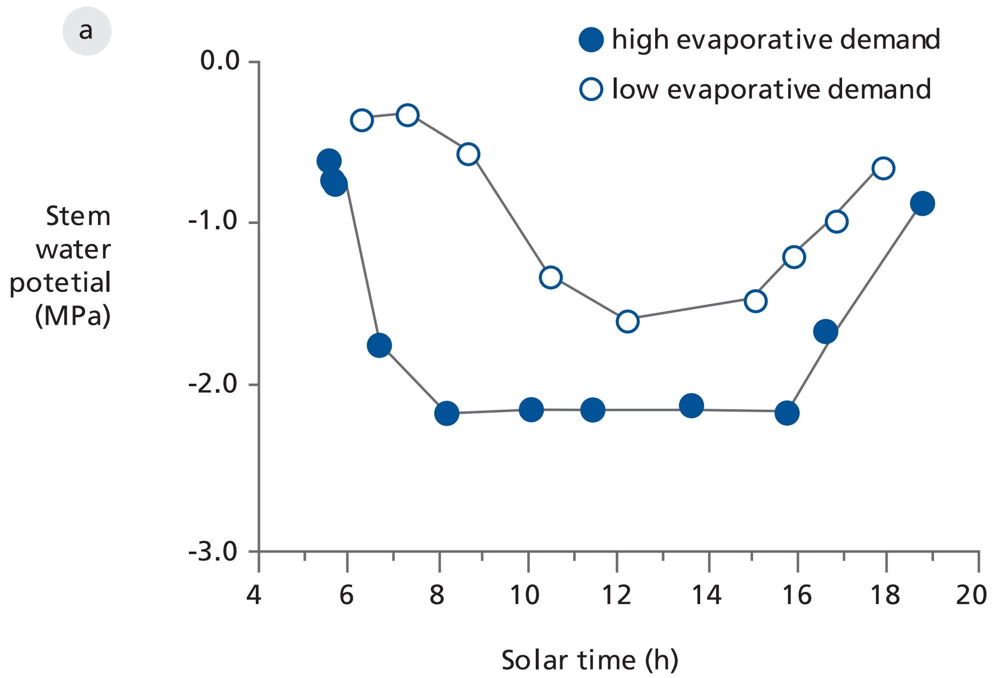


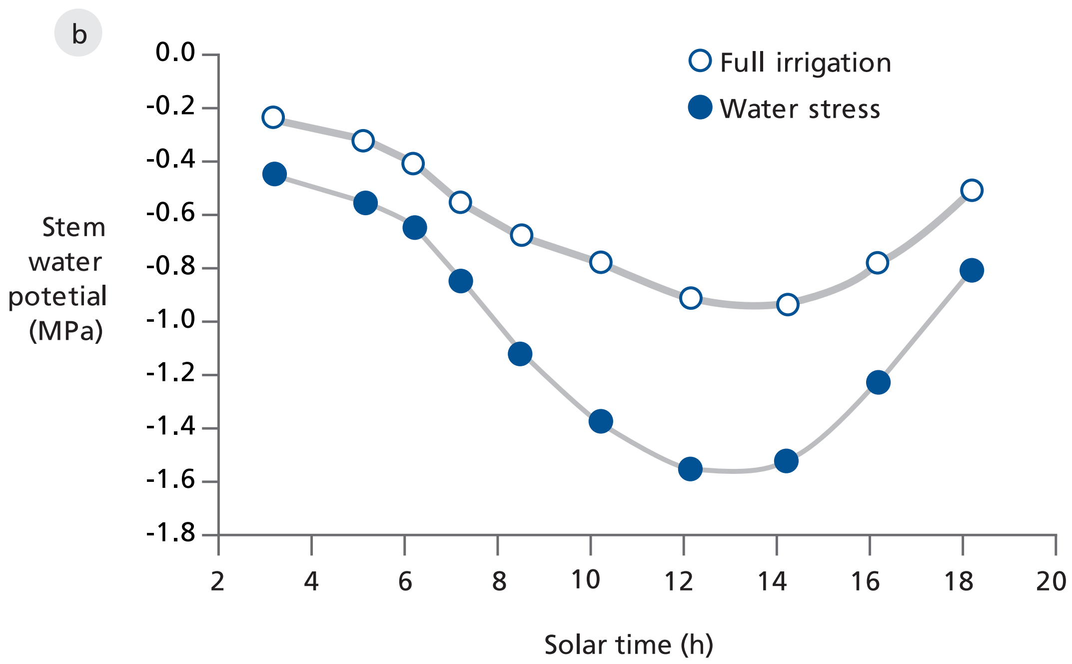
The three soil water status trends were obtained with sensors installed in shallow (dotted lines) and deep (solid lines) soil layers. The top example indicates **insufficient** water application (deficit irrigation), based on the decline of soil water in the lower depth (solid line). The center graph shows an increase with time in soil water deep in the profile which indicates **excessive** applications. The soil water fluctuations in the shallow depth (dotted line) show the typical responses to irrigation applications followed by fast extraction at shallow depths. The third graph at the bottom represents a pattern indicative of **adequate** irrigation applications. Note that even if the water content in the deep layer does not change deep percolation may occur even without apparent water content changes.

overlaid with aluminum foil or any opaque, sealed bag) for a period of time (around 20 min) prior to excision. The practical elimination of transpiration by enclosing the leaf equilibrates its water status with that of the adjacent stem and presumably, the trunk. The SWP is less affected by evaporative demand (and by leaf-to-leaf variations in stomatal opening) and is more representative of the water status of the whole tree than the water potential of an exposed leaf. In some species, measurements of the water potential of uncovered, shaded leaves inside the canopy have proven to be closely correlated with SWP. Thus, taking the measurement on shaded leaves may be a viable, faster alternative to having to bag the leaves.

Plant water status varies in response to atmospheric demand and soil water levels. Even when the soil water level is high, the SWP varies, declining from predawn hours until about solar noon when a plateau is reached through the midday hours, at least on clear days. The SWP measurements are normally taken during this plateau period; from solar noon to 1400, and represent the minimum for the day. The maximum value taken at predawn is used in some cases to represent a SWP close to equilibrium with the soil water. It is not practical to measure predawn water potential for commercial scheduling given the time of day and the limited time to make the measurements.

BOX 10 This page: Examples of the diurnal evolution of leaf water potential for: a) olive (rainfed trees in early spring and mid-summer); and, b) for peach trees under full irrigation and under water stress. Next page: the pressure chamber instrument used to measure the plant water status.





BOX 10 (CONTINUED)

The major limitation of using SWP for irrigation management is its labor requirement, a limitation that greatly increases for the predawn measurements, because the measurements require trips to the fields, and they cannot be automated. Alternative techniques to the pressure chamber have been proposed, such as measuring the diurnal trunk diameter changes with dendrometers. This technique provides continuous records automatically and it has been tested in a few species, although it is not widely used outside research activities. Another shortcoming of plant-based scheduling approaches is that they do not provide quantitative information on how much water should be applied, as the soil water monitoring and the water budget methods offer. Research information on SWP of the various tree and vine species is available to diagnose the relative level of water status in an orchard, and this is one of the most useful applications of SWP measurements. Box 11 provides indicative values for some tree species and further details are given in the specific crop chapters. Both evaporative demand and time of the season may affect the reference SWP values.

Canopy temperature

Tree canopy temperature is another indicator of water stress. The underlying mechanism is that the closure of stomata induced by water deficits causes an increase in canopy temperature because of a lower transpirational cooling. On a clear day, plant canopies well supplied with water are cooler than the surrounding air by several degrees. As water supply is restricted and water stress is imposed, the canopies warm up as transpiration is reduced, and their temperatures can be equal or higher than that of the air. In a given environment, canopy temperature increases with the severity of water stress. The development of the infrared thermometer (IRT) made it possible to measure canopy temperature remotely, without physical contact with the plant and this made it possible to use canopy temperatures for irrigation management. As an example, the difference between canopy and air temperature may range from -3 °C when canopies are well watered to +3 °C under significant stress, which offers a wide window to detect stress.

BOX 11 Reference values of stem-water potential (SWP) in some species of fruit trees and vines.

Range of SWP values for well-irrigated trees (no stress) of several perennial crop species. Values were observed around midday on clear days. The range indicates the variation observed at the low and high evaporative demands, and early (soon after full canopy development) vs. late in the season (before leaf senescence visual symptoms).

SWP (MPa)	Early season	Mid-to-late season
Olive, Citrus	-0.8 to -1.0	-1.0 to -1.2
Grapes	-0.4 to -0.6	-0.6 to -0.8
Pistachio	-0.7 to -0.8	-1.0 to -1.2
Almonds	-0.6 to -0.8	-0.8 to -1.0
Peach	-0.5 to -0.6	-0.7 to -0.9
Walnuts	-0.4 to -0.5	-0.5 to -0.7

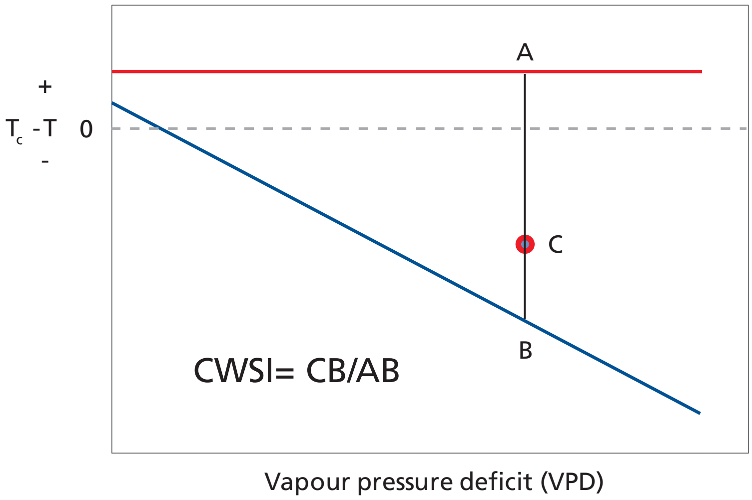
Based on canopy temperatures, a crop water stress index (CWSI) has been developed to quantify the level of water stress of crop canopies. The CWSI uses the temperature difference between the canopy (T_c) and surrounding air (T) which is normalized for differences in climatic conditions using the vapour pressure deficit of the air.

Box 12 shows how the CWSI is calculated using two baselines, one for a fully irrigated canopy (lower baseline) and another for a severely stressed canopy (upper baseline). Both lines are either empirically determined or theoretically derived under equivalent evaporative demand conditions. Protocols for use in irrigation scheduling focus on not exceeding predetermined CWSI thresholds during specific periods of the season. Canopies under no stress have CWSI values near zero while in severely stressed crops, CWSI approaches one.

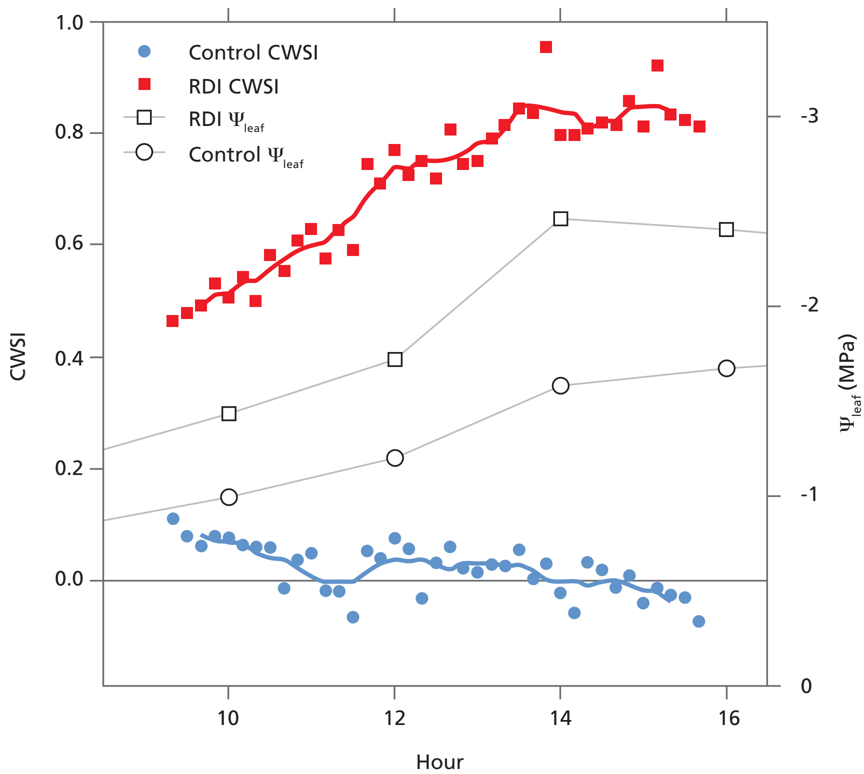
The CWSI indicator has been successful in detecting the water status of homogeneous canopies of the major field crops. It is more difficult to apply it to the heterogeneous canopies of trees and vines because the bare soil, which has a much higher temperature, interferes with the readings of surface temperature of isolated tree crowns within hot soil surfaces. Also, in the case of tree crops, the use of CWSI has been limited by the smaller differences in the canopy-air temperature gradient because of the rougher tree canopy as compared to the smooth canopies of homogeneous field crops. With the latter, the crop canopy temperatures get hotter than tree canopies for the same relative decline in temperature. However, recently it has been shown that the CWSI approach is capable of detecting water stress in fruit tree canopies, as seen in Box 12 for pistachio trees.

BOX 12 Definition of CWSI and an example showing the relations between CWSI and Leaf WP in pistachio trees.

The point C depicts the measured T_c - T of a canopy; B is the lower limit of T_c - T for the canopy transpiring at its maximum potential, and C is the T_c - T of a non-transpiring canopy, both for the existing VPD.



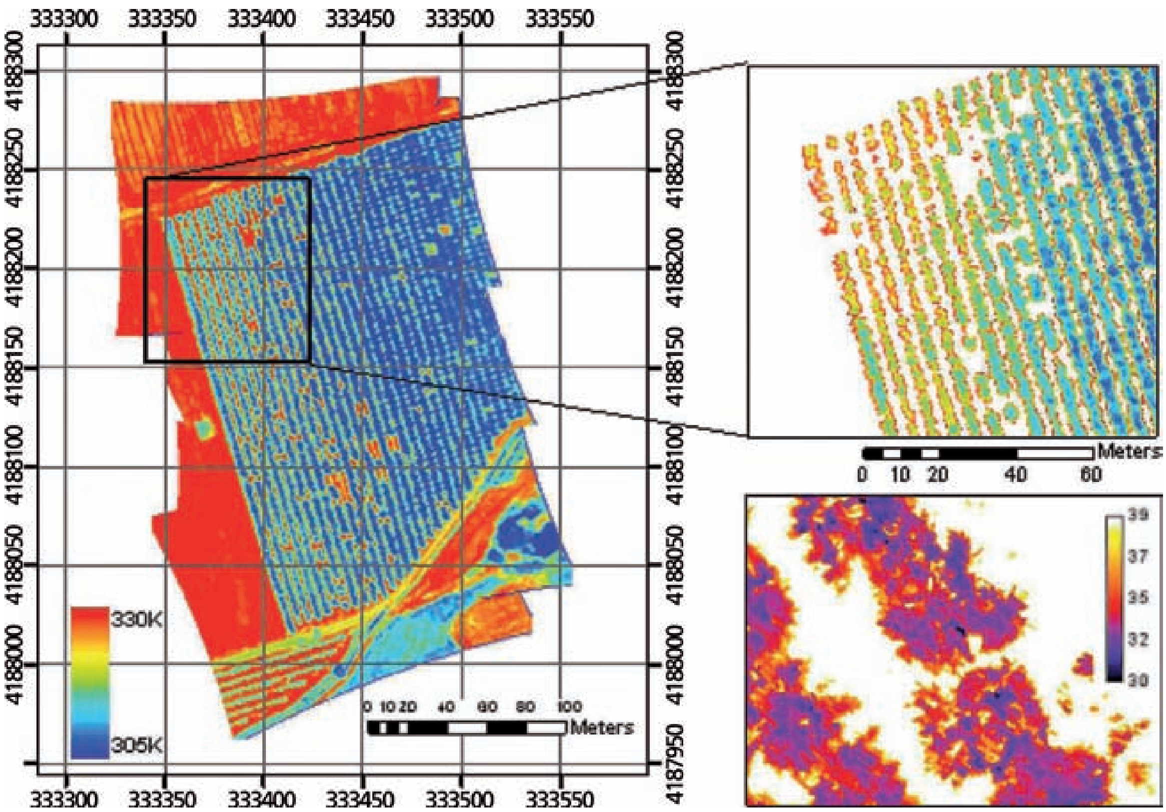
Diurnal CWSI trends in control pistachio trees (dots) and in trees under water deficits (RDI; black squares) on 3 July 2006, in Madera, California. The values of leaf water potential are also represented in the Figure (adapted from Testi *et al.*, 2008).



A major advantage of the canopy temperature techniques is the possibility of acquiring thermal images that represent complete orchards from aerial vehicles or satellites. This allows an entire field to be characterized rather than monitoring only a few points or trees, as is now the case with soil and plant-based techniques. Additionally, analysing the tree-to-tree variability of remotely sensed canopy temperature data may produce other indicators of orchard water needs. Box 13 shows maps of CWSI for an orchard and the degree of detail that can be obtained from thermal images that have sufficient resolution to map each tree crown with detail.

BOX 13 Thermal orthomosaic obtained from the UAV over the peach orchard at 40-cm resolution.

The zoomed image on the top shows the water stressed trees (warmer, in red and yellow) as compared with the fully irrigated trees (blue). The bottom right image shows a low-altitude image where within-crown thermal variability is observed (adapted from Berni *et al.*, 2009).



The water budget method

With this method, the tree root zone is considered a reservoir of soil water that is depleted as E and Tr take place. The soil reservoir of available water that the tree depletes through ET is allowed to lose water until a soil water threshold (allowable depletion) is reached, below which water stress is detrimental to crop production, quality or both. At this point, irrigation must be applied to refill the soil profile and the amount needed is equivalent to the ET_c losses since last irrigation. Box 14 describes the process of how to schedule irrigation with the water budget for tree crops.

BOX 14 Applying the water budget method of irrigation scheduling.

Information needed

- Available soil water holding capacity or total available water (TAW)
  Defined as the difference between field capacity and permanent wilting point, it varies according to soil texture between 50 mm/m to 200 mm/m.

- Rooting depth
  Tree roots extend deeply into open soils and can reach several metres, but their depth may be much more limited by mechanical restrictions in the soil profile.

- The allowable depletion(AD)
  This is the threshold level of the root zone storage capacity below which the level of water deficit in the tree is undesirable. At this point, an irrigation is applied. Usual AD levels vary between 50-70 percent of TAW.

- The ET_c rate
  The ET_c losses are accumulated until the allowable depletion level is reached.

Practical considerations

Although tree roots may reach several metres, the effective depth of rooting for irrigation purposes is considered much less for practical reasons. Even in deep, open soils, 1.5 to 2 m is the maximum depth considered for water budget calculations. A 2 m soil profile can hold up to 400 mm of H_2O, and if the AD is 50 percent of the TAW, the crop can extract 200 mm before the next irrigation is applied. At an ET_c rate of 5 mm/day, the next irrigation would be applied after 40 days! This is not practical for many reasons; for example, it would be difficult to replenish that deficit in a reasonable time period, as it is very difficult to infiltrate 200 mm of water into most soils within the standard irrigation time. Therefore, what is commonly done is to fix a certain depth of water to be applied, often much less than the AD, (between 50 and 100 mm of water), and vary the irrigation intervals according to the ET_c loss. Thus, setting the AD is primarily a management decision, and must consider all practical aspects of the farm irrigation processes.

The water budget technique is very useful when significant labour is needed to irrigate, because it permits water to be applied as infrequently as possible, minimizing the number of irrigations per season and thus, labour costs. This is the case for the surface and portable sprinkler methods. When the irrigation system is permanent and covers the whole orchard or vineyard, such as for microirrigation, the issue of irrigation frequency is much less relevant, and the grower should irrigate as frequently as desired, taking into account the potential E losses. Nevertheless, it is important to keep some account of the water budget for seasonal planning, even under high-frequency irrigation.

Under microirrigation, the goal is not to refill the entire profile but only to replace the water consumed by ET_c since the previous application. Thus, the primary role of the water budget using microirrigation is to determine the amount of water that needs to be applied. However, it can also be used to keep track of the soil moisture depletion of the root zone. This can be beneficial if deficit irrigation is practised or, in the event of a water delivery problem, because it can be used to determine how much available water is left in the profile. It is therefore a good planning tool, as shown in Box 15.

RESPONSES TO WATER DEFICITS OF TREE CROPS AND VINES

In every diurnal cycle, water evaporates from the leaves, internal water deficits develop and water flows from the bulk soil towards the leaves to replace the losses. For water to move from the soil to the leaves, the trees must experience some water deficits during the course of the day. However, when the soil cannot supply water at a sufficient rate to replenish the losses, or when Tr is very high because of the evaporative demand, the tree dehydrates partially and experiences water deficits that may be excessive and may affect important physiological processes that result in lower yields, fruit quality deterioration or both.

Effects on phenological development

Water deficits affect the development of fruit trees and vines. Flower bud formation, floral development and fruit set are the main processes relevant to fruit production. For deciduous trees, fruit evolves from bud differentiation that occurs in the previous year. Thus, water deficits in one year may affect the return bloom and production of the following year. For some tree crops, water deficits negatively affect floral viability the following year, but there are also reports of enhanced return bloom following water stress in the previous summer. This response is critical for determining fruit load and therefore yield in relation to water. Since this response is species-dependent it is presented in the specific crop sections. However, a general truism is that periods of floral development and fruit set are very sensitive to water deficits, and thus, damaging water stress should be avoided. Nevertheless, occurrence of water stress during these developmental events is relatively rare for deciduous species since Tr is very low early in the season because of lack of leaf area and the generally low evaporative demand in temperate climates. In subtropical climates and for evergreen species, the likelihood of stress at flowering and fruit set is greater and should be managed accordingly.

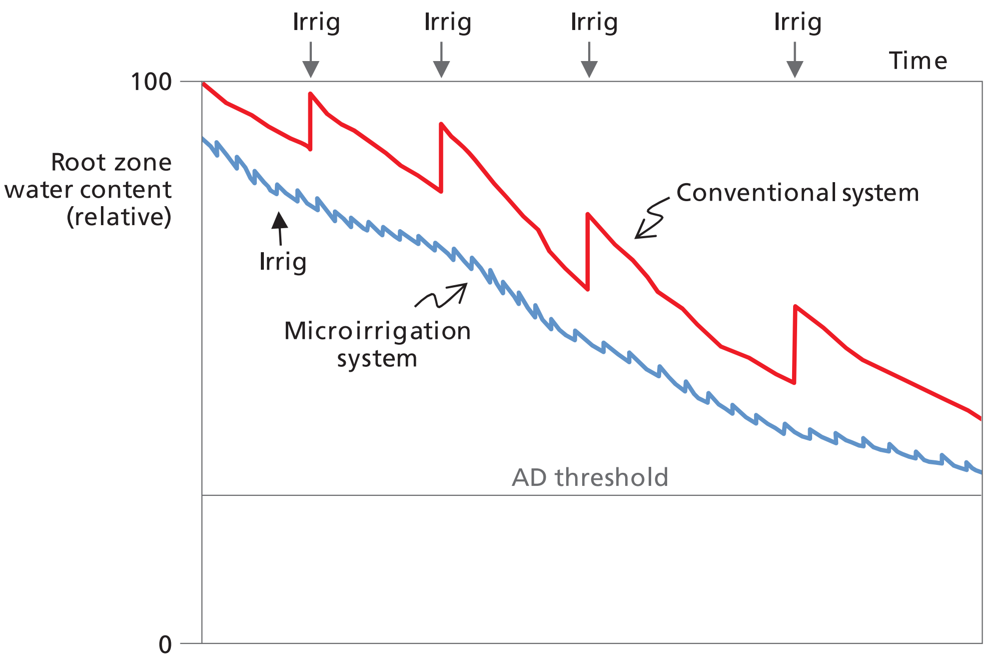
Effects on vegetative growth and CO_2 assimilation

Growth is among the first processes that are affected by water deficits. When a water deficit

BOX 15 Evolution of soil water under deficit irrigation.

If irrigation is applied at rates below the ET_c, soil water deficits develop. Such deficits may not be detrimental unless they reach levels that negatively impact the orchard or vineyard. When microirrigation is applied with a fixed rate, water budget scheduling keeps track of the soil water reservoir and facilitates the safe extraction of part of this reservoir, making the best use of the stored soil water. However, note that, in areas or years where seasonal rainfall is insufficient to wet the potential root zone, the soil water reservoir with microirrigation may be much smaller than under full-coverage irrigation.

Thus, deficit irrigation will manifest crop water stress sooner with microirrigation under those specific conditions. On the other hand, since irrigation can be applied frequently, it is easier to overcome the onset of detrimental stress with frequent applications under microirrigation, provided the system has enough capacity. The graph below shows the seasonal evolution of soil water under deficit irrigation, with both conventional and microirrigation systems. In both cases, the applied water is less than the ET_c and the soil water reservoir is being depleted, but the threshold is not reached.



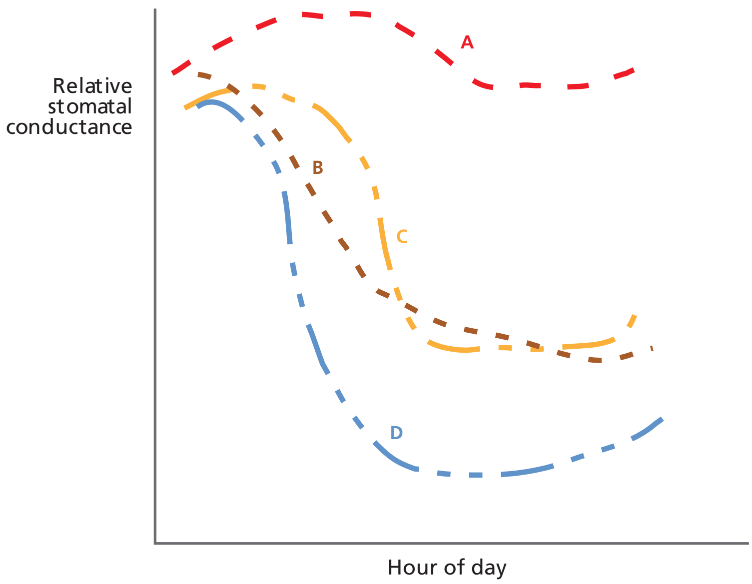
develops, any organ that may be expanding at that time, be it a leaf, a fruit, a branch, or the trunk, slows its rate of growth. This is because high rates of expansion require high internal pressure inside the growing cells, or turgor, which is directly dependent on the water status of the tissue. The high sensitivity of shoot growth to water stress has important implications for tree irrigation; on the one hand, it may be desirable in some cases to reduce the growth of vegetative shoots relative to their potential growth under unlimited water supply. On the other hand, if large fruit size is an important factor in determining growers' revenues, water stress must be completely avoided during the period of fast fruit expansion. There is evidence for different species that the various growth processes, shoot initiation, shoot extension, leaf and fruit growth, and trunk growth all have differential sensitivity to water stress within a generally high sensitivity level, as discussed in the different crop sections. It should be emphasized that during the first years of the orchard or vineyard, canopy expansion is the most important process leading to high productivity. As the plantation reaches maturity, the importance of water deficits that affect vegetative growth is reduced. Another important response to water deficits is accelerated leaf senescence. In some species such as almonds, this response is quite marked, while in others it requires severe water deficits to be detectable, as for olives.

Carbon assimilation of plants depends on CO_2 uptake through stomata, which responds to water deficits by partially closing. The behaviour of stomata in many fruit trees follows a pattern that maximizes CO_2 uptake per unit water loss. However, stomatal regulation may also involve trade-offs between maximizing CO_2 uptake per unit water loss (which may require stomatal closure at times of high evaporative demand) and tolerance to heat stress (which requires high stomatal conductance to allow for evaporative cooling). Different patterns of stomatal behaviour are shown in Box 16 for several tree species. Stomatal conductance is highest during the morning when the vapour pressure deficit is low and declines to a plateau at midday when VPD is high (Box 16, C). This pattern has been observed in many fruit tree species but is different in others, such as apple and in grapevines (Box16, A) where stomata stay wide open for most of the day if the plant is well supplied with water.

It has been thoroughly documented that stomatal conductance and the rate of CO_2 assimilation per unit leaf area of the major field crops are not as sensitive as is vegetative growth to water deficits. Significant water deficits are required in most annual crops to reduce stomatal

BOX 16 Examples of diurnal patterns of stomatal conductance

The graph below shows A) wide open stomata with a small midday depression, typical of apple or grapevines under ample water supply; B) continuous decline of stomatal opening following the increase in VPD, typical of citrus; C) Morning peak with substantial midday depression, typical of many deciduous fruit species, and of the olive; D) same pattern as in C but when the trees are under significant water stress. The relative scale may differ for the different patterns.



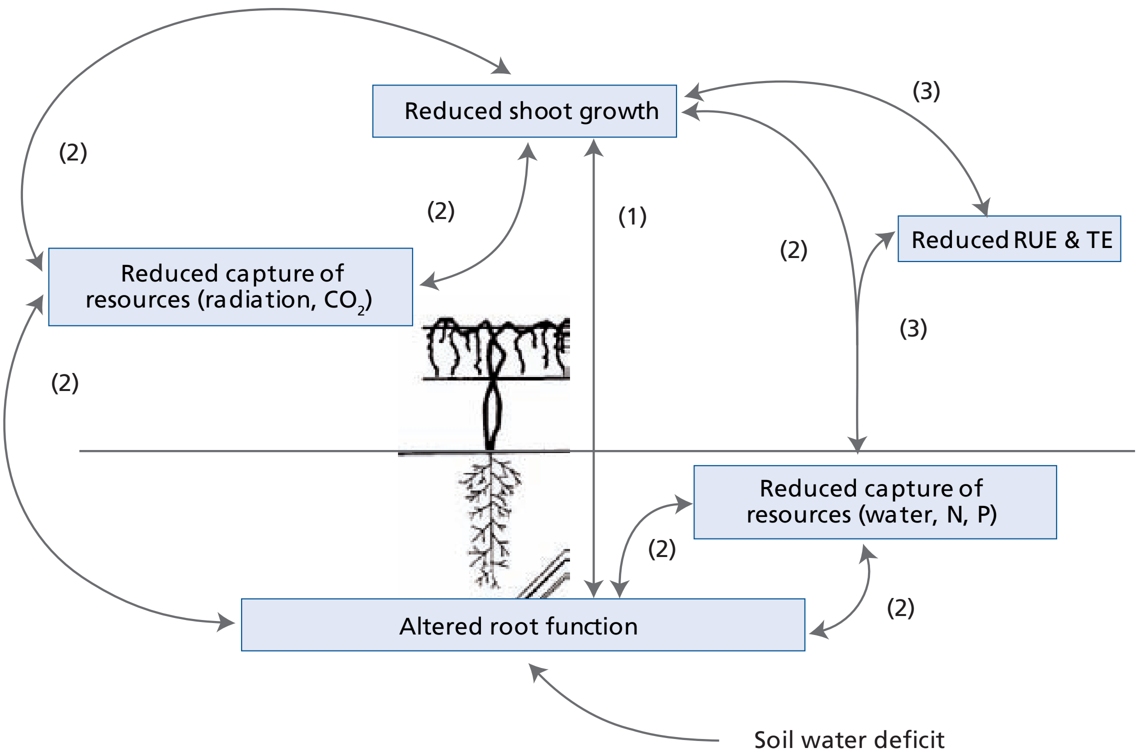
opening and photosynthesis relative to maximum levels. The response of many fruit tree species appears to be similar, although there is less solid evidence that for fruit trees and vines these two processes are as insensitive to mild water stress as they are for the major annual crops. In addition to trees' stomatal regulation, in response to water status, crop load and other endogenous factors can also affect gas exchange rates, making it difficult to generalize the observed patterns of stomatal behaviour across species. Also, there are gradients of water status within the tree and these differences in water supply can induce partial stomatal closure for some branches of the tree but not in others. The characteristic response of stomata to water deficits is shown in Box 16, where increasing stress levels impact both the magnitude of the peak and the plateau levels of stomatal conductance.

Mechanisms involved in the responses

The understanding of the physiological mechanisms involved in the response to water deficits is well developed for water relations and hydraulic and chemical signals, but there is a need to have a framework that integrates these processes into a whole-crop model accounting for both resource capture and efficiency in the use of resources. Box 17 shows the mechanisms

BOX 17 Physiological mechanisms of crop responses to soil water deficit.

Pathway (1) involves direct root perception of soil water deficit, and root signals inducing reduction in shoot growth; the two-way arrow allows for shoot-to-root feedback signalling. Pathway (2) involves a strong, reinforcing loop of reduced shoot and root growth, which is mediated by impairment of the ability of root systems and canopies to capture resources. Pathway (3) involves reductions in the efficiency in the use of resources, as exemplified by radiation use efficiency (RUE) and transpiration efficiency (TE) (Sadras, 2009).



of crop responses to water deficits grouped into three classes. Pathway (1) involves root-to-shoot and shoot-to-root hydraulic and chemical signals, which have attracted profuse attention. Pathway (2) contains a very strong reinforcing loop, whereby initial reduction in growth of shoot, root or both, forms a loop that may eventually override other processes. Pathway (3) involves changes in radiation- and transpiration-efficiency; these efficiencies are stable except for conditions of severe stress. This model illustrates the interactions and interdependence of the multitude of physiological processes involved in water relations and plant growth and, as such, is an integral part of understanding crop responses to water deficits. This understanding is fundamental and forms the basis for the development of improved irrigation practices.

Effects on yield

Knowledge of yield and fruit quality responses to water deficits is required to predict the orchard response to reductions in water supply in water-short years or in areas of water scarcity, where it is not possible to supply the amounts needed to meet maximum ET_c. Normally, the prospect of water deficits increases the risk of yield reductions and these fears are often realized if the water deficits are severe enough and occur at critical stages when some of the components of yield are determined. However, it is sometimes possible to avoid the negative impacts of reduced irrigation supplies by confining the plant water deficits to stress-tolerant periods of the season. Moreover, there are some cases where it is possible to actually exploit the positive responses to water deficits to improve fruit quality and thus, enhance crop value with reduced consumptive use. Thus, growers would profit from both higher gross revenue and reduced water costs.

To assess the response of fruit trees and vines to water deficits, multiyear trials are necessary because perennial plants require time to acclimatize to a new water regime and because there may be carryover affects of water deficits on subsequent season(s)' productivity. In other words, stress history is an important aspect of permanent crop deficit irrigation. Normally, stored soil water, shoot, leaf, root, and fruit development are all affected by the first season of water deficits and all that influences the results of that year. After the first year, a minimum of two additional years are needed to evaluate the response, primarily is the result of both carryover impacts of stress and the alternate bearing tendency of many tree species that would affect the yield, regardless of the water deficits. To characterize the yield response to water for perennial crops it is necessary to conduct experiments for 3-4 years minimum, and preferably more. The tree-to-tree variability increases the number of replicate plots needed to detect statistically significant differences in both physiological processes and yield components among treatments. All these make tree and vine irrigation experiments very time consuming and expensive and thus scarce, particularly those that are long term.

Fruit and product quality

Many fruit quality features may be affected by water deficits and it is ultimately the cumulative impact on yield and quality of a product that will inform deficit irrigation strategies. Thus, only those quality factors that influence product prices should be considered when evaluating the effects of water deficits on quality. The size of fresh fruit is one of the most important quality aspects affecting orchard revenue. Fruit size is generally reduced by water deficits that occur during the periods of fruit growth. However, the impact depends on stress timing; early season growth rate reductions may not be evident at harvest because of accelerated fruit growth if and when full irrigation is restored. Regardless, since large fruit at harvest is generally desirable, water deficits should be avoided during most species' fruit growth. On the contrary, the eating quality of many pome and stone fruit is enhanced by mild water deficits, normally by increasing their sugar content, or by increasing the sugar/acid ratios and other chemical compounds responsible for flavour and aroma. There are other positive responses of fruit quality to water deficits, such as improved colour, but the incidence of a number of disorders have been known to increase with water stress. The responses are certainly species and even cultivar-specific (see specific crop Sections). In the case of grapevines, the quality issue is of paramount importance for wine production. The price that grapes fetch may differ by an order of magnitude in some regions, depending on their fruit size, chemistry, and colour, and water management is the primary factor determining this quality, as discussed in the Section of Grapevine.

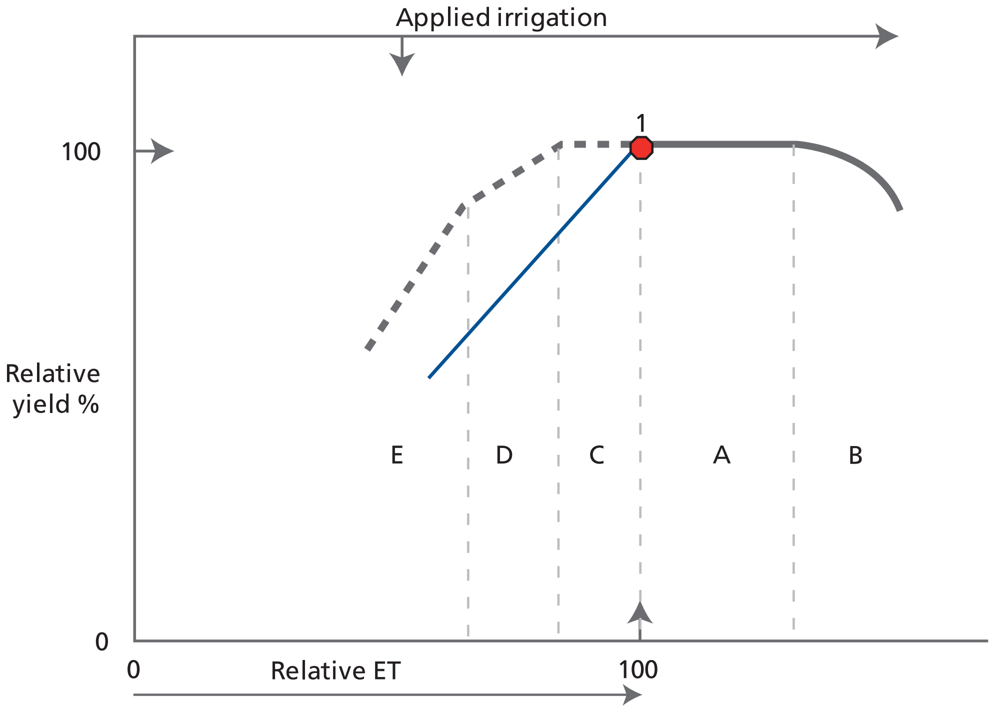
WATER PRODUCTION FUNCTIONS IN TREE CROPS AND VINES

From the practical standpoint, it is important to know how yield and quality responds to variations in water used; i.e. the relation between water and yield, which is termed the water production function. Such functions quantify the sensitivity of yield to a reduction in the consumptive use or ET below the maximum potential, and therefore describe the expected yield response to water. Water production functions were defined in the *FAO I&D No. 33* Publication for most field crops, but at that time, there were insufficient data to formulate similar functions for the tree crops and vines. An important goal of the following paragraphs is to develop the production functions for different fruit tree species based on research conducted over the last 30 years. While each species has its own response, there is a general pattern of response for most fruit tree species, as shown in Box 18.

The generalized relationship between applied irrigation water (AIW), ET_c and yield of tree crops shown in Box 18 has different response regions. Starting at Point 1, maximum yield is normally achieved at maximum ET; at this point, the level of AIW is such that there are no drainage losses and the level of allowable depletion has been reached. To ensure that ET needs are met, some growers apply more irrigation (Region A) but the yield is maintained at maximum, albeit with some drainage losses. For many tree crops, there is an irrigation level beyond which yield starts to decline, either as a result of the direct effects of waterlogging or the indirect effects caused by diseases associated with very high soil water levels, which may even cause tree death in extreme cases (Region B).

When AIW is reduced below the level of Point 1 (deficit irrigation), initially, yield may not be reduced (Region C, Box 18); the extent of this region depends on the species and the irrigation regime, but is generally limited to a range of actual ET_c between 75 and 100 percent. As AIW is further reduced, yields finally decline due to the irrigation deficit (Region D), and will be further reduced at a faster rate if AIW is decreased further (Region E). In this last region, the likelihood of large yield losses is high because of the sharp decline in yield in response to the decrease in AIW. Note that because of the steep slope in Region E, the water productivity (yield per unit AIW) of the initial irrigation amounts is highest.

BOX 18 Generalized relationships between yield, ET_c and applied irrigation water in fruit trees. The dotted line represents the expected response of fruit and nut trees while the solid blue line indicates the typical response of an annual field crop for comparative purposes.



A = Maximum yield region with increasing drainage losses after Point 1. (The soil water level increases with the amount of irrigation).
B = Region of excess water reducing yield.
C = Region of yield maintenance with deficit irrigation.
D = Region of yield loss with deficit irrigation.
E = Region of high risk of commercial losses as a result of severe water stress.

Yield response functions and fruit quality

Farmers' objectives are focused on achieving the maximum net income, and in many cases in fruit production, income is not only determined by the amount of production but there are quality factors that may also affect the price of the product. In these cases, the crop value not only depends on the total weight of the harvest, but on its quality as well. As discussed above, water has been shown to affect fruit quality parameters, and water stress can have positive and negative effects on fruit quality.

Markets value fruit quality in complex ways; in some, a high premium is paid for the large fruit of some species (apple, peach) while other markets do not value size as much even for the same species. Markets do not specifically consider quality features of most fruit, such as high sugar or better flavour, because quantification is difficult, and the price is based solely on weight and general appearance. Some varieties are valued more than others but this also depends on the market. The same variety may be appreciated more in some countries and regions than in others. Although fruit quality has not been an important factor in the past for determining the value of fruit, the situation is changing, as a result of both better consumer education and new techniques that permit the quantification of some quality features.

The crop, where price can vary more depending on its quality, is wine grapes. In this case, it is known that prices may vary almost an order of magnitude even for the same variety and region, depending on the quality of the grapes. This is (partly) reflected in the price of the wine, which is known to vary widely depending on its quality, as assessed by the markets. It has been shown that, generally, water stress improves the quality of wine grapes, depending on its severity and on how the stress is managed.

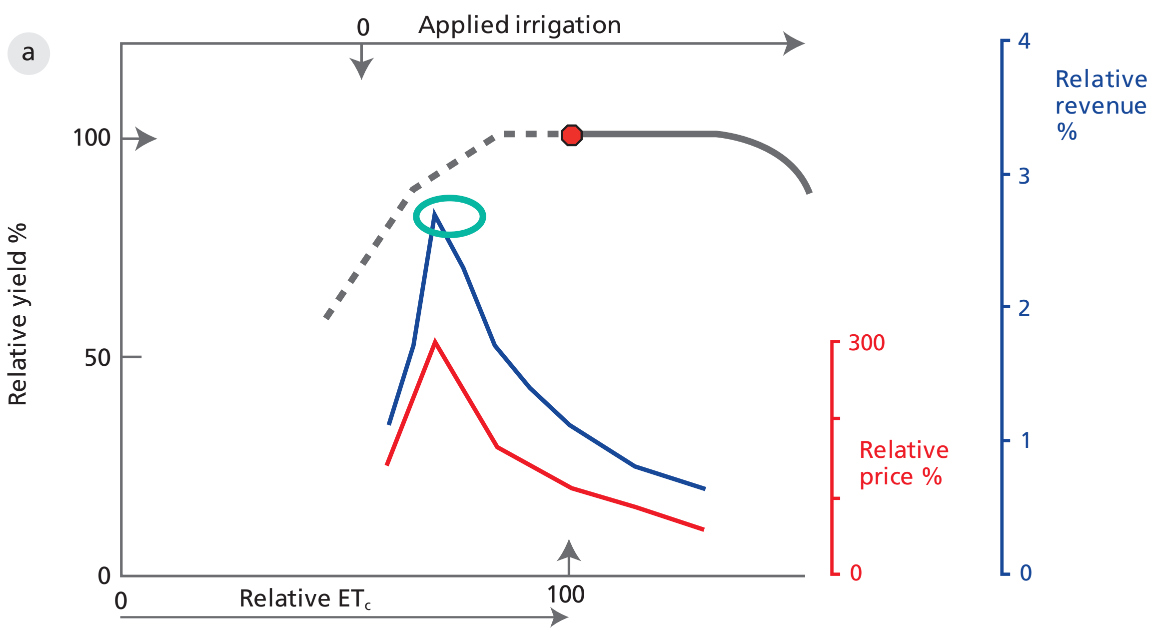
To quantitatively illustrate the influence of quality as affected by irrigation, Box 19 shows the general yield production function of Box 18 with a revenue (relative gross income) production function for two cases, which differ in the response to irrigation of fruit quality. In the first case (Box 19 a), water deficits have beneficial effects on fruit quality up to a point, after which quality is reduced and so is the price of the product (red line).

Strategies for reducing irrigation water use in fruit trees and vines

A major purpose of this publication is to offer practitioners a number of options for dealing with water scarcity; where the supply of irrigation water is insufficient to meet the full crop demand. In some cases, the strategies devised to apply less irrigation than that needed to

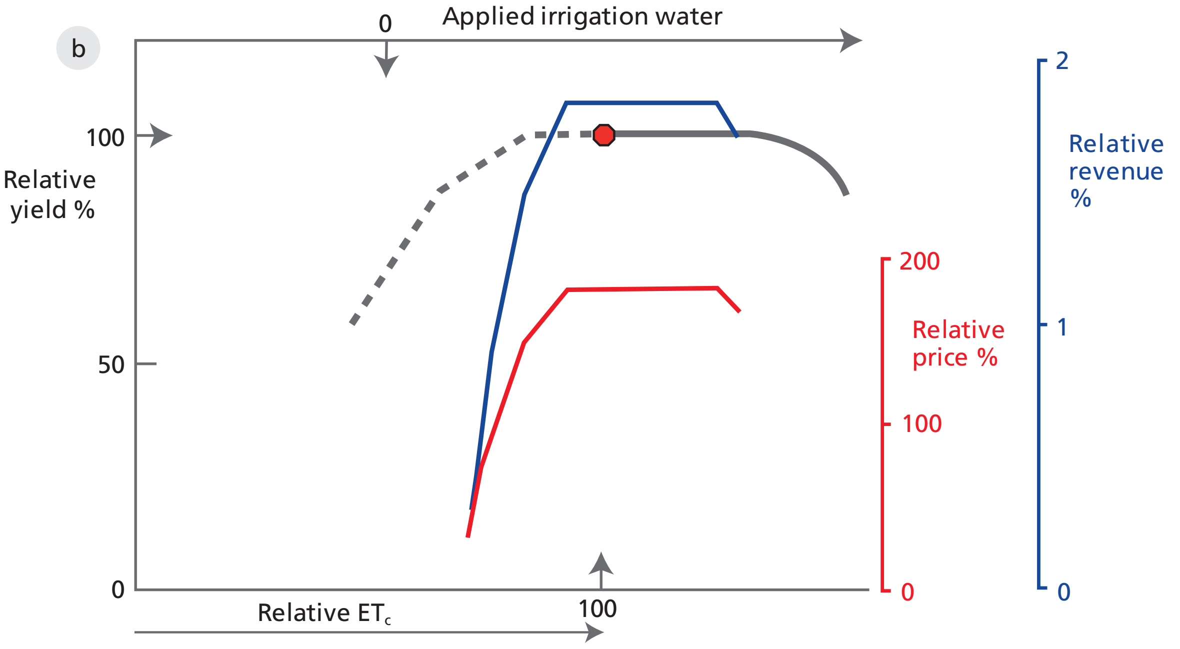
BOX 19 Relative revenue responses to variations in ET_c when fruit quality affects product prices.

In the first case (a), the revenue (blue line) increases with water deficits because prices (red line) are directly related to quality, which increases with water deficits until a point, and then decreases as water deficits become more severe. The price curve together with the yield response line yield a revenue production function that has an optimum ET_c and AIW below that needed to obtain maximum yields.



BOX 19 (CONTINUED)

(b) In the second case where fruit size determines the crop value, the price (red line) is negatively affected by the water deficits as water stress reduces fruit size, even more severely as the deficits intensify. Here, the revenue function (blue line) is different and steeper than the yield function, thus favouring the application of high levels of AIW at or very close to that needed to ensure maximum ET.



achieve maximum ET_c may also be the best for maximizing revenue. There are many possibilities that can be effective for increasing the efficiency of water use when the supply is scarce, as presented below.

Irrigation system management

Improving the uniformity of water distribution over the field and maximizing application efficiency are two key goals that must be pursued in deficit situations. The goal is to eliminate, as much as possible, any unproductive water loss; to ensure that most of the applied water is available for plant use. High application efficiency requires both good scheduling decisions (when to irrigate and how much water to apply) and irrigation systems designed and maintained to achieve high uniformity. Lack of uniformity, when water is in short supply, might leave areas in the orchard with supply levels so low that severe water stress could be induced. The maximum attainable uniformity depends on the method of irrigation and it is difficult to exceed 90 percent in practice, but it is critical to reach the highest possible level with any method used. An important consideration when irrigation scheduling with limited water is to exploit all the stored soil water available in the root zone of the tree so that the season ends with a dry soil profile ready to be refilled by seasonal rainfall, in the geographical areas where this is feasible.

Modify horticultural practices

Pruning – More severe pruning may be effective in reducing water use since Tr is related to canopy size and leaf area density. However, the relationships between canopy size and Tr are not linear (see Figure 11) and significant pruning may be needed to change Tr. When the reduction in water supply is going to be drastic (a small fraction of tree Tr), a mature plantation can be saved for later years by heavy pruning (sometimes called 'dehorning' or 'stumping'). The objective is to remove most of the canopy, leaving only short primary scaffolds. This effectively eliminates any yield for that season but it permits the tree to survive the drought. Full production may not resume for several years.

Fruit thinning – Heavy fruit thinning under limited water allows the grower to produce fruit of marketable sizes, thus increasing crop value relative to normal thinning. This practice is common and achieves higher grower revenue, even though yields are lower. Also, because the presence of fruit enhances Tr, heavy thinning can reduce Tr rates somewhat in many tree species and decrease the level of water stress in the trees, leading to an acceptable commercial size for the remaining fruit. As a general conclusion, it must be said that there is not much evidence that these measures are very effective, relative to others discussed in this Section, except in extreme, very low water supply situations. Further, because the reduction in transpiration associated with fruit thinning is mediated by reduced stomatal conductance, this practice might increase heat damage where water deficit and high temperatures occur at the same time.

Reduce evaporation from soil – If runoff is avoided and deep percolation is minimized, the only option left to decrease unproductive water use is to reduce or even eliminate E loss. In full coverage systems, irrigating as infrequently as possible would also minimize E. Evaporation losses from drip irrigation are low but they can be reduced further if the systems are not run daily, but every few days. The optimum interval would depend on the depth of water required and on soil type, as deep percolation must also be avoided. Because the depth of applied water is reduced under deficit, the irrigation set (duration of irrigation) should not be changed, but the interval between applications should be expanded (irrigation frequency lowered). Having the drip lines under the canopy will contribute to the E reduction because of both the shade and the mulch layer of dead leaves over the wetted soil. Buried drip networks can theoretically eliminate E. However, some surface wetting has been reported with many buried drip systems, even with line placement 45 cm deep. The magnitude of this problem seems to depend on soil transport properties, the installation depth, the method used for line installation, and the duration of the irrigation. Moreover, these systems are relatively expensive and more difficult to maintain. Thus, the installation of buried drip systems for the purpose of reducing E is generally not justified, as the savings relative to surface drip would be small in absolute terms. In cases where the amount of water applied is very low, the relative importance of E increases, and the small E savings from buried drip may pay off.

Deficit irrigation

Once all the measures described above have been considered and adopted as needed, the only option left to cope with water scarcity is to reduce the application of irrigation water. Deficit irrigation (DI) is defined as a regime where the irrigation water applied is less than the orchard ET requirements. When the irrigation rate is below the ET rate, there will be a net extraction of water from the soil reservoir. Two situations may then develop. In one case, if sufficient water is stored in the soil and transpiration is not limited by soil water, the consumptive use (ET) is unaffected even though the volume of irrigation water was reduced. However, if the soil water supply is insufficient to meet the ET demand, crop water deficits lead to a reduction in growth and transpiration. In the latter situation, DI reduces ET below its maximum potential. It is important to consider the sensitivity of the specific crop to water deficits. As described in the specific sections, some crops are very sensitive to water deficits and are not amenable to DI, such as walnut, avocado and kiwi. Others ranked from moderately sensitive to somewhat tolerant and, therefore, are amenable to DI strategies of variable intensity.

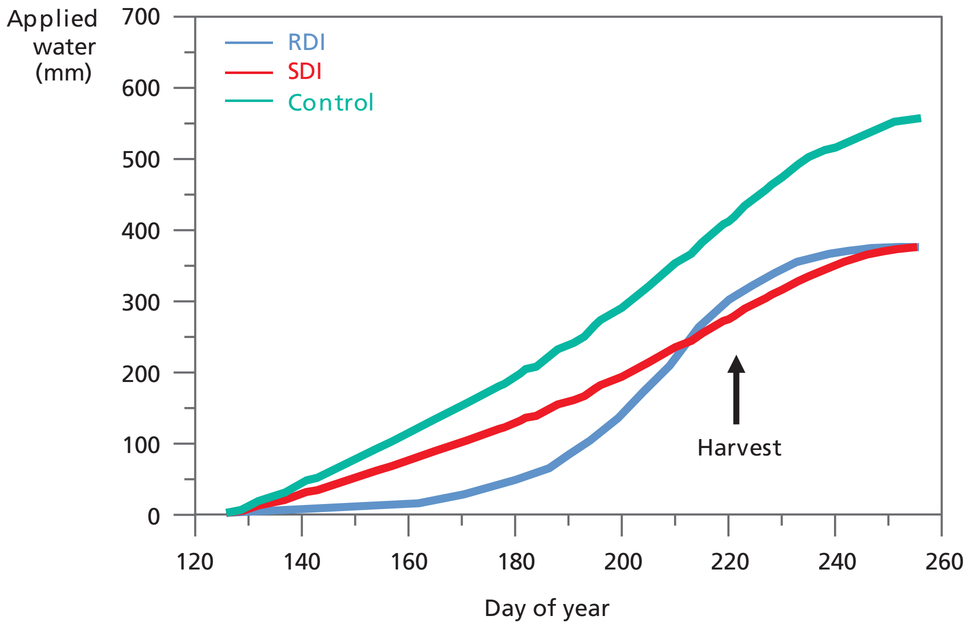
Deficit irrigation strategies

There are many approaches in designing a DI programme but they follow two different strategies. In one, called continuous or sustained DI (SDI), a constant fraction of the crop ET is applied at regular intervals. If the soil profile is full at the start of the season, the trees take up soil water to compensate for the deficits; as the season progresses, the soil is progressively depleted and the water deficits increase with time in the absence of rainfall. The other approach is called regulated DI (RDI), and is defined as a regime that purposely stresses the trees or vines at specific developmental stages of the crop that are considered to be the least sensitive to water deficits. The goal of RDI, when water supplies are relatively high, is to have little, if any, negative impact on the yield of marketable products and on gross profits. It should be emphasized that under RDI, the trees are subjected to irrigation deficits only at certain stages of development but they generally receive full irrigation outside these periods. The water stress is normally imposed in RDI at stages when reproductive growth is relatively low. Water deficits imposed at these stages also generally reduce vegetative growth (and thus pruning costs and agricultural burning potential problems) and may impact on other plant processes, often improving fruit quality. Figure 12 shows graphically one example of the two SDI and RDI strategies in relation to full ET_c.

With plentiful water supplies, RDI is designed to reduce consumptive use without negatively impacting, and in the cases where water deficits enhance fruit quality, improving grower income and hopefully net profits. However, the RDI concept can also be used in drought years, where available irrigation supplies are limited. In practice, the manager must decide whether to impose more severe water deficits during the stress-tolerant periods or begin to expand the stress into the less stress-tolerant stages of the season or a combination of both. Thus, the timing, magnitude, and duration of the stress periods will depend on the water supply with the goal being maximum grower profit; both in the current and subsequent season(s).

One form of deficit irrigation is to irrigate alternatively either side of the tree or vine, to generate wet-dry cycles on both sides of the root system. Thus, only half the root system is irrigated at any one time while the other dries out. After some time (every two weeks or so), the system is shifted and the dry side is irrigated; this technique is called Partial Root Drying (PRD). Even though one side of the root system is always in a drying cycle, plant water deficits may not occur under PRD since the other side of the root zone can be irrigated to meet the ET requirements. Experiments and commercial practice has shown that under PRD, less irrigation water can be applied than under full irrigation resulting in higher production per unit water used. The hypothesis is that the drying cycle induces the production of chemical signals in the roots, which are translocated to the leaves and result in partial stomatal closure and the regulation of growth. This, in turn, reduces vegetative growth and enhances fruit cell turgor, resulting in positive impacts on yield and/or quality. In practice, most of the PRD experiments to date have also imposed DI, making it impossible to distinguish impacts of the water deficit

FIGURE 12 Patterns of seasonal applied water to an orchard under full, regulated (RDI), and sustained (SDI) deficit irrigation.



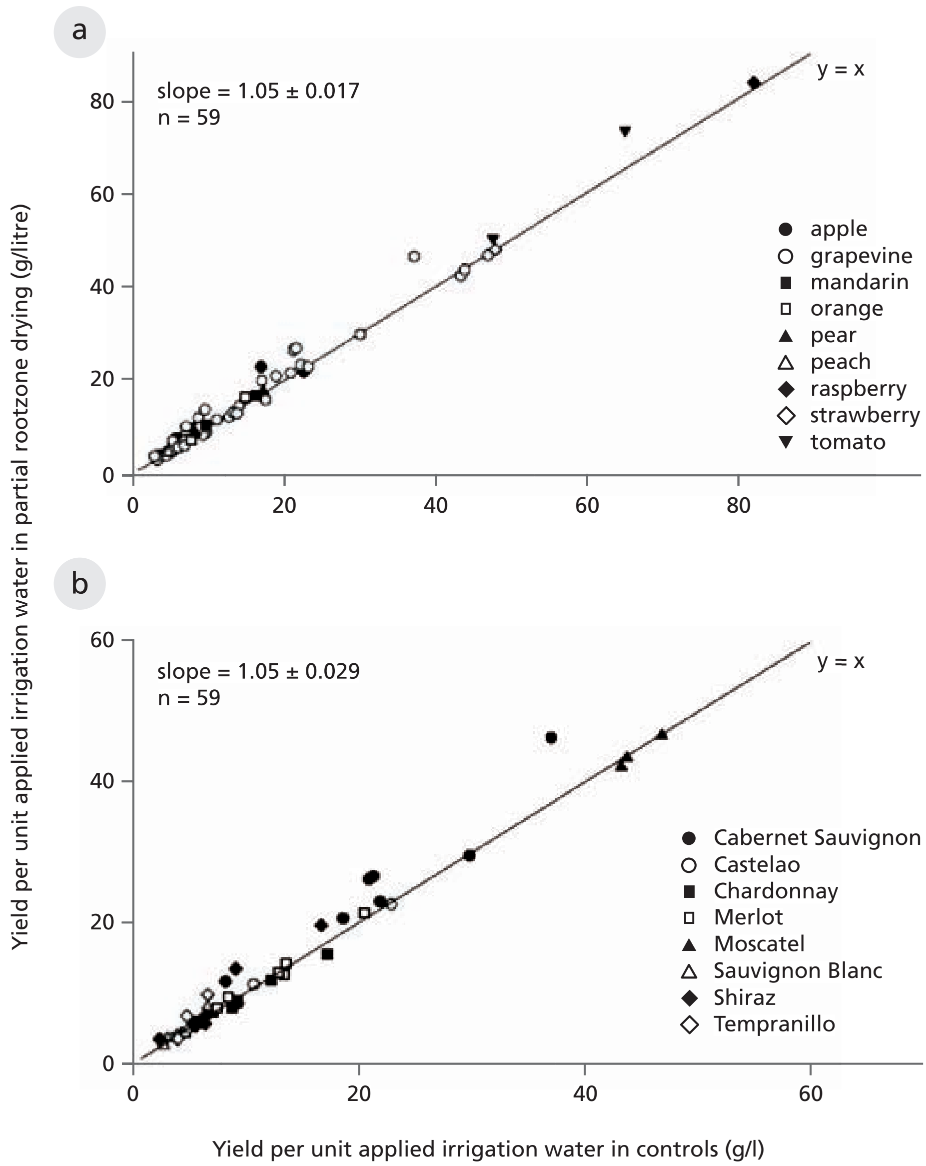
versus the alternate drying cycles. Indeed, the comparisons between PRD and other forms of DI, which apply the same irrigation levels under field conditions, have not shown any specific advantage of PRD over RDI in terms of production per unit irrigation water in a significant number of experiments (Figure 13) (Sadras, 2009).

Responses to deficit irrigation

All DI strategies aim to control crop water deficits by manipulating water supply as best as possible to maintain growers' revenues in water–limiting situations. Contrary to the responses of most annual crops, where yield declines linearly with ET under many watering regimes, the modulation of water deficits have a different impact on tree crops and vines. As an example, Figure 14 shows that three different DI strategies for almond trees had very different impacts on the yield response to applied water.

Most current RDI management approaches are based on irrigating a certain percentage of ET during stress-tolerant periods of the season. This concept works relative well in the mid and later parts of the season, after the soil moisture reservoir has been depleted of winter rainfall. However, early in the season stored water in the soil profile often buffers the impact of deficit irrigation on plant stress. Thus, even though one reduces irrigation, there will likely be a lag in terms of producing the desired plant stress. The duration of the lag depends on the depth of the root zone, soil water holding capacity, effective winter rainfall, and atmospheric evaporative demand. Therefore, there is greater need for precise plant-based water stress indicators, such as pressure chamber measurements, early in the season when using RDI. For example, one winegrape RDI strategy recommends delaying irrigation until a target leaf water potential is reached and then irrigating at a certain percentage of ET until after fruit colour change (*veraison* stage).

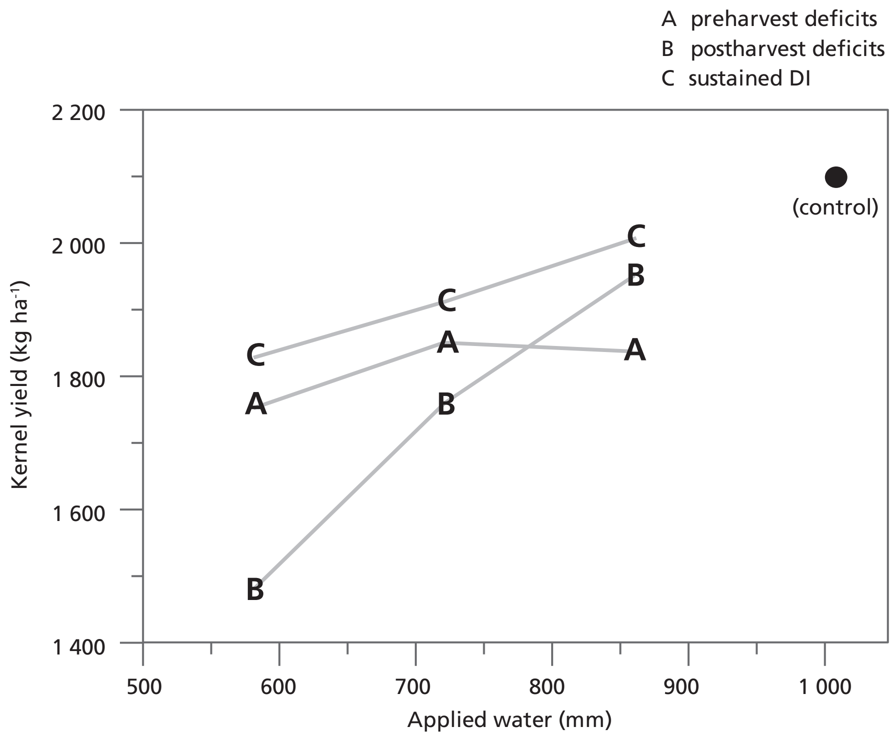
FIGURE 13 Comparison of yield per unit irrigation between crops managed with partial root-zone drying (PRD) and conventionally irrigated crops with similar amounts of water. (a) Fruit trees (b) Detail of grapevine cultivars (Sadras, 2009).



The DI practices discussed here refer to mature trees and vines. It has been shown that developing orchards should not be stressed until their canopies reach mature size to ensure that maximum production is achieved as early in the life of the orchard/vineyard as possible. Vegetative growth is very sensitive to water deficits and should be avoided if possible. Therefore, meeting the full needs of young orchards and vineyards is particularly important from the economic viewpoint, and the allocation of total farm supplies should take into consideration the objective of meeting full needs of the young orchard blocks whenever possible.

Soil fertility and pest management under DI has not been sufficiently researched to make generalizations. Since fertilizers are commonly applied through the irrigation system, reduced applied water will have a concomitant reduction in the amount of applied fertilizer. This should

FIGURE 14 Response of an almond orchard to three DI regimes: pre- and postharvest DI, and SDI over four years. Note that the yield decline is highest for the postharvest DI and that in this case, the SDI is the most advantageous DI strategy (after Goldhamer *et al.*, 2006).



be avoided by adjusting the fertilizer application scheme to ensure that the recommended amounts are added. There is little evidence that RDI results in lower levels of nutrients in the plant, at least based on leaf tissue analysis. This may be because RDI reduces leaf growth and thus, tissue concentrations are the same even though there is less nutrient uptake from the soil. There are positive and negative interactions between DI and the incidence of pest and diseases. In the specific crop sections, stress-related pest management and plant disease considerations are presented where appropriate.

Salinity management under deficit irrigation

All irrigation water contains salts but only pure water evaporates from plants and from the soil and the salts are left behind. Therefore, the process of irrigation concentrates salts in the soil profile to the point that they can reach harmful levels unless they are leached out of the root zone. The rate at which salts are concentrated as a result of irrigation depends on the quality of the irrigation water, the amount of annual rainfall, the irrigation amounts and the ET_c. If the seasonal water balance is such that there is a certain amount of drainage, salts will be displaced from the root zone and will move with the drainage waters below the root zone. In many cases, artificial drainage networks are needed to evacuate the excess water and the salts outside irrigated areas to ensure the sustainability of irrigated agriculture. The *FAO I&D No. 25* publication provides water quality guidelines and procedures to assess the leaching requirements, and on how to quantify the impact of salinity on crop yields.

When DI is practised, the amount of applied irrigation water is less than the ET_c and the water balance of the root zone is such that little or no leaching would occur during the irrigation season. Thus the risks of salinity buildup are higher under DI than under full irrigation. When reductions in water supply last only a year or two, it is possible to use mild to moderate DI with limited impact on yield and net income and with little salt accumulation. This is because normally, there is sufficient stored soil water to contribute to ET from the previous, normal year, and the salinity risks are limited if full irrigation resumes one or two years after the imposition of DI.

If DI is practised over the long term, a strategy for salinity management under DI must be devised to make DI sustainable. In areas where annual rainfall is significant (average, above 300 mm) and drainage is feasible, salinity buildup is controlled by the annual rainfall for waters of good to medium quality. Poor quality water may require some additional leaching in dry years, depending on the rainfall patterns. When annual rainfall is insufficient to leach the salts and microirrigation is practised, salts will accumulate and remain at the boundaries of the wetted zones by the emitters, and they may be harmful to the crop. Light rainfall may move these salts into the active root zones, and this is why in some dry areas drip irrigation systems are turned on when light rainfall is predicted. Sometimes, full coverage irrigation systems are used to leach the salts after leaf fall in deciduous tree plantations. Monitoring salinity is essential to anticipate possible problems, more so in dry areas and poor quality irrigation waters.

An important consideration in the case of salinity is that it is a gradual problem that in most cases takes time to build up. The limited experience with DI is that salts may be periodically controlled, even in dry areas, in the high-rainfall years or when irrigation supply conditions permit the return to full irrigation once every several years. Nevertheless, to sustain the plantations throughout their normal life cycle under DI, salinity monitoring and a sound management strategy for salinity control will be critical.

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4.1 Fruit trees and vines

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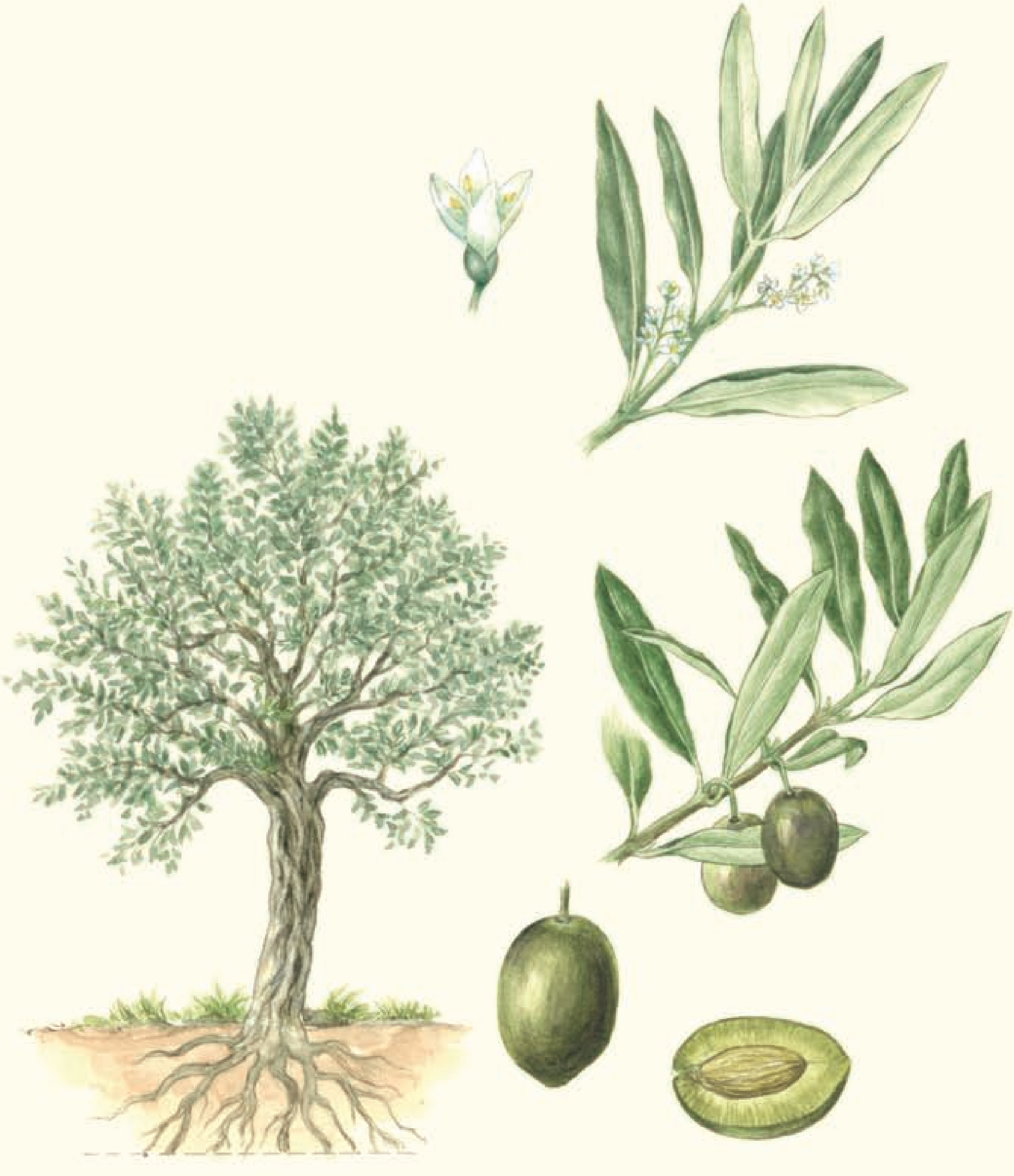

Olive

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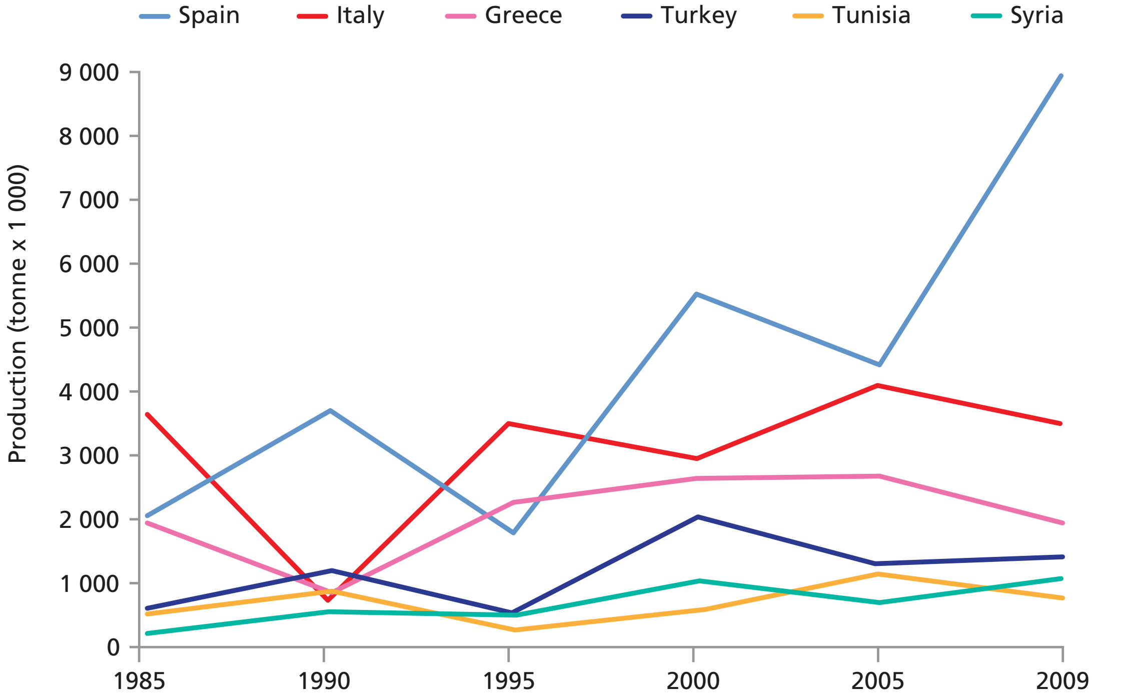
Olive

GENERAL DESCRIPTION

Olive (*Olea europaea L.*) is an evergreen tree grown primarily between 30 and 45° latitude in both hemispheres. In 2008 total harvested area was over 10 500 000 ha, 95.5 percent of which was concentrated in ten countries surrounding the Mediterranean Sea (FAO, 2011). Spain, Italy and Greece are the main producers of virgin oil followed by Tunisia, Syria, Turkey and Morocco (years 2002-2008). About 90 percent of the world production of olive fruit is for oil extraction, the remaining 10 percent for table olives. The world cultivated area of olives in 2009 was over 9.2 million ha with an average yield of 2.1 tonne/ha (FAO, 2011). Figure 1 shows the evolution of olive production over the last decades in the principal countries. European Union countries produce 78 percent and consume 68 percent of the world's olive oil.

Olive trees have been sparsely planted for centuries, without irrigation, on marginal lands in Mediterranean climate conditions because of their high resistance to drought, lime and salinity. Typical densities of traditional groves are between 50 and 100 tree/ha with trees severely pruned to stimulate vegetative growth and renewal of the fruiting surface, and the soil periodically tilled. Fruit yields are low, ranging from less than 1 up to 5 tonne/ha of olives. Although traditional groves vary in cultivar composition, tree density, training system, degree of mechanization and chemical inputs, they are still the most widespread production system and a landmark of Mediterranean landscapes. Intensive orchards have a density of between 200 and 550 tree/ha, which translates into a higher fraction of intercepted radiation that leads to higher productivity per unit land area than traditional systems, particularly during the first 10 years of production. Trees are trained to a single trunk for mechanical harvesting and the soil is often managed by temporary or permanent grass cover to reduce erosion and ease traffic in wet periods. In areas of annual rainfall higher than 600 mm, production can be maintained under rainfed conditions in soils with good water-holding capacity. However, irrigation plays an important role in the drier areas, and/or for soils with limited water storage. Elsewhere, irrigation plays an important role to stabilizing yields in the years of low rainfall. Irrigation is becoming common in the intensive orchards as it allows early onset of production (from the second to forth year after planting), high yields (averages up to 10-15 tonne/ha) under optimal conditions and less variability because of alternate bearing.

FIGURE 1 Production trends for olives in the principal countries (FAO, 2011).



Quality considerations

Of the several categories of olive oils, defined according by the European Union legislation (Reg. EEC 2568/91, UE 702/07 and 640/08), and widely accepted internationally, the concept of quality only pertains to virgin olive oil (VOO), the main product of the olive industry. In order to qualify as VOO, it is required that oils satisfy analytical parameters and be tested and approved for their sensory characteristics by a panel of experts. Moreover, the current perception of quality is mainly based on the sensory and health-related properties, which are closely related to the concentration and composition of the phenolic and volatile fractions, respectively. Oleic acid is the most abundant fatty acid followed by palmitic acid, linoleic acid and others that do not exceed 2 percent of fatty acid composition. Fatty acid composition is cultivar dependent and changes with climatic conditions and progression of ripening. The ratio between mono-unsaturated and poly-unsaturated fatty acids first increases, then it reaches a maximum and then decreases in overripe fruit. The concentration of phenolic compounds in the fruit, and consequently in the oil, is also cultivar dependent and reaches a maximum at the beginning of ripening, when the skin (epicarp) is still partially green, to decline sharply in overripe fruit. Qualitative features of table olives are similar to those of other stone fruit used for fresh consumption and include fruit size, pulp-to-pit ratio, pulp firmness, colour and soluble carbohydrate concentration.

Most of the world's olive area is composed of the two systems described above. However, in the last 15 years very high density, hedgerow type, olive orchards (from 1 000 to 2 000 tree ha) have been developed to further reduce harvesting costs using over-the tree harvesting machines. Because of the higher ET_c demand of the dense canopies and the low soil volume available for each tree, irrigation is needed. Average yields can be quite high (5-15 tonne/ha) in the first years of production (third to seventh year after planting) and may average 10-14 tonne/ha over a 10-year period, but there are questions about the sustainability of high yields in the long term, and about the adaptation of many cultivars to this production system. The area devoted to these super-intensive plantations is about 100 000 ha worldwide.

STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Yield is the result of three main developmental processes that occur between flowering and harvest: fruit set, fruit growth and oil accumulation in the fruit pulp (mesocarp). Vegetative growth is critical in terms of olive fruit production, because flowering and fruit set originate in the axillary buds of past year's growth. The reproductive cycle from flower bud induction to fruit ripening takes 15-18 months depending on cultivar and growing conditions, as it starts in the summer and ends in the autumn of the following year. Flowers are usually borne in inflorescences at the axil of leaves of one-year old wood, whereas the terminal bud of the shoot is almost always vegetative (Rapoport, 2008). Shoot growth starts with bud break in spring and resumes when temperatures are above 12 °C, as long as it is not inhibited by temperatures above 35 °C, soil water deficit or other environmental stresses. A second flush of shoot growth is common after the summer. Olive trees are sensitive to waterlogging and temperatures below -10 °C.

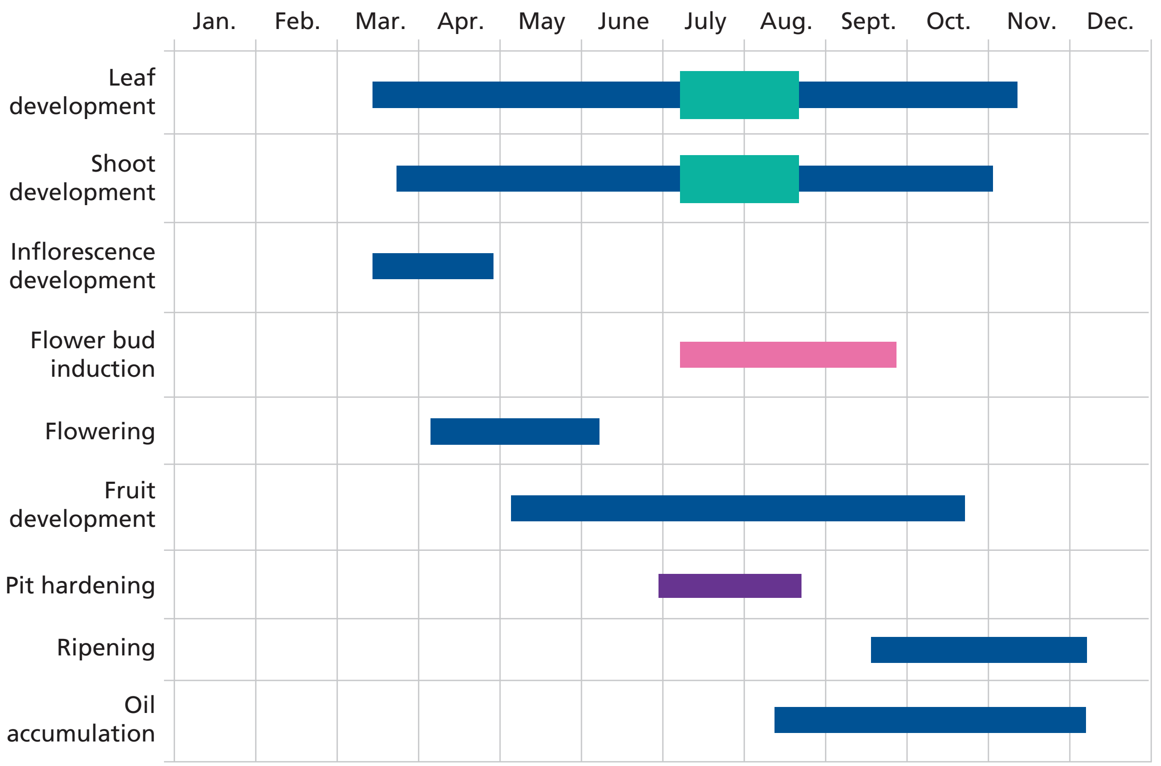
Chilling is needed for flower bud differentiation. Lack of chilling results in scarce and uneven formation of flower buds. Chilling requirements vary with the cultivar but at least 10 weeks below 12 °C are usually needed for abundant flowering. Main phenological stages for olive trees, described according to the two-digit Biologische Bundesanstalt, Bundessortenamt and Chemical industry (BBCH) scale, include bud break, bud development, leaf full expansion, beginning of flower cluster development, full elongation of flower clusters, full flowering, fruit set, fruit development, maturity and senescence. The time sequence of main developmental processes is reported in Figure 2.

Olives flower in late spring, a month or two later than to many deciduous trees; timing and duration depend on cultivar, temperature and soil water availability. Fruit set is generally low (less than 2 percent of flowers) but suboptimal conditions (temperature, rain, winds) can reduce it further. Fruit growth apparently follows the typical double-sigmoidal pattern of stone fruit, although there are some questions as to whether this pattern is inherent to olive fruit development or is a consequence of the interaction with environmental constraints in midsummer such as high temperature and low water availability. Fruit pit hardening occurs about two months after fruit set. Oil accumulation in the fruit is proportional to the intercepted solar radiation and becomes substantial in late summer for most cultivars, right after the end of massive pit lignification. At harvest, fruit contain between 10 and 25 percent oil on a fresh weight basis, depending on cultivar, crop load and growing conditions. Oil accumulation patterns in the mesocarp follow a simple sigmoid curve, but may vary with cultivar and environmental conditions.

RESPONSES TO WATER DEFICITS

Olive trees are very resistant to drought and show a high capacity to recover from prolonged drought periods. Trees can completely re-hydrate within three days of irrigation after a water deficit that reached a leaf water potential (LWP) of -4.0 MPa. Even during a severe drought that

FIGURE 2 Occurrence and duration of main phenological stages of olive trees during the growing season (n). Flower bud induction occurs during the summer of the previous year (n-1). Shoot and leaf development are often inhibited by high temperatures and water deficit during the summer (vertical shading). Modified from Sans-Cortes *et al.*, (2002).



lowered the LWP down to -8.0 MPa, the trees rehydrated in less than a week following the onset of rains (Connor and Fereres, 2005). Nevertheless, as for all terrestrial plants, expansive growth of olive leaves, branches, fruit, and trunk, is sensitive to water deficits. Water stress also affects stomatal opening and photosynthesis. It is well known that olive stomata close partially during the day (Fereres, 1984) in response to increases in vapour pressure deficit, even if the trees are well watered, with corresponding decreases in CO_2 assimilation. Leaf photosynthetic rate is relatively high, of the order of 12-20 μmol CO_2 m^{-2} s^{-1}, but is reduced under and following water stress because of stomatal closure. When water deficits are severe (LWP below -4 to -5 MPa), photosynthetic rate does not exceed one-third of normal values, reaching a maximum early in the morning and then declining as the day advances (Angelopulos *et al.*, 1996).

The olive root system is extensive and vigorous and, therefore, can explore the soil profile thoroughly after the first years of tree establishment. In general, it can be assumed that most of the absorbing roots are in the first 1 m depth. However, in deep alluvial soils, roots can reach 2-3 m depth or more, whereas in marginal soils the rooting depth may be less than 0.5 m. Given the capacity of olive trees to lower their LWP to -7 MPa or less, the soil water content in parts of the root zone can easily reach values below the standard permanent wilting point. Given the shape of the moisture release curve of most soils, the amount of additional water extracted would be small. Nevertheless, such small amounts may be critical for surviving extreme droughts.

Because olives flower late, the risk of low temperature damage is significantly reduced; however, the risk is increased of being affected by water and/or high temperature stress in the Mediterranean climate, and also fruit growth is delayed into the summer, normally an extended period of water shortage. It has been observed that for rainfed trees in years when winter rainfall has been very limited, that flowering and fruit set are processes that are quite sensitive to water deficits. Thus, water stress should be avoided from floral development to fruit set in spring. However, in relatively humid climates (e.g. central and northern Italy) stress seldom develops in spring and irrigation is usually unnecessary. Once the fruit is set, it grows more or less linearly by cell division and subsequent expansion, unless water deficits and high temperatures slow its growth rate. Initial rapid fruit growth (Stage I) and the period when oil is actively accumulated in the fruit (Stage III), are also sensitive to water deficit.

Given that water deficits reduce fruit growth, irrigation that avoids water deficits increases fruit size, although the effect is mediated by the amount fruit borne on the tree. Once the fruit is set, its growth rate may be slowed down by water deficits, but growth quickly resumes upon relief from stress by rainfall or irrigation. Complete recovery of endocarp growth occurs even after several weeks of deficit, whereas recovery of mesocarp growth is less certain. The pulp-to-pit ratio, an important quality feature for both table and olive oil fruit, is increased under irrigated conditions, but it has been observed that mild water deficits during fruit development have a positive effect on the pulp-to-pit ratio (Gucci *et al.*, 2007).

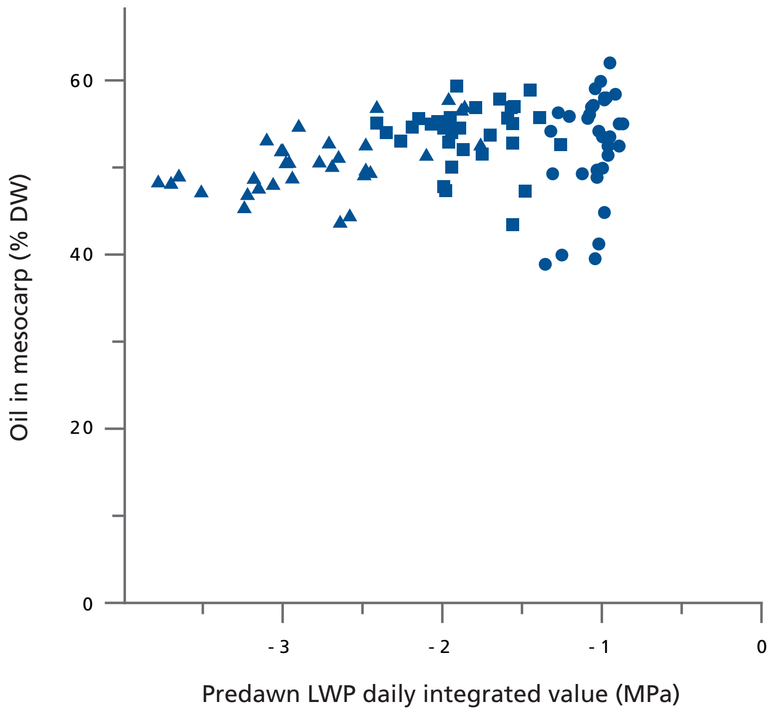
Soil water availability affects colour change and ripening of fruit. The effect of irrigation on oil content may be apparently contradictory as it affects water content and the process of oil accumulation in the fruit in different ways. It is well known that severe stress during the oil accumulation period (from mid-August through the end of October for most cultivars in the Northern Hemisphere), reduces the oil percentage on a dry weight basis at harvest. As stress becomes less intense the oil percentage increases, although at a relatively low rate. Under non-stress conditions the variability of data on the relationship between predawn LWP and oil content increases and oil concentration may be even less than for mildly stressed fruit (Figure 3).

While irrigation does not usually alter the fatty acid composition or basic parameters used for the classification of VOO (e.g. free acidity, peroxide value, spectrophotometric indexes), increasing volumes of water applied decrease the concentration of phenolic compounds in the oil, namely the concentration of secoiridoid derivatives of oils, such as 3,4-DHPEA-EDA, 3,4-DHPEA-EA and p-HPEA-EDA (Gomez-Rico *et al.*, 2007 and Servili *et al.*, 2007), which act as natural antioxidants during oil storage and play important functions in human diet and prevention of cardiovascular diseases. As a result, oils from irrigated orchards are usually less bitter and pungent that those from rainfed ones (Servili *et al.*, 2007).

Assessment of tree water status

The established method of measuring tree-water status is the measurement of stem-water potential or leaf-water potential. Exposed leaves are used for the latter while shaded or covered leaves are used for SWP; in some cases, small terminal branches have been used to characterize tree water status. Predawn LWP is a reliable indicator of tree water status in mature trees, but it is inconvenient in practice because of the need for early morning measurement.

FIGURE 3 The relationship between oil in the mesocarp on a dry weight basis measured at harvest and predawn leaf water potential (LWP) for olive trees cv. Leccino grown under three irrigation regimes over two consecutive years (modified from Gucci *et al.*, 2007).



The LWP measured on exposed leaves at midday depends not only on soil water availability but also on environmental conditions that influence canopy conductance during the day. Water potential values of exposed leaves are more variable as they are affected by the degree of stomatal opening. With stomata fully open, the gradient between stem and sunlit LWP is about 0.5 MPa when water supply is adequate. Such value may increase (up to 1 MPa) as water stress increases, but it tends to decrease again as stomata close.

Stem-water potential (SWP) is considered a more reliable indicator of tree-water status than midday LWP, because it is less dependent on diurnal changes in radiation and humidity. The midday SWP of olive trees grown under adequate soil water supply, ranges between -0.5 and –1.2 MPa, depending on the evaporative demand, with a tendency to decrease even to lower values in mid- to late summer under conditions of high evapotranspirative demand (Gimenez *et al.*, 1997). SWP values for olive are higher than -0.5 MPa have been only occasionally measured. Typical reference values for midday SWP for mature, fully-productive olive trees vary between -1.0 and -1.2 MPa for summer, sunny days with an ET_o of 5-6 mm/day.

Under water deficit conditions, stress develops and SWP values decrease. Typical values of SWP for moderately-stressed trees are between –1.7 and -2.5 MPa, and become severe when values approach -3.5 to -4.0 MPa. Although olive trees have exceptional resistance to drought, and SWP or LWP values as low as –7.0 to -8.0 MPa have been measured in rainfed olive trees during severe drought periods (Fereres, 1984), these values should be considered exceptional and close to a survival state rather than acceptable for satisfactory yields.

The use of displacement sensors to monitor olive trunk growth and trunk diameter fluctuations has yielded information that confirms the high sensitivity of expansive growth to water deficits. These highly sensitive sensors could be used in young, intensive plantations where the objective is to maximize canopy growth and reach full production as early as possible. Sap flow sensors have also been used to determine changes in sap velocity, which are indicative of transpiration rate and of its changes in response to water deficits. All these instruments are still in the research and development stages and are not yet used commercially for irrigation scheduling.

WATER REQUIREMENTS

Olive trees withstand long periods of drought and can survive in very sparse plantings even in climates with only 150-200 mm annual rainfall. However, economic production requires much higher annual precipitation or irrigation. Table 1a summarizes the crop coefficient (K_c) values proposed by various authors that have been developed in different environments. The range of K_c values is quite wide, varying from less than 0.5 to about 0.75, average values varying

TABLE 1a Monthly crop coefficients (K_c) used for olive orchards in different olive-growing regions and recommended average values.

Site, region	Latitude	ET_o (mm)	Rainfall (mm)	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
Bibbona, Tuscany	43° 16 N	1 000	772 (30-year mean)	-	-	-	0.60	0.55	0.65	0.65	-	-
Metaponto, Basilicata	40° 22 N	1 270	492	0.7	0.65	0.6	0.55	0.5	0.5	0.6	0.65	-
Sassari, Sardinia	40° 42 N	-	-	-	0.55	0.5	0.5	0.5	0.5	0.5	0.55	-
Cordoba, Andalusia	37° 50 N	1 420 (mean of 3 years)	639 (mean of 3 years)	0.65	0.6	0.55	0.55	0.5	0.5	0.55	0.6	0.65
Fresno, California	36° 44	-	-	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	-
Benevento, Campania	41° 06 N	1 240 (20-year mean)	714 (20-year mean)	-	-	-	0.65	0.65	0.65	0.65	-	-
Recommended values, clean cultivated	-	-	0.45 * to 0.75	0.45 to 0.75	0.5 * to 0.65	0.55	0.55	0.5 to 0.55	0.5 to 0.55	0.55 to 0.6	0.6 to 0.65	0.6 to 0.65

** In winter and spring only, the low K_c applies to dry, cold climates, while the high K_c applies to areas frequently wetted by rainfall.*

TABLE 1b Summary of recommended olive K_c values.

Climate*	Semi-arid	Arid
Spring	0.65-0.75	0.45-0.55
Summer	0.50-0.55	0.50-0.55
Fall	0.60-0.70	0.55-0.65
Winter	0.65-0.75	0.40-0.55

** Mediterranean-type climates; the one labelled semi-arid has seasonal rainfall values around 500 mm or more, mostly between autumn and spring, while the arid climate would have less than 400 mm rainfall and is more continental, with relatively cold winters. The higher K_c values of the range should be used for high rainfall situations. K_c values to be used with ET_o calculated following FAO I&D Paper No. 56.*

from 0.55 to 0.65, depending on the season. A synthesis of current estimates of K_c developed recently (Fereres *et al.*, 2011) is given at the end of Table 1b.

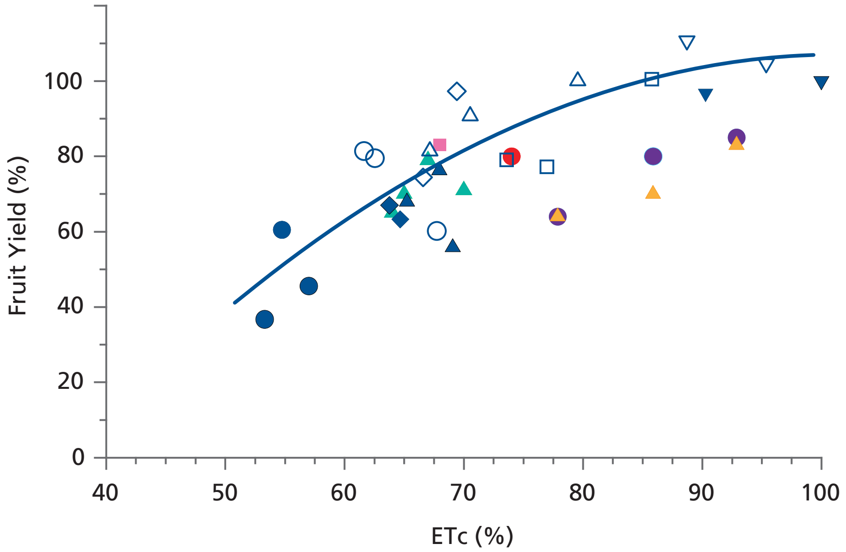
Despite the evergreen nature of the olive, the K_c is not constant throughout the year, because of tree transpiration responses to environmental and endogenous factors. Measurements have shown that relative transpiration is lowest in spring and highest in early autumn. However, the K_c also must reflect the rate of evaporation from the soil surface, which is quite high in spring in many Mediterranean environments. Thus, K_c values reflecting olive orchard water use do not differ as much between spring and autumn (see Table 1). In midsummer relatively low values of K_c are found because of partial stomatal closure in response to high vapour pressure deficit.

If more precise estimates of water use are needed, an alternative method has been proposed to calculate transpiration and evaporation independently (Orgaz *et al.*, 2006) (See Chapter 4, Box 5). For table or canning fruit production, the higher range of K_c values is recommended. Crop coefficients should be further increased (up to about 0.8 to 1.0 in winter and early spring, depending on the type of the cover crop and its density) if the orchard floor has a permanent grass cover.

WATER PRODUCTION FUNCTION

Olive fruit yield decreases as ET_c decreases below its maximum. However, it has been found that the decline in production is hardly detectable with small reductions in ET_c (Figure 4). As ET_c is further reduced, however, yields decline more. Thus, the response curve of yield (fruit or oil) to ET_c is almost linear at low levels of consumptive water use, but levels off when water consumption is high. As a result, the overall response curves are parabolic and can be described by second order equations, such as the one presented in Figure 4. The shape of the curve implies that the water productivity (WP) increases as ET decreases and, therefore, one can find an economic optimum, in terms of ET and therefore of irrigation amount, if the price of oil and the irrigation water costs are taken into consideration. The curve shown in Figure 4 is the best fit line to a dataset obtained for the cv. Picual at Cordoba, Spain (Moriana *et al.*, 2003). Additional data published for the cvs. Arbequina, Morisca, Mulhasan, Frantoio, Leccino, and also for the cv. Picual collected at another location, are also plotted in Figure 4. It appears that the data from other varieties/locations fall within the margins of error, on the curve originally obtained at Cordoba, with perhaps the cv. Morisca showing higher sensitivity

FIGURE 4 Relationship between relative fruit yield and relative ET_c for olive. Curve was obtained for the cv. Picual in Cordoba, Spain (Moriana *et al.*, 2003), and data points obtained from additional studies (Lavee *et al.*, 2007; Iniesta *et al.*, 2009; Martin-Vertedor *et al.*, 2011; Gucci *et al.*, 2007 and Caruso *et al.*, 2011) for different cultivars, as shown in the graph.



to mild ET_c deficits than the cv. Picual. More research is needed to characterize the response of the other cultivars in different environments. From the original data sets and equations in Figure 4 for Cordoba, Spain, over 700 mm of water consumed in ET_c are needed to reach the maximum olive fruit yield in that particular environment. If the effective rainfall is 400 mm, at least 300 mm would have to be supplied by irrigation to achieve maximum yields in that particular location. However, because of the shape of the yield response to ET_c, olive production responds very well when small irrigation amounts are applied to rainfed orchards. In different locations in southern and northeastern Spain (between 350-500 mm of annual rainfall), farmers are achieving WP values of up to 30 kg/ha/mm (fresh fruit) with seasonal irrigation applications of 100 to 150 mm in orchards that were previously rainfed. In coastal, central Italy (about 600 mm annual precipitation), less than 100 mm of irrigation water are sufficient to obtain yields that are over 80 percent of those of fully irrigated orchards (Gucci *et al.*, 2007). Significant increases in yield were obtained in Israel using a single irrigation of 75 mm in the middle of the summer (Lavee *et al.*, 2007).

The yield response curve to applied irrigation water is similar to Figure 4 but flatter at high irrigation levels, because the olive is capable of extracting substantial stored soil water and can compensate for reductions in applied water, as long as there is sufficient water in the root zone. The level of irrigation savings depends on the storage capacity of the soil and on the amount of rainfall needed for the sustainable replenishment of stored soil water. The response of oil production is similar to that of the response of fruit production, and the responses of oil quality are discussed below.

The yield response of table olives to a reduction in applied water (AW) is shown in Table 2 from one study (Goldhamer *et al.*, 1994). A reduction in AW of 21 percent did not affect fruit yield or revenue. A further reduction down to 62 percent of maximum AW, decreased relative fruit yield by 10 percent, and relative revenue by 25 percent. The more drastic reduction in revenue was associated with a lower price due to the reduction in fruit size.

TABLE 2 Relative yield and gross revenue of table olives under deficit irrigation (Goldhamer *et al.*, 1994).

Regulated deficit irrigation regime	Consumptive use (mm)	Gross fruit yield (t/ha)	Gross revenue (US$/ha)	Relative ET_c (%)	Relative yield (%)	Relative gross revenue (%)
Control	881	12.0	6725	100	100	100
T2	759	12.3	6750	83.9	103.1	100.4
T3	693	12.5	6700	75.4	103.7	99.6
T5	546	10.8	5050	56.3	90.0	75.1

SUGGESTED RDI REGIMES

Several specific cases are developed below for different environments and water supply situations. Table 3 illustrates an example of the water budget approach for irrigation scheduling of a young olive orchard in central Italy. Values are reported on a monthly basis, but during normal irrigation practice water budgets are calculated weekly. Two irrigation levels are used, full irrigation and 50 percent deficit irrigation. It should be noted that the early water deficit that occurred in April was unusual for this location, where the irrigation season normally starts in June. In more arid climates it is normal that irrigation starts in spring and may extend well into the fall season. Water is preferably applied to satisfy tree daily needs by microirrigation, but in poorly-drained soils it is desirable to reduce the frequency of irrigation to 1-2 times a week. The use of longer intervals with microirrigation is often inefficient because there may be significant losses to deep percolation. When water agencies supply water at longer intervals (2-4 weeks), it is desirable to build on-farm storage facilities to irrigate as frequently as needed.

Three different RDI strategies have been successfully demonstrated for olive irrigation. In the first, the planned deficit is distributed evenly throughout the whole irrigation season (sustained deficit irrigation or SDI). In the second, the deficit is concentrated in the summer period, from pit hardening until the end of the summer (RDI_1). The third strategy (RDI_2) which is intermediate between the previous two, alternates short cycles of stress and relief during the irrigation period, maintaining the SWP or predawn LWP at variable levels which are moderately low during the fruit development period. The hypothetical seasonal course of tree water status under the three different DI strategies is represented schematically in Figure 5.

There is no evidence to demonstrate the superiority of one RDI strategy over the others, as they all seem to give good results (see below). In areas where rainfall patterns are typically Mediterranean, and where soils have a reasonable water storage capacity (over 100 mm of extractable water), the RDI strategies are easily implemented with irrigation systems that have limited (below the ET needs) and fixed capacity (i.e. two emitters per tree). The irrigation system is run for the same period more or less throughout the entire season. In late spring,

TABLE 3 Sample calculation of monthly water budget for irrigation scheduling in a high density (510 tree/ha), 5-year-old olive orchard grown in a loam soil at Venturina (central Italy). Two levels (full, deficit) of irrigation are reported yearly ET_o = 965 mm; precipitation 708 mm. Flowering occurred on 13 May 2007. The crop coefficient was 0.55, the coefficient of ground cover 0.8. Average monthly min and max temperatures and ET_o are reported. Effective rainfall (ERain) was calculated as 70 percent of total rainfall (Rain), excluding precipitations less than 4 mm. (Caruso *et al.*, 2011)

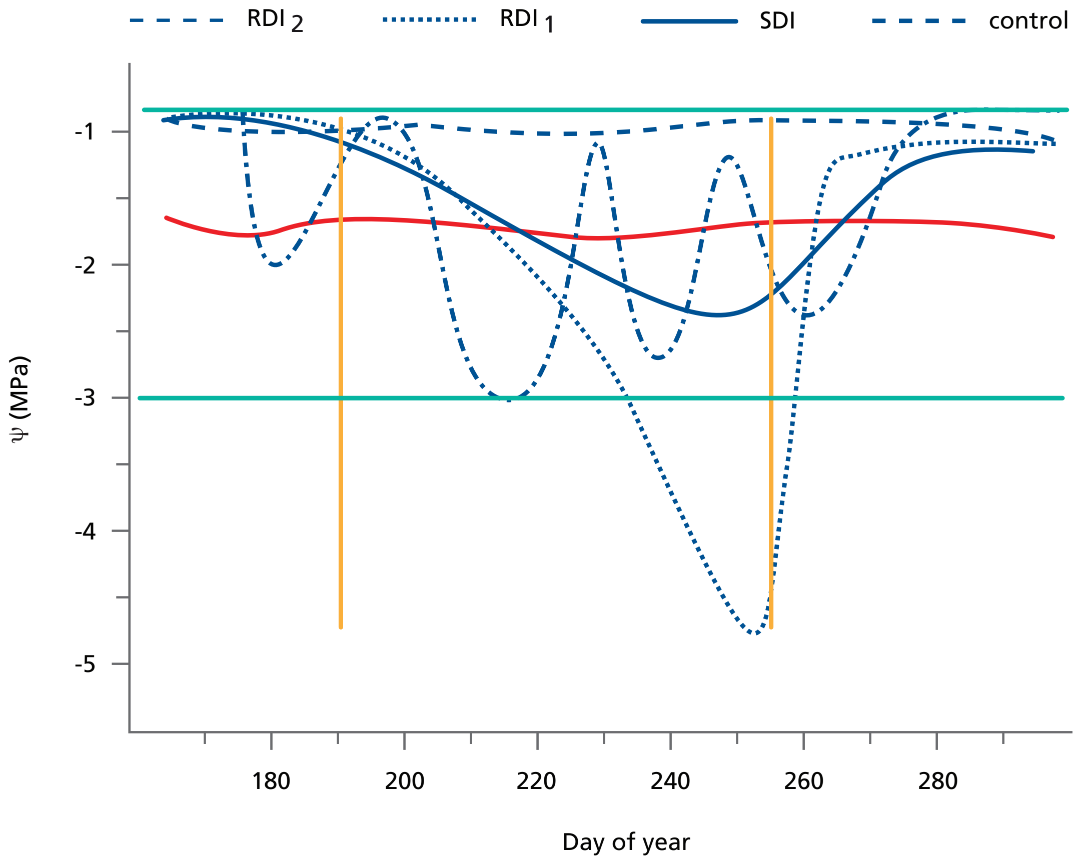
Month	T_{max} (°C)	T_{min} (°C)	ET_o (mm/day)	ET_c (mm/ month)	Rain (mm/ month)	ERain (mm/ month)	ET_c - ERain (mm/ month)	Full irrigation (mm/ month)	Deficit irrigation (mm/ month)
J	14.7	5.5	0.7	9.6	30	21	-11.4		
F	15.6	4.6	1	12.3	96.6	67.62	-55.32		
M	16.4	5.3	1.9	25.9	76.6	53.62	-27.72		
A	22.3	6.9	3.3	43.6	6.8	4.76	38.84	2.8	2.8
M	24.2	10.6	4.3	58.7	130.8	91.56	-32.86	2.8	2.8
J	27	14	4.8	63.4	68.8	48.16	15.24	3.9	3.9
J	30.3	14.6	5.4	73.7	0.6	0.42	73.28	58.9	19.7
A	29.8	12.9	4.3	58.7	36.2	25.34	33.36	36	13
S	26.7	10.2	2.8	37	19	13.3	23.7	30.4	30.4
O	22.5	7.9	1.5	20.5	88	61.6	-41.1		
N	16.8	4.7	0.9	11.9	102.6	71.82	-59.92		
D	18.1	-1.6	0.7	9.24	52.2	36.54	-27.3		

the water supply is normally adequate to meet the full ET needs, but as the summer starts and the ET_o increases, supply from the drip system is insufficient and water is extracted from the soil reservoir to meet the demand.

As the season progresses, water deficits set in, to increase in severity as the summer advances, but by the end of summer ET_o start to decline and the rains may arrive. At this time, the level of stress is reduced or eliminated, which is desirable during the fruit growth and maturation period. By manipulating irrigation frequency, the grower can run the system a fixed time (normally at its maximum capacity) and scheduling becomes straightforward. The RDI_2 approach permits the installation of irrigation systems designed to cope with situations of very limited water allocation, for instance in cases when water is drastically restricted during midsummer (mid-July, end of August) for conflicting urban uses (e.g. tourism in Liguria, Italy). A key factor for success with the RDI_2 approach is to start irrigating early enough to conserve the soil water reserve for when the ET_o demand is high.

The sustained deficit irrigation strategy (SDI) is planned by distributing the water deficit proportionally to the monthly ET requirements. In this case, for the same amount of water, the anticipated water deficits are of less magnitude at midsummer than in RDI_1, while the stress that develops earlier and later in SDI, should be of greater magnitude than in the RDI_1.

FIGURE 5 Hypothetical seasonal course of leaf or stem-water potential for olive trees subjected to different strategies of deficit irrigation. Green horizontal lines bracket the range between fully hydrated trees and turgor loss point, vertical orange lines limit the interval of water deficit. Values will vary in different climate and soil conditions. Legend: broken line, fully-irrigated baseline; solid line, SDI; dotted line, RDI_1; broken and dotted line, RDI_2.



The RDI_2 strategy may be useful in soils with a high clay percentage to allow the root system not to be exposed to high humidity for long periods.

Other RDI strategies that have been sought include the concentration of the water deficit in the 'off' year, when the crop load is so low that vegetative growth in not affected much by the water deficits. In the 'on' year, the water saved in the previous year is applied to maximize fruit production with minimum water deficits. The only published test performed with this strategy (Moriana *et al*., 2003) did not give as good results as the previous three strategies described above. Also, the management of water supply under this strategy is not easy, and it will require commitments of water supply that exceed the current season and that, therefore, may be hard to implement by many water agencies.

Because olive irrigation is a relatively new practice, often irrigation authorities cannot deliver sufficient water to meet the full orchard requirements and are promoting deficit irrigation practices. Reasons include lack of sufficient water supply, equity considerations, the limitations imposed by the original tree spacing of the rainfed orchards, and priority for urban uses. When supply is limited to such levels, use of drip irrigation is a must, with as few emitters per tree as possible. Also, growers should irrigate as infrequently as feasible (once or twice a week) to minimize E losses and avoid prolonged exposure of olive roots to high soil-water levels in clayey soils. If supply is very limited, and a new irrigation system is going to be installed, one option would be to use subsurface drip as E losses would then be negligible.

The goals of water saving using RDI in olive orchards appear particularly interesting. Most documented evidence indicates that RDI strategies supply only 30 to 70 percent of the volume needed for fully-irrigated trees. Seasonal water volumes of as little as 50 mm are sufficient to increase yields significantly in subhumid climates, whereas about 100 mm are needed in drier climates. These amounts are definitely much less than that used in most other crops.

Today, an important issue is the use of RDI to optimize oil quality. Recent evidence shows that the concentration of phenolic compounds and volatile compounds with sensory impact can be optimized using RDI strategies rather than by applying full irrigation or under rainfed (Gomez-Rico *et al.*, 2007; Motilva *et al.*, 2000 and Servili *et al.*, 2007). The beneficial effects of moderate water deficits that are imposed by RDI on olive oil composition stemmed the term 'qualitative irrigation', an aspect which will probably be more important. There are some reports that recommend restricting irrigation before harvest to limit or avoid trunk damage during mechanical harvesting by trunk shakers and/or problems of oil extractability during processing in the mill. Deficit irrigation appears to be beneficial for optimizing the pulp-to-pit ratio in of table olives (Gucci *et al.*, 2009).

Additional considerations

Introducing irrigation to rainfed olive growing involves a number of potential side effects. Increasing incidence of Verticillium wilt (*Verticillium dahliae*) disease has been reported, especially for young orchards. There is documented evidence that inoculum density of the pathogen is higher in wet areas than in dry. Although the cause of greater incidence of Verticillium wilt in irrigated orchards is unclear, it is likely that susceptible secondary olive roots increase close to the drippers where the soil may be quite wet favouring infection, weeds survive longer and temporarily host the pathogen, and infected leaves decompose quicker under high humidity conditions (Lopez-Escudero and Blanco-Lopez, 2005). The Verticillium wilt disease is a limiting factor for irrigated orchards in some areas where localized, low-frequency irrigation is recommended as a management technique.

Further, reportedly here is an increasing damage by the olive fruit fly (*Bactrocera oleae* Gmel.) in irrigated orchards, but supporting evidence is not strong. The olive fruit fly preferably damages large fruit (cultivars of large fruit size and olive fruit with high water content are more susceptible than small), so its effect may be indirect because irrigation increases fruit size. However, it is likely that the fruit fly also enjoys more favourable conditions when humidity is higher because of irrigation in the olive orchard.

Problems of the low oil yield of fruit from fully-irrigated, very high density orchards of some cultivars have been reported, but they appear to be related to technological problems in oil extraction when fruit is highly hydrated rather than to less oil in the fruit itself. Because of the relatively high resistance to salinity, olive trees yield well when irrigated with saline waters (Gucci and Tattini, 1997).

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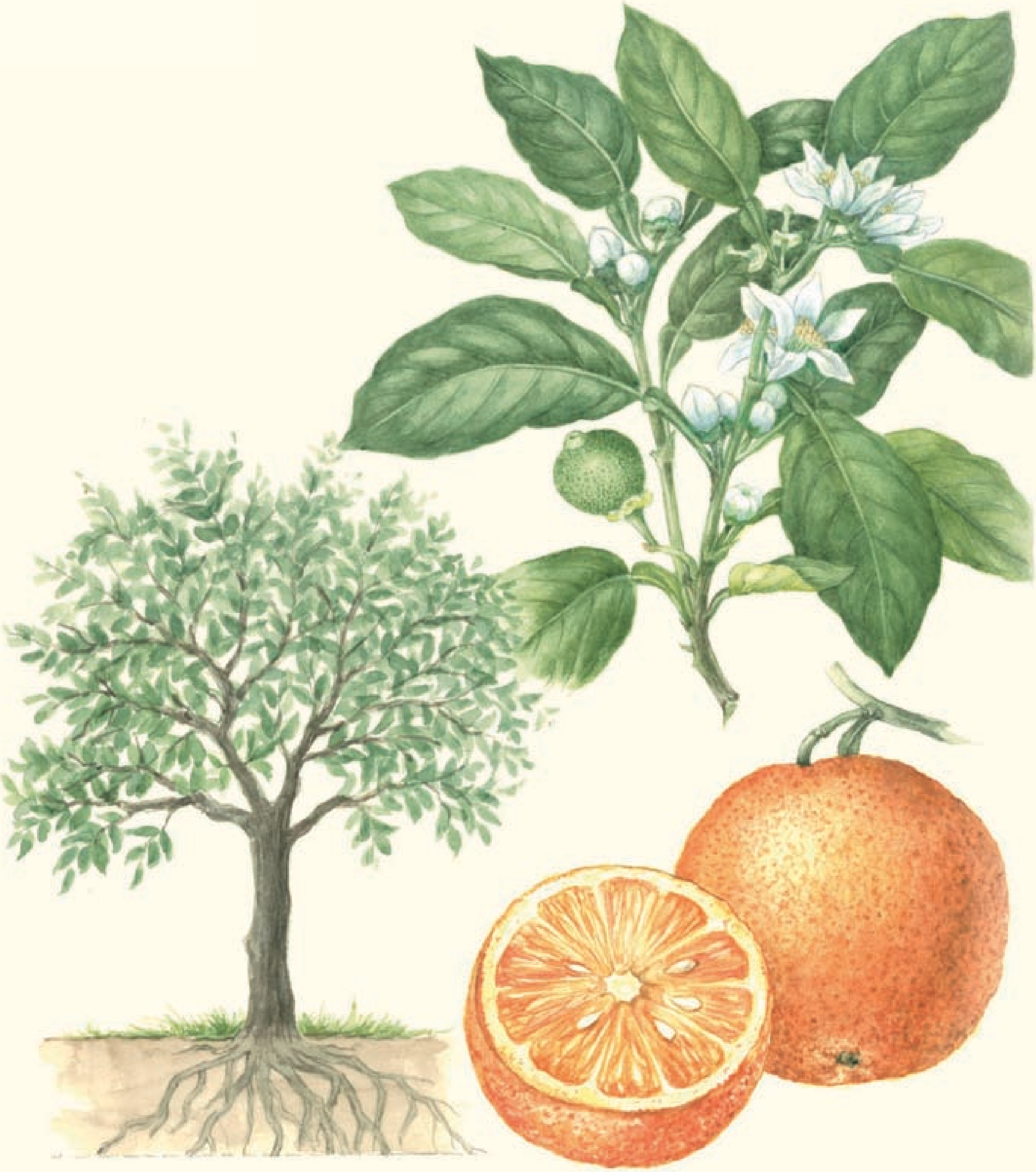

Citrus

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Citrus

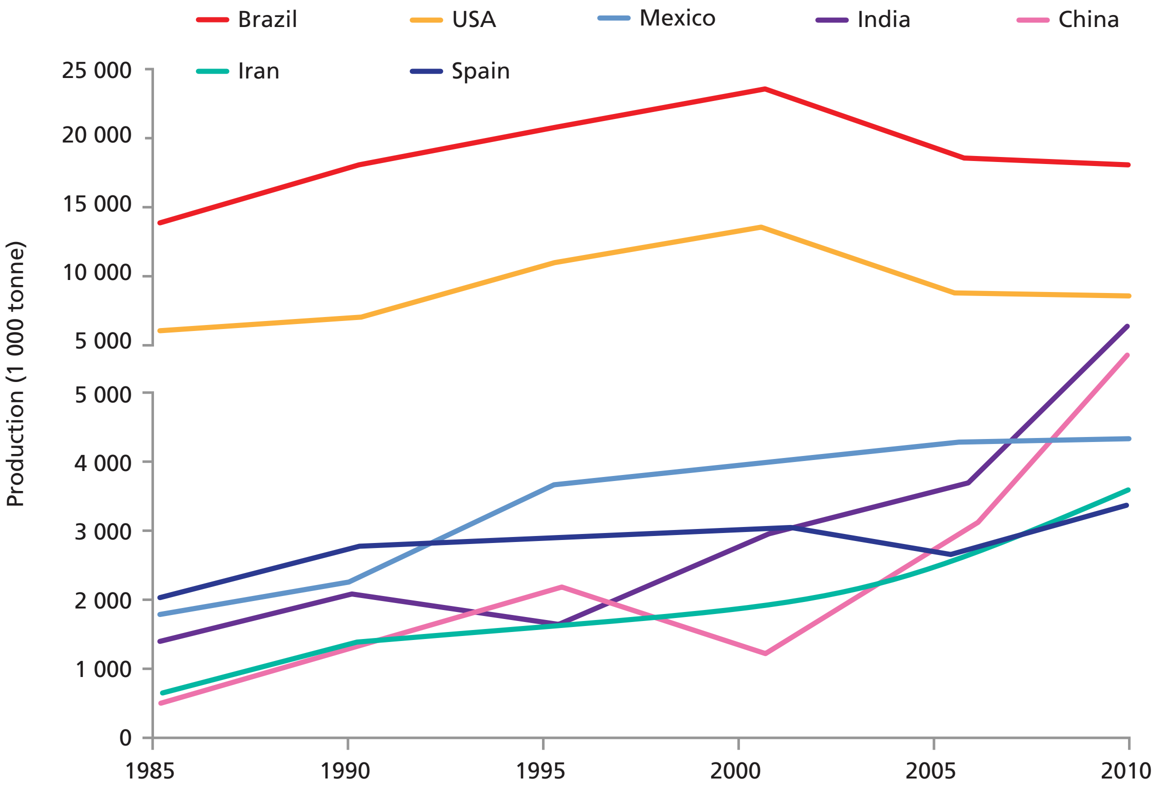
INTRODUCTION AND BACKGROUND

C**itrus** fruit include oranges, which account for about 70 percent of worldwide production, small citrus fruit, such as mandarins, tangerines, tangelos, clementines, satsumas, lemons, limes and grapefruit. Oranges are produced for both the fresh market and for juice — chilled single strength and concentrate. Until the middle of the twentieth century, citrus was almost exclusively cultivated locally. Speed and care when shipping the perishable fruit was of great concern. However, the development of citrus concentrate had a lasting impact on the citrus industry worldwide. Concentrating the fruit permitted the storage, transportation, and transformation of the product far from the groves. In addition to fresh fruit and juice, there are citrus by-products such as food additives, pectin, marmalade, cattle feed (from the peel), cosmetics, essential oils, chemicals and medicines.

Because citrus is an evergreen crop sensitive to low temperatures, subtropical regions produce the bulk of the world's citrus. Tropical cultivation is not as productive since seasonal changes in temperature favour adequate blooming patterns, fruit growth and fruit colour development during ripening. In fact, the high temperatures of the tropics induce fast development and production of large fruit that ripen quickly, remaining marketable for a very short time. In contrast, growth in the subtropical zones slows in the winter and fruit can remain mature on the tree for longer before it is harvested and marketed. Frost damages citrus fruit although the trees can withstand short periods of light frost. However, hard frosts of long duration kill trees and can be devastating.

Citrus fruit value ranks first in international fruit trade. In 2009, there were over 5.4 million ha of citrus (4.1 million ha of oranges) with an average yield of 16.3 tonne/ha. Figure 1 presents the trends since 1985 of the production of the world principal countries (FAO, 2011). As a result of trade liberalization and technological advances in fruit transport and storage, the citrus fruit industry is becoming more global. During the last decades, citrus production and trade have increased steadily; although the intensity of growth varied according to the type of fruit (it has been stronger for small fruit and juice). Citrus production is evolving in a context of highly competitive global markets. There is an apparent ever-increasing focus on the quality and the value-added aspects of the products. Citrus is often promoted for its health and nutritive properties; rich in Vitamin C, folic acid, and fibre.

FIGURE 1 Production trends for citrus in the principal countries (FAO, 2011).



Quality considerations

The goal of citrus production is to harvest as large and as high-quality crop as possible. In this case, quality refers to fruit size, peel colour and appearance, chemical constituents, and taste. Fruit size is usually the primary factor in determining fruit value. In general, larger fruit is more valuable than smaller. However, cultivars, harvest time, local preferences, and market factors can exhibit extreme influences on fruit value. Of the quality factors, peel appearance is usually most important with a smooth, deep coloured and blemish-free peel being most desirable. One limitation of citrus production in the tropics is that fruit remain green and do not change colour when mature. In terms of taste, most people prefer a balance between sweetness and tartness, as measured by the soluble solids-acid ratio (TSS/TA). Juice content is another quality factor, particularly for lemons and limes. In general, citrus fruit have a high postharvest storage potential; from weeks for mandarins and up to six months or more for lemons.

GROWTH AND DEVELOPMENT IN RELATION TO YIELD DETERMINATION

The growth of citrus trees can be divided into vegetative and reproductive stages. Vegetative growth includes the growth of roots, stems, leaves and new flushes. Reproductive growth includes flower bud initiation, differentiation, flowering, fruit set, fruit development and fruit maturity.

Early vegetative and reproductive growth

Under subtropical climate conditions in the Northern Hemisphere (California, for example), the main vegetative growth flush occurs in late February and March. There are normally additional growth flushes in the summer and autumn. Leaves are viable for about two years. Leaves are continuously replenished although leaf drop is generally highest during the spring.

Most citrus cultivars produce flowers in the spring and are self-compatible; they may be fertilized by their own pollen. In cool, coastal climates, flowers may be produced throughout the year but maximum flowering is also in the spring. Flowers develop in leaf axils on older shoots as opposed to shoots developing in growth flushes.

Citrus trees produce a large amount of flowers resulting in small fruit. However, a large percentage of these small fruit drop from the tree apparently because of a combination of physiological and environmental factors. There appears to be a hierarchy of flowers relative to fruit drop; flower in locations with a higher flower/leaf ratio are more subject to drop. Flowers that open late in the bloom period are more likely to set fruit that survives to harvest than fruit set from early flowers. Likewise, faster growing fruit is less apt to drop than slow growing fruit.

The primary factor controlling the dropping of flowers and young fruit is a weakening of tissue in a preformed abscission zone at the point of attachment at the base of the ovary to the disk or of the pedicel to the stem. The actual mechanism of the process is not well understood but is believed to be triggered by growth regulators in response to either external or internal changes. Young fruit that remain after the first period of dropping presumably are capable of developing to maturity if the weather is favourable. Nevertheless, some dropping of fruit occurs throughout the season. As the weather becomes hotter in the early summer months, there is generally a period of accelerated fruit drop, which is often referred to as the 'June drop' period. If the heat is severe and prolonged for several days, fruit drop can be heavy, resulting in a greatly reduced crop. This has been observed in several cultivars of the navel and Valencia types. Some cultivars, notably Valencia and mandarins, have an alternate bearing cycle; light crop years following heavy crop years.

Fruit development stage

Following early season fruit drop, and after the leaves of new flushes have fully expanded, the remaining fruit begin to develop initially by rapid cell division. At this point, a cross-section of the fruit clearly reveals its component parts:

- **Flavedo** (*epicarp*) – a rough, robust and bright colour (from yellow to orange) skin or rind that covers the fruit and protects it from damage. Its glands contain the essential oils that give the fruit its typical citrus fragrance.

- **Albedo** (*mesocarp*) – a white, spongy tissue that, together with the flavedo, forms the peel (pericarp) of the fruit.

- **Pulp** (*endocarp*) – the internal part is comprised of individual segments or juice sacs. This is the edible part of the fruit and the source of the juice.

Fruit growth during this stage is temperature dependent; extremely high or low temperature can slow growth. Cell division is followed by cell enlargement. It is during this period that the peel reaches maximum thickness. Later, as the pulp expands, the peel becomes thinner. The fruit continues to grow as long as it is on the tree, albeit slower as temperatures fall.

The potential fruit size at harvest is highly dependent on environmental factors that exist during cell division. The conventional wisdom is that any decrease in the rate of cell division will directly translate into reduced potential fruit size at harvest. Once the fruit growth cycle passes from a predominant cell division phase to a primarily cell expansion phase, fruit size at harvest is not as susceptible to growing conditions. As for other fruit crops, there are trade-offs in citrus between fruit number and size; large numbers per tree leads to small individual size. Both very small and very large fruit fetch lower prices in most fresh markets but there is a wide range of acceptable sizes for citrus. When citrus are grown for juice, fruit size is relatively unimportant.

Fruit maturation stage

The beginning of this stage is usually characterized by the onset of fruit colour change, triggered by the cooler night temperatures in the subtropical regions. The fruit is still increasing in size but at a much slower rate than previously. During fruit maturation, the juice content of the pulp increases. The acid content of the fruit decreases as the sugar content increases. Unlike many deciduous fruit, there is no precise point that indicates maturity in citrus. In California, the basis for legal maturity of oranges is a ratio of 8-to-1 for total soluble solids to titratable acidity (TSS/TA); the so-called sugar-acid ratio. The balance between sugars, which accounts for about 75 percent of the total soluble solids, and the sourness produced by acidity is the best criterion in correlating fruit quality with consumer acceptance.

Peel colour is also used as a maturity index but this approach is not reliable since peel colour depends on temperature. Moreover, harvest timing is highly influenced by market prices and processor availability. Hormonal sprays, such as gibberellic acid, are used to prolong the viability of fruit on the tree. If left on the tree too long, the fruit is subject to drop, insect/disease damage, and breakdown of the acid and flavor components.

RESPONSES TO WATER DEFICITS

There is a large body of work on the responses of different citrus physiological processes to water stress. Many species, cultivars, and growing conditions have been studied. Since responses vary with the timing of stress during the season, the year was divided into seasons and unless otherwise noted the information focused on orange response.

Spring stress

In terms of eventual impact on yields, the flowering and fruit set period has been repeatedly identified as the most sensitive to stress for small citrus, such as clementines (Gonzalez-Altozano and Castel, 1999) and oranges (Pérez-Pérez *et al.*, 2007). This resulted in the increased abortion of small fruit (June drop). On the other hand, there are reports indicating that early season stress significantly reduced peel creasing in a particularly vulnerable navel cv. (Frost Nucellar) without negative impacts on harvest fruit load or size (Goldhamer and Salinas, 2000).

Summer stress

During this period of cell expansion in the fruit, deficit irrigation can reduce the fruit growth rate. In fact, severe stress can result in fruit shrinkage. However, reintroduction of full irrigation can increase the fruit growth rate, such that harvest fruit size is unaffected (Goldhamer and Salinas, 2000). This has been attributed to the maintenance of dry matter accumulation in the fruit during the stress period and/or full rehydration of the fruit upon reirrigation. Under the experimental conditions on the east coast of Spain (Gonzalez-Altozano and Castel, 1999), summer stress had no impact on clementine yield as long as predawn leaf water potential (LWP) was not reduced below -1.3 MPa. However, severe stress for a prolonged duration during the summer can reduce harvest fruit size, tree growth and increase sugars (Mantell, 1977). Harvest sugar concentration can increase because of summer stress, presumably the result of fruit dehydration. Of the two primary yield components, fruit size is more susceptible to reduction than fruit load as a result of summer stress. Working with cv. Valencia, it was found that moderate stress in the summer and fall did not reduce yields in Arizona (Hilgeman and Sharp, 1970).

It should be noted that the imposition of severe stress during the summer has been used with lemons to induce an off-season bloom and resulting summer harvest fruit. This is known as the Forzatura technique or the Verdelli effect. In one study that withdrew irrigation for nine weeks starting in June, predawn LWP reached - 2.7 MPa (Barbera and Carimi, 1988). This regime yielded 30 kg/tree in each of the summer and winter harvests. They found that insufficient stress resulted in the lack of off-season flowering but that when stress was too severe, it produced excessive leaf drop, higher flower abortion, winter fruit drop and reduced winter harvest fruit quality (Barbera and Carimi, 1988).

Autumn stress

As opposed to stress-induced reductions in fruit growth being overcome upon the reintroduction of full irrigation, reducing fruit growth in the autumn usually results in smaller fruit at harvest. Irrigation of clementines at 25 and 50 percent ET_c during late summer/early fall reduced harvest fruit size by 11 and 25 percent, respectively (Gonzalez-Altozano and Castel, 1999) and produced more fruit peel creasing, as has been found with navel oranges (Goldhamer and Salinas, 2000). Both studies found no influence of autumn stress on fruit load.

In addition to reducing fruit size, numerous studies have shown that autumn stress can increase both the sugar and acid content of the fruit as well as increase the peel thickness.

Winter stress

In most citrus producing areas of the world, winter soil water deficits are unlikely to occur because of rainfall. However, in Florida, water restrictions applied to Valencia oranges, during the winter were used to modify the timing of flowering, delaying bloom dates by two to four weeks (Melgar *et al.*, 2010). The fruit were able to overcome a fruit size reduction during the following spring when irrigation was restored to full crop water needs. This was because Valencia is a very late-season cultivar and fruit had three to four months to recover to the optimum size. In this case, winter stress was used to reduce immature fruit drop for the next season's crop during mechanical harvesting with trunk shakers.

Season-long stress

Several studies have imposed deficit irrigation throughout the season. Some of these imposed irrigation regimes based on tensiometer readings. A value of 70 kPa as a threshold was used which caused delayed bloom, flower opening, and decreased fruit set with cv. Valencia (Davies and Bower, 1994). In a study with the cv. Shamouti where tensiometers were used, with 35 percent less applied water than fully irrigated trees, flowers per tree increased by 52 percent but the flower abscission rate was high. This resulted in a 20 percent lower yield but higher sugars and acid (Moreshet *et al.*, 1983). Another study showed that allowing 80 percent depletion of available water in the surface 1 m in the summer and winter and 60 percent depletion in spring and autumn did not reduced yields with navels (Wiegand and Swanson, 1982). The same regime reduced fruit weight in cv. Valencia. No applied water data was given and it was difficult to judge the level of stress that the depletion of soil water induced in the trees. Another approach to produce season-long stress is to irrigate at fractions of ET_c. For grapefruit, applying 35 percent less than full ET_c delayed maturity and reduced yield by 13 percent due to both smaller fruit and lower fruit load. The sugar and acid content was higher while there was no impact on the sugar/acid ratio (Eliades, 1994). For navels, irrigating with 22 and 46 percent less than full ET_c reduced yields by 7 and 22 percent, respectively (Brych and Luedders, 1988). Finally, for clementines the application of 55 percent of tree water needs during the entire season reduced yields by only 17 percent (Gonzalez-Altozano and Castel, 1999).

Indicators of tree water status

The established indicator of tree water status is the stem-water potential (SWP) as measured with the pressure chamber. A simpler and less time-consuming approach is to measure the water potential of shaded leaves. Both Goldhamer with navels, and Castel with clementines, found the slope of regression lines very close to unity and high correlations between this measurement and SWP (slopes of 0.97 and 0.98; R^2 of 0.95 and 0.96, respectively). Midday SWP values above – 1.0 MPa indicate the absence of water stress for a typical summer day of ET_o about 6-7 mm/day. Values between – 1.0 and -1.5 MPA are indicative of mild stress. Citrus can withstand more negative SWP than other fruit trees and vines. Trees show hardly any visual symptoms of stress with SWP of -2.0 to -2.5 MPa. Severely stressed orange trees that had predawn LWP around -6.5 MPa recovered their water status within a week of rewatering although they experienced severe defoliation and took several weeks more for complete functional recovery (Fereres *et al.*, 1979).

WATER USE REQUIREMENTS

Orchard transpiration, the primary component of ET_c, depends directly on stomatal conductance and scientists recognized early on that the stomatal behaviour of citrus differs significantly from that of most other crop plants. An early comparative study found that maximum stomatal conductance (Gl) of soybean, wheat, and orange under fully irrigated conditions was 1.0, 0.60, and 0.48 cm/s, respectively, and occurred at about 09:00 hours. They attributed this to differences in stomatal opening and densities (Meyer and Green, 1981). A comparison of citrus Gl against that of almond and pistachio under similar conditions in the San Joaquin Valley of California carried out by Goldhamer showed that citrus reached a Gl maximum of around 0.4 cm/s at 08:00 hours and declined steadily thereafter. By contrast, almond had its highest Gl of close to 1 cm/s at 12:00 hours, and pistachio reached an even greater Gl value of 1.15 cm/s at 10:00 hours, more than twice the maximum citrus Gl. Both pistachio and almond maintained similar high values throughout most of the day.

Since citrus is an evergreen plant, many water use studies report a single crop coefficient (K_c) value. These include 0.62 for Valencia in Sunraysia (Grieve, 1989), 0.44 for clementines in Mazagon, Spain (Villalobos *et al.*, 2009), and 0.52 for lemons in Ventura, California (Grismer, 2000). Others have divided the season into winter and summer and suggested that the K_c was 0.70 and 0.65, respectively. They suggested increasing these values by 0.1 or 0.2 for humid and semi humid regions (Allen *et al.*, 1998).

Many studies indicate that, compared to the summer, the citrus K_c is slightly higher in the winter and early spring and appreciably higher in the autumn. This is generally attributed to the citrus stomata being sensitive to evaporative demand (the air vapour pressure deficit, VPD), closing under dry, hot, windy conditions and opening under the opposite conditions. Thus, the K_c in the mild Mediterranean and coastal climates should be higher than those of more arid, inland valleys. In addition, in Mediterranean environments, high K_c values in winter reflect high soil evaporation rates from frequent rainfall during that part of the season. Not all studies found that the K_c was minimum in the summer. One study for cv. Valencia (Hoffman *et al.*, 1982) and another for navels (Chartzoulakis *et al.*, 1999) reported just the opposite.

The monthly K_c values published in six studies are summarized in Table 1. These include the cvs. Salustiana and Valencia under a variety of different climatic conditions. Spring K_c ranged from 0.49 in Valencia, Spain (navel) to 0.77 (Valencia) in Kiyú, Uruguay with a mean value of 0.63. For the summer, minimum and maximum values were 0.52 for cv. Shamouti in Rehovot, Israel and 0.87 for cv. Valencia in Kiyú, Uruguay, respectively, with a mean value of 0.66. Autumn minimum and maximum values were 0.58 for Shamouti in Rehovot, Israel and 0.85 for navels in Tempe, Arizona, respectively, with a mean value of 0.73.

Working with drip irrigated clementines in a precise weighing lysimeter in Valencia, Spain, Castel found that the annual K_c was linearly related to ground cover and reported the following relationship:

$$K_c = 0.006 \text{ ground cover} + 0.272 \quad (R^2 = 0.96)$$

He also emphasized that the K_c will depend on the frequency of wetting of the orchard floor; he found that without rain, surface evaporation for young drip irrigated trees varied between 8 to 30 percent of total ET_c while after a rain, it reached 30 to 50 percent of total (Castel, 1997).

Actual annual ET_c values will, of course, depend not only on the K_c but on evaporative demand and, to some degree, irrigation frequency and the amount of wetted surface area. The range of reported ET_c worldwide include 820-1 200 mm in Florida and 1 080-1 500 mm in Arizona, Unites States, 1 300 mm in South Africa, and 800- 850 mm for the coastal areas of East Spain and Israel.

TABLE 1 Published monthly crop coefficients (K_c) for different mature orange cultivars from different locations. All studies used the water budget to determine consumptive use.

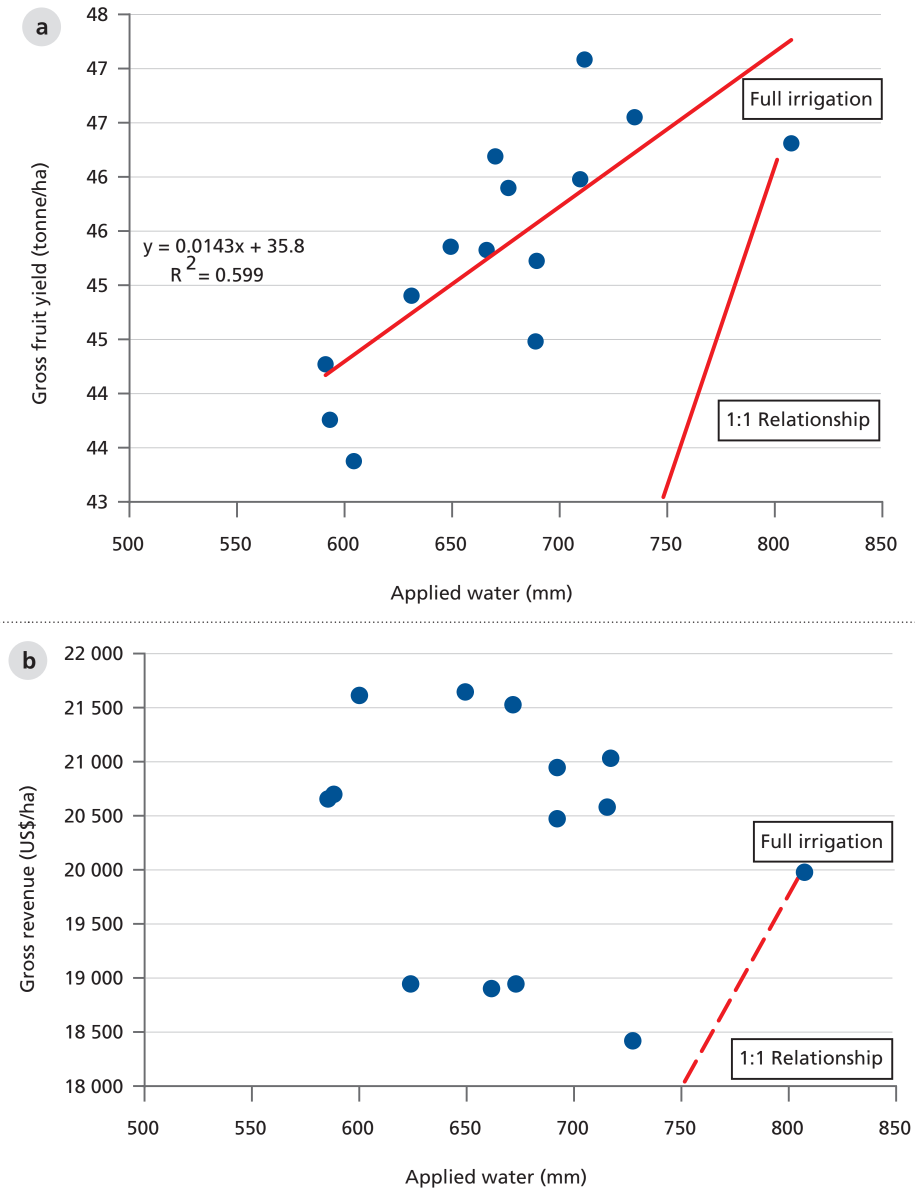
Source:	**Castel & Buj, 1989**	**Castel *et al.*, 1987**	**Van Bavel *et al.*, 1967**	**Hoffman *et al.*, 1982**	**Kalma and Stanhill, 1969**	**García-Petillo and Castel, 2007**
Cultivar:	Salustiana	Washington Navel	Washington Navel	Valencia	Shamouti	Valencia
Location:	Valencia, Spain	Valencia, Spain	Tempe, Arizona	Yuma, Arizona	Rehovot, Israel	Kiyú, Uruguay
January	0.66	0.54	0.57	0.43	1.08	0.51
February	0.65	0.63	0.46	0.42	1.37	0.62
March	0.66	0.47	0.43	0.66	0.73	0.71
April	0.62	0.53	0.55	0.56	0.63	0.78
May	0.55	0.48	0.72	0.69	0.70	0.83
June	0.62	0.57	0.74	0.74	0.56	0.86
July	0.68	0.59	0.75	0.78	0.56	0.88
Aug.	0.79	0.68	0.76	0.87	0.45	0.87
Sept.	0.74	0.62	0.76	0.87	0.41	0.85
Oct.	0.84	0.68	0.85	0.79	0.62	0.81
Nov.	0.73	0.75	0.93	0.45	0.70	0.75
Dec.	0.63	0.79	0.75	0.34	1.34	0.67
Mean	0.68	0.61	0.69	0.63	0.76	0.76
Dec., Jan., Feb.	0.65	0.65	0.59	0.40	1.27*	0.87
March, April, May	0.61	0.49	0.57	0.64	0.69	0.80
June, July, Aug.	0.70	0.61	0.75	0.80	0.52	0.60
Sept., Oct., Nov.	0.77	0.68	0.85	0.70	0.58	0.77

* *High K_c values in winter ref ect high soil evaporation rates from seasonal rainfall in a Mediterranean environment.*

WATER PRODUCTION FUNCTIONS

The two primary yield components of citrus are fruit load and individual fruit weight. Visual appearance and the market values of different size fruit play a large role in determining the net worth of a citrus crop, as they are in many tree and vine crops. This is illustrated with two examples from orange navels in the San Joaquin Valley, California (Goldhamer and Salinas, 2000 and Goldhamer, 2007). The mean gross tonnage from the final three years of a four-year experiment where 13 different RDI regimes of various stress timings and durations were imposed is shown versus applied water in Figure 2a. A linear expression fairly well describes the relationship (R^2=0.59) with a slope of about 2:1 in terms of reduced applied water: gross tonnage reduction. The primary difference in crop performance between the RDI regimes was

FIGURE 2 (a) Crop, and (b) Gross revenue versus applied irrigation water for Frost Nucellar navels grown in the southern San Joaquin Valley of CA, USA. Data are mean values of the final three years of a four year RDI study (adapted from Goldhamer and Salinas, 2000).



that early stress significantly reduced creasing; the primary peel defect. There was relatively little impact of any of the regimes on fruit size and fruit load. The reduced creasing resulted in a higher percentage of the fruit being graded as Fancy and thus, highly marketable in the fresh market, rather than being designated as Choice that has much less value to the grower. This caused the value of the fruit in the early stress regimes to be significantly higher than the fully irrigated trees. This materially changed the relationship between gross grower revenue and applied water, as shown in Figure 2b, as compared with the yield-applied water relationship (Figure 2a).

Fruit size plays an important role in determining the value of fresh market fruit. Generally, large size fruit is preferred – very large size fruit as well as smaller fruit is normally worth less. However, the prices paid in the United States market for different fruit sizes can vary widely over the season for both grades of marketable fruit – Fancy and Choice (Table 2). For early harvest fruit where sizes tend to be smaller, the most desirable size is large (40 to 48 fruit/box). However, as the harvest period progresses and the fruit on the tree continues to grow, large fruit becomes the dominant size and the value of the scarcer smaller fruit increases. With the very late harvest varieties, fruit may became very large, which makes it almost worthless; in the example provided, the value is only US$5.00/box for the 24-36 fruit/box size compared with over US$14/box for the medium fruit size of 56-72 fruit/box (Table 2). On the other hand, this same very large size category (24-23 fruit/box) is worth twice that with the early harvest. Because of the desirability of having smaller fruit for the late harvest varieties, RDI can be an effective tool if the fruit size distribution can be shifted toward smaller sizes and there is no concomitant negative impact on other yield components.

The classical water production function relates yield to consumptive use. There are two issues with citrus that limit the usefulness of this relationship. First, crop revenue (US$/ha) depends not only on yield (kg/ha) but also on fruit value (US$/kg), which, in turn, is a function of fruit size, peel appearance, and fresh market prices. Second, most published studies of the impact of irrigation on production only report applied water, (many do not even report that), and do not attempt to quantify consumptive use (ET_c), limiting the applicability of the reports.

TABLE 2 Typical early (Frost Nucellar) and late (Lane Late) harvest fresh market fruit values to the packer for different navel fruit sizes in the southern San Joaquin Valley, California. Values are shown as US$/box (Goldhamer *et al.*, 1994).

		Fruit size category			
		88-163 (fruit/box)	56-72 (fruit/box)	40-48 (fruit/box)	24-36 (fruit/box)
Early harvest	Fancy	7.50	12.00	12.50	10.00
Frost Nucellar	Choice	6.64	7.87	8.00	5.17
Late harvest	Fancy	12.26	14.15	7.50	5.00
Lane Late	Choice	7.62	8.44	5.72	3.00

Four crop-water-production functions are shown in Figure 3a, each for a different cultivar. Three are from California and one from Spain. Each of the data sets involved field experiments on mature trees that were conducted over at least four years. First order best fit lines for all studies show fairly strong correlations with correlation coefficients ranging from 0.68 to 0.98. The best fit linear expressions for the Frost Nucellar and the Lane Late studies in California have slopes less than one; the Parent Washington study in California has a slope of almost exactly one, and the Clementine study in Spain has a slope greater than one, suggesting that this cultivar may be more sensitive to water deficits than navel oranges.

The revenue-water-production functions (Figure 3b) generated from three of these studies (the Clementine study did not include revenue data) have a much different appearance than their companion crop-water-production functions. With the exception of the Parent Washington study, it is obvious that the relationships between gross revenue and consumptive use are not linear. The Lane Late study shows that revenues can be increased by about 80 percent with RDI regimes that reduce consumptive use by either 10 (late season stress) or 40 percent (season-long stress). On the other hand, a less successful RDI regime (midseason stress) reduced revenue by 15 percent with a 23 percent reduction in consumptive use. This large range in relative gross revenues for different RDI regimes clearly illustrates the importance of stress timing in some citrus varieties.

Both the Lane Late and Frost Nucellar orange studies show that gross revenue can be increased and/or consumptive use dramatically reduced with optimal RDI regimes. The results from these cultivars differ markedly than that of Parent Washington. The reason is that both of the former cultivars had production problems that were lessened with the successful RDI regimes — peel creasing with Frost Nucellar and excessively large fruit with Lane Late. There were no identifiable issues of peel appearance and/or fruit size with the Parent Washington. Nevertheless, the Parent Washington data show that consumptive use can be reduced by 7 percent with no impact on gross revenue or 18 percent with only a 6 percent decrease in gross revenue (Figure 3b).

SUGGESTED RDI REGIMES

Soil water instrumentation has been used for many years to monitor irrigation and impose water deficits in citrus. Hilgeman and Sharp (1970) used tensiometers in their RDI work with Valencia oranges. They recommend full irrigation from March through mid-July, then irrigating when tensiometers reach 75 cbar. This regime reduced irrigation by 66 percent relative to fully irrigated trees. Yield was not reduced, sugars were higher, and the resulting smaller trees were easier to pick. However, since fruit value depends on many factors discussed previously, it must be emphasized that a successful RDI approach on a given cultivar in a given location will not likely be optimal for other cropping situations. Additionally, it is dangerous to recommend soil-based stress thresholds because of differences in soils, placement of the instrument (depth and location), irrigation methods, and varieties/cultivars.

The easiest approach to imposing RDI regimes is to irrigate at given percentages of maximum ET_c at specific periods of the season. For the Frost Nucellar cv., it is recommended to irrigate at 50 percent ET_c from mid-May through early July (Goldhamer and Salinas, 2000). Goldhamer found that a late summer/early autumn stress was optimal with Lane Late in shifting the fruit

FIGURE 3a Crop-water production functions for four studies of different orange cultivars from Spain (Castel and Buj, 1989) and CA, USA (Goldhamer and Salinas, 2000; and Goldhamer *et al.*, 2007). Each study was at least four years in duration. Slopes, intercepts, and correlations coefficients for the best fit lines are shown in Table 3.

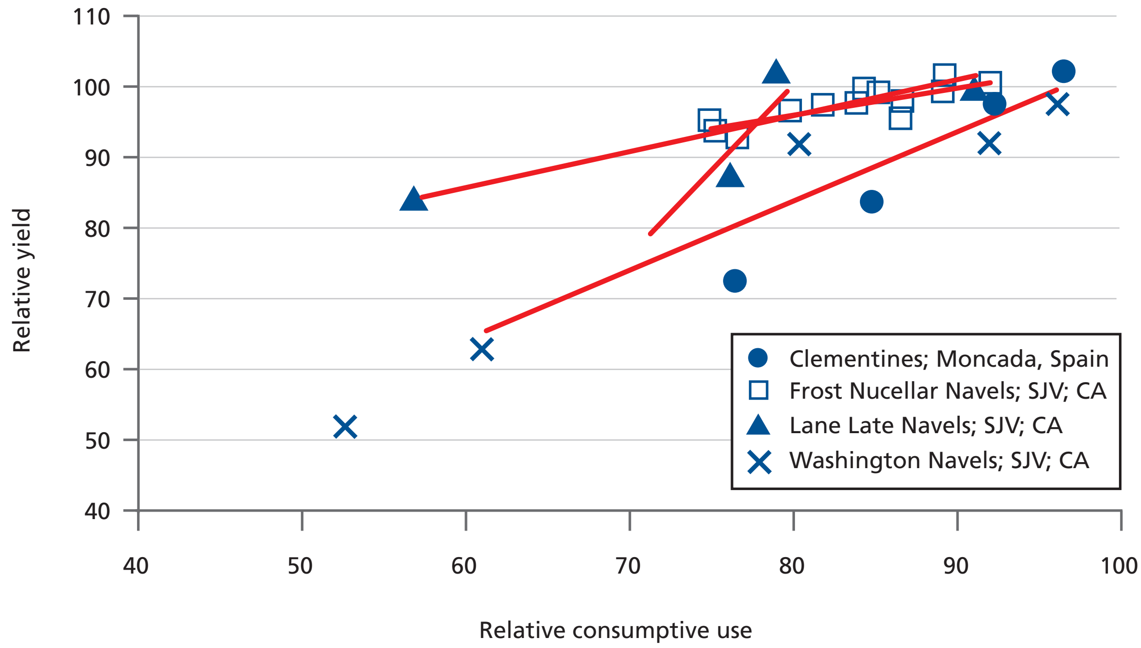
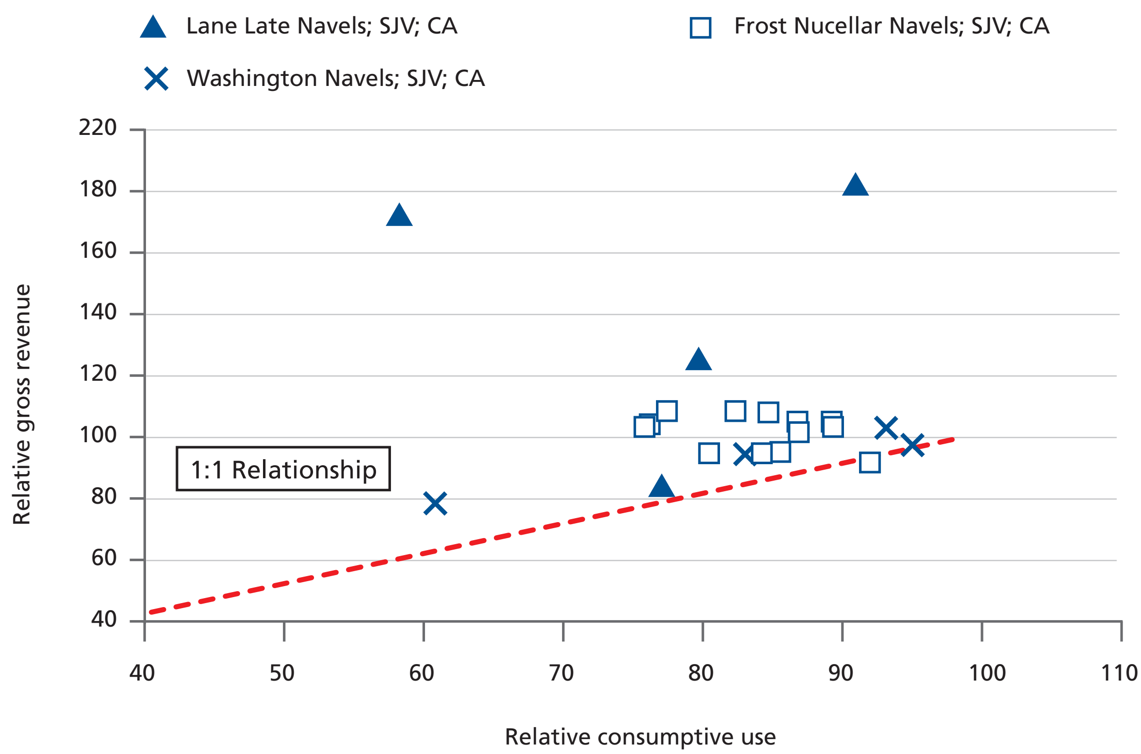


FIGURE 3b Gross revenue-water production functions for three of the studies shown in Figure 3a.



size distribution toward more favourable fruit value and thus, increasing grower revenue. On the other hand, in a small citrus fruit such as Clementina de Nules, it was concluded that the best RDI strategy was irrigation at around 50 percent ET_c from July (after June fruit drop) to the beginning of September when late summer autumn rainfall helped to quickly release plant water stress (Gonzalez-Altozano and Castel, 1999). The usefulness of this strategy has also been recently corroborated in commercial situations (Ballester *et al.*, 2011).

It should be noted that the utility of ET_c-based RDI regimes depends, in part, on soil conditions and the amount and storage of winter rainfall in the root zone, especially early in the season. For example, with relatively high winter rainfall, deep soils, and a full coverage irrigation system that promotes roots in the entire potential root zone, reducing applied water early in the season may not induce tree water deficits and will not have much impact on tree water status. On the other hand, with the opposite conditions — low winter rainfall, shallow soils, and localized (drip, microsprinkler) irrigation, there will likely be a rapid decline in tree water status in response to deficit irrigation soon after is imposed.

For this reason, the use of a plant-based indicator of tree water status is highly recommended when applying RDI for validating that the desired stress level is being achieved in the tree. In conclusion, given the very wide diversity of combinations of species, cultivars, market and growing conditions that exist in citrus, the need to tailor RDI strategies to specific conditions is even more pressing that for other fruit trees and makes it difficult to recommend generalized RDI programmes.

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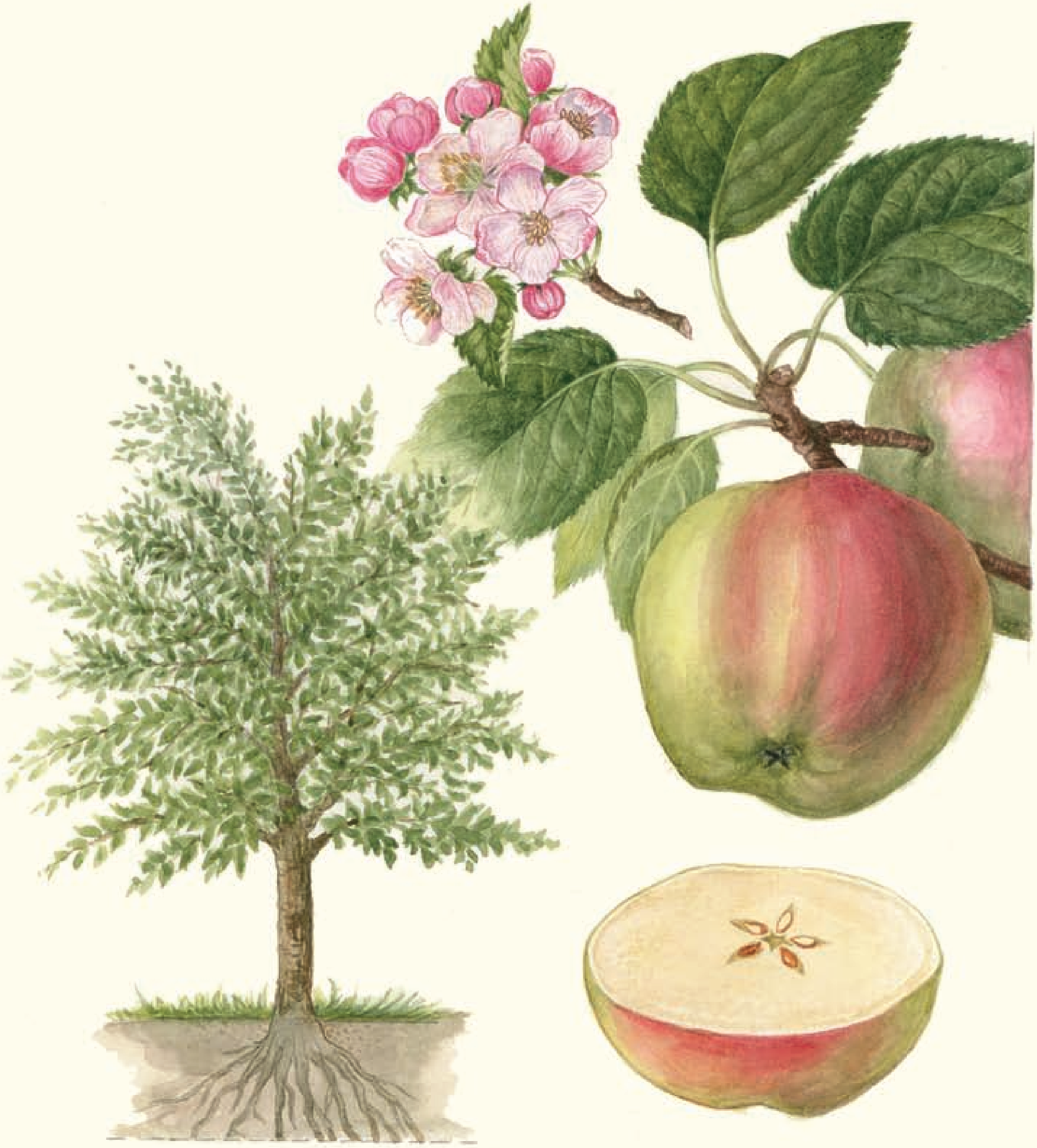

Apple

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Apple

INTRODUCTION AND BACKGROUND

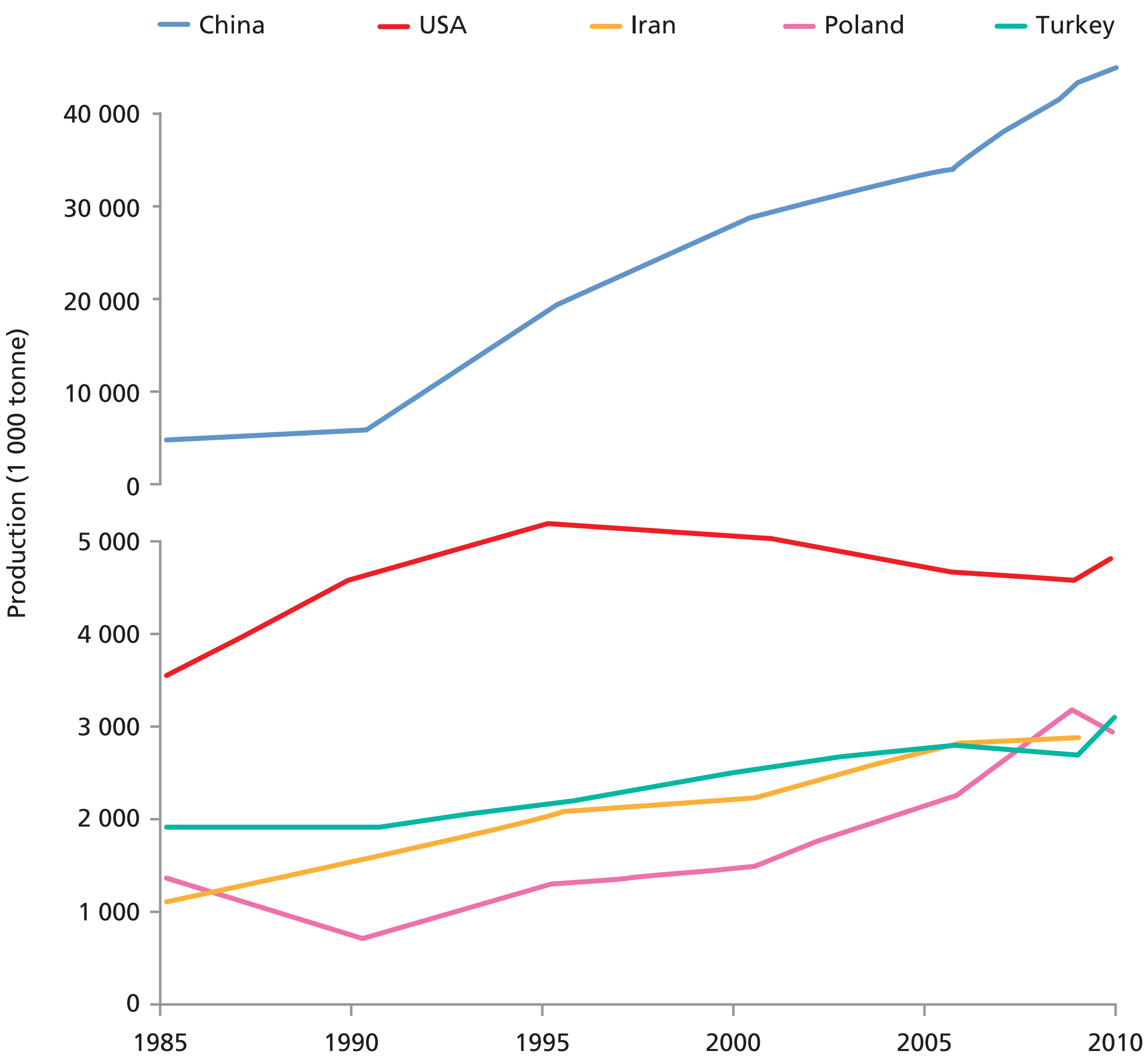
Apple (*Malus domestica* Mill.) is one of the most widely cultivated fruit crops and is produced commercially in over 80 countries around the world (FAO, 2011). Its production is the third highest fruit crop in the world after banana and grape and is ranked second behind grape for area. Most apples are grown in temperate zones because of the high chilling requirements for proper bud break in the spring. The development of apple varieties with low chilling requirement and the use of dormancy-breaking chemicals has enabled the migration of apples towards warmer regions. Production areas have increased significantly in recent decades until 2000, when China took the lead in production. Total production of apples stabilized during 2000-2010 at 60 to 70 million tonne/year. In 2009, the harvested area exceeded 4.9 million ha with an average yield of 14.7 tonne/ha (FAO, 2011). Figure 1 shows the production trends of the principal countries. China is the largest apple-producing country (42 percent of world production) and its production is six-fold larger than the second country (United States, 7 percent).

The duration of the season from bud break to harvest varies widely among varieties, from 70 days up to 210 days (Westwood, 1993) and it is correlated with the storability duration.

Apple originated in Central Asia, where its wild ancestor is still found today. There are more than 7 500 known cultivars resulting in a wide-range of fruit characteristics. Cultivars vary in their yield, fruit size, colour, taste, and the ultimate size of the tree, even when grown on the same rootstock. Apple is grown in a wide-range of environments, in many areas of Asia and other continents. In Europe from Scandinavian countries in the north to Italy in the south, in South Africa, Australia and New Zealand, United States and Canada, and in the southern countries of South America. The optimum climatic requirements might be characterized as cool to cold winters followed by a rapid rise in temperature in spring.

Apple has two types of buds, pure vegetative and mixed buds containing a floral bud that has several vegetative buds at its base. The floral bud generates an inflorescence that usually has five flowers. Flower buds are borne terminally on shoots and spurs and, to some extent, on lateral buds of one year-old shoots. Most apple varieties have self-incompatibility (Goldway *et al.*, 2007) thus growers usually include more than one variety within each plot, and some orchard growers use crab apples as pollinators.

FIGURE 1 Production trends for apples in the principal countries (FAO, 2011).



Quality considerations

There are many features that affect apple fruit quality for the fresh market. External features such as size, colour, shape and appearance are very important. For many markets, fruit that is smaller than 65-70 mm in diameter have a price penalty. Depending on the variety, the background and superficial skin colours, whether green, yellow, red or red striped play an important role in fruit appearance, and therefore its fresh market value. Skin blemishes such as sunburn, russeting and other markings negatively affect fresh quality. Flesh texture and firmness are important attributes, and are affected by environmental factors, cell wall properties and calcium content. Fruit composition in terms of sugars, acids and different aromas is variety dependant and has a strong influence on fruit taste and quality. Postharvest handling in controlled atmospheres, now commonly for this fruit months after harvest, is critical in terms of maintaining fruit quality and to limit the numerous physiological disorders that may appear during storage.

Apples tend to have a biennial bearing pattern where the degree of biennial bearing varies with varieties (Lauri *et al.*, 1996) and potential crop yield is highly affected by the timing of fruit thinning and the crop load in the previous season.

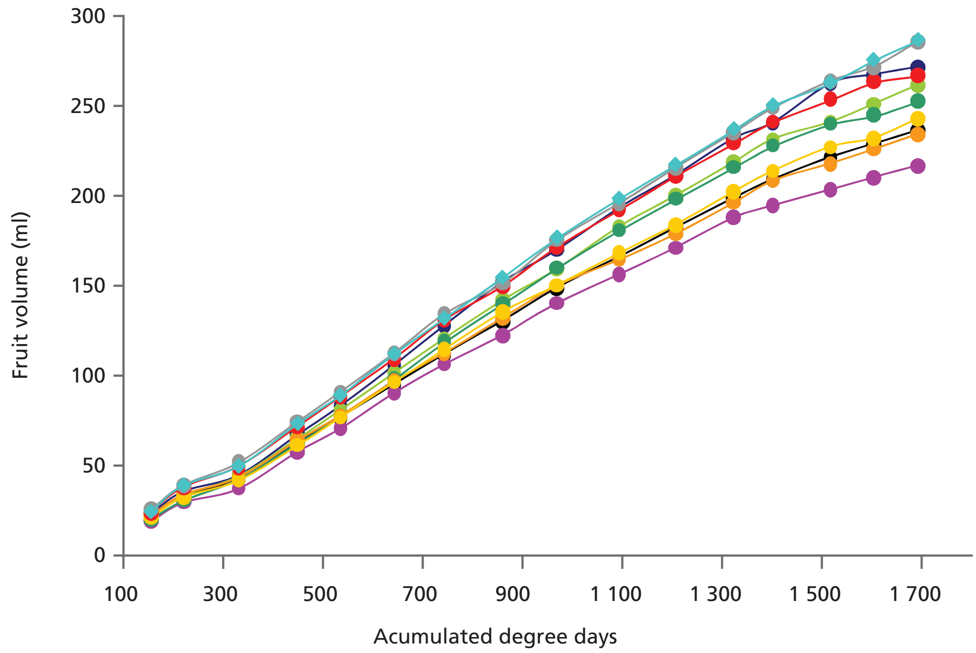
STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Bloom date varies with varieties and climatic regions. Most varieties flower in April (Northern Hemisphere), whereas early (low chilling requirement) varieties can bloom at the end of February and early March. Apple fruit has an expo-linear growth pattern where much of the dry mass accumulation occurs in the linear phase that starts ~30 days after full bloom in some varieties while in others the linear phase starts ~60 days after full bloom (Goffinet *et al.*, 1995) Figure 2 shows the patterns of fruit growth as affected by different irrigation treatments. The reproductive cell division phase lasts 40-50 days post bloom (Westwood, 1993).

Fruit size is a major determinant of fresh fruit quality and is highly dependent on tree water status and irrigation. However, there are many other factors that will affect the response of fruit size to irrigation including the number of cells in the fruit pericarp, crop load, the number of seeds per fruit, factors that interact with each other.

Temperatures lower than 25 °C during the reproductive cell division phase reduce apple fruit size (Tromp, 1997 and Warrington *et al.*, 1999); on the other hand, it has been found that the number of cells in apples decreased when the trees were grown at 35/15 °C (day/night) rather than at 25/15 °C. This suggests that there is an optimum temperature for reproductive cell

FIGURE 2 Seasonal patterns of apple fruit growth in response to various irrigation treatments: Dark and light blue, grey and red – 100 percent of estimated ET_c for various drip irrigation arrangements; Dark and light green – 100 percent of estimated ET_c applied after two years of severe water restrictions (between 50 to 70 percent of estimated ET_c); Light and dark orange, black and violet - Different water restriction levels (50 - 70 percent of estimated ET_c) (Girona *et al.*, 2011 and unpublished data).



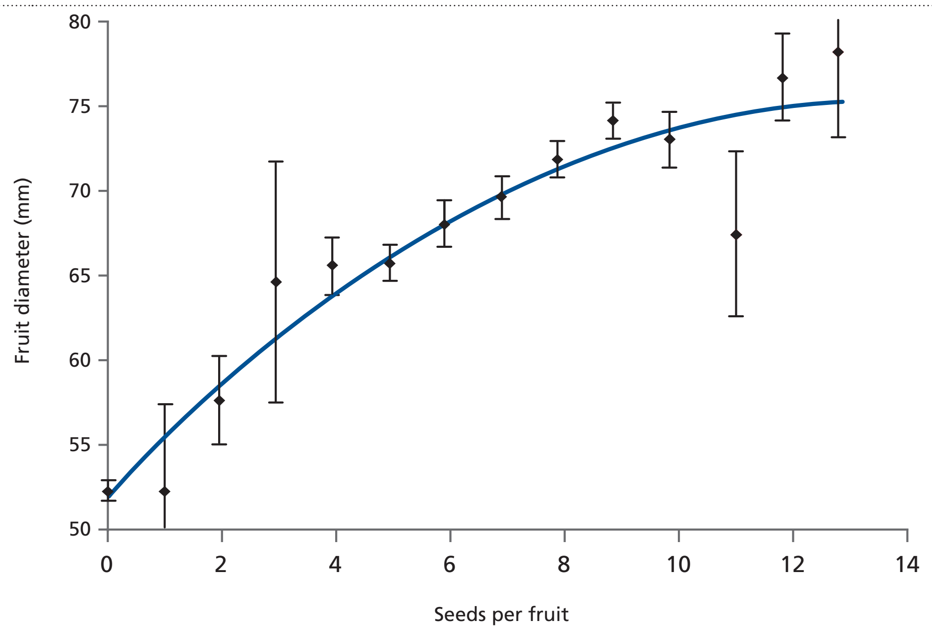
division, and that limitation of potential fruit size should be expected in both cold and hot climates. The previous-year crop yield (Bergh, 1985), the current-year crop level, and the timing of fruit thinning affect the number of cells and therefore potential fruit size (Goffinet, 1995 and Quinlan and Preston, 1968). The number of seeds per fruit has a dramatic effect on final fruit size as shown in Figure 3 where, for the cv. Golden Delicious, the fruit diameter when no seeds were apparent was ~52 mm, while it reached ~73 mm when ten seeds per fruit were apparent. There is the perception that water stress affects cell division, however, studies of other fruit trees (olives and pears) showed no effect of water stress on fruit cell numbers even where predawn leaf water potential (LWP) reached -4.0 MPa in olive (Rapoport *et al.*, 2004).

Crop load in the current season affects the fulfillment of potential fruit size and it interacts with irrigation and fruit water status, which is discussed later. Information about the positive or negative effects of postharvest water deficits on the yield and quality responses of apple in the following growing season is limited, but it appears that severe stress can have negative effects on return bloom.

RESPONSES TO WATER DEFICITS

Irrigation is a major horticultural activity and is the most intensively practiced operation throughout the season. Its importance depends on the climate, and increases as one moves from temperate to drier and to arid zones. Rainfed apple orchards can survive and be productive in temperate zones without irrigation, whereas the survival of apple orchards in arid and semi-arid zones depends on the availability of water for irrigation throughout most of the growing season. The performance of apple in terms of crop yield, fruit size, fruit quality, storability, and long-term productivity are highly dependent on irrigation and irrigation management. Irrigation level and water status are known to affect yield and yield components: crop yield, fruit size and quality, growth habit, precocity, and long-term productivity. Apple fruit size is very sensitive to

FIGURE 3 The effect of the number of seeds per fruit on fruit size at harvest for Golden Delicious apples in Israel (Naor, unpublished).



water stress and thus highly responsive to irrigation (Naor, 2006; Naor *et al.*, 1995 and Girona *et al.*, 2010). It is also highly responsive to crop load (Naor *et al.*, 2008). Assimilate availability is thus the limiting factor for fulfilling potential fruit size (Naschitz *et al.*, 2010). Water stress not only limits cell and fruit expansion but also reduces photosynthesis (the source for assimilates), while primarily crop load determines the demand for assimilates and to a certain extent the photosynthetic rate.

Unlike peach, apple does not have distinct stages of fruit growth and a large part of vegetative and reproductive growth overlap during the growing season. For this reason, deficit irrigation researchers normally use the terms 'early-season' or 'late-season' to describe the timing of their treatment application. Early season normally indicates the time period before flowering buds are formed for the next season fruit. For most varieties, early season will be before July in the Northern Hemisphere and before January in the Southern Hemisphere.

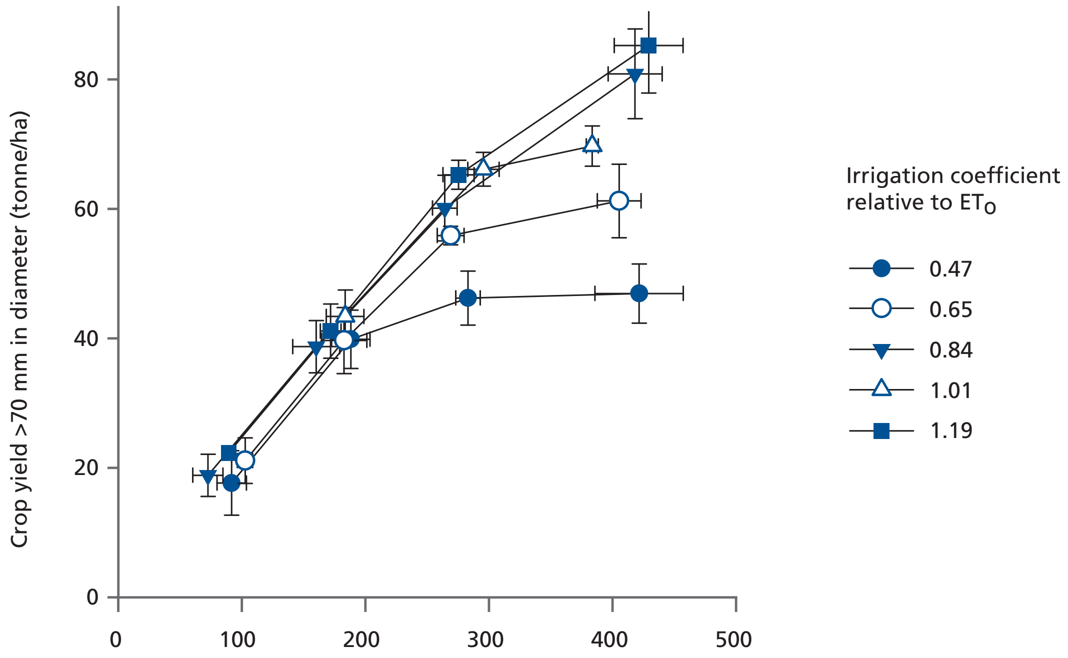
Early-season water stress reduces apple fruit size (Failla *et al.*, 1992 and Rufat *et al.*, 2003). It also reduces fruit set by dramatically increasing fruitlet drop in temperate zones; in one experiment (Powell, 1974), final fruit set decreased from 24 percent for irrigated trees to 8.7 percent for non-irrigated trees. In a semi-arid area of Israel, final fruit set of fully-irrigated trees was 15 percent decreased to 8 percent in severely stressed trees. Water storage from winter precipitation avoids rapid development of severe water stress in most temperate climatic conditions, but for containerized apples with a limited rooting zone, severe water stress may cause up to 100 percent fruitlet drop. This suggests that growers should be aware of the risk of severe water stress development early in the season especially during drought years, and/or in very shallow soils having low water-holding capacity.

Late-season water stress that occurs in the post-reproductive cell division stage affects apple depending on the degree of severity. Moderate water stress up to 102 days after full bloom reduced canopy growth (Behboudian *et al.*, 1998), whereas water stress after this period had no effect. This indicates that shoot growth ends within three months after bloom (Forshey and Elfving, 1989). An early deficit created moderate water stress and resulted in a lower return bloom, whereas no reduction in return bloom was apparent in a late-deficit treatment (Behboudian *et al.*, 1998). However, if water stress is severe during these later stages it may affect next year's growth (Ebel, 1991 and Girona, 2010a). Reductions in return bloom and productivity under severe water stress have been found in apple. Fruit numbers in the following years were affected by severe stress the previous year generated by terminating irrigation in early summer. This was particularly evident in early varieties (Ebel, 1991).

The other, above-mentioned studies, where return bloom was not reduced, did not involve such a severe level of water stress (Behboudian *et al.*, 1998). The reduction in the proportion of return bloom of apple trees that were moderately stressed early in the season could reduce the size of the bourse shoot that emerges from apple flower buds below the threshold required for its terminal bud to produce a viable flower bud (Lauri *et al.*, 1996). It may well be that bourse shoots had already reached the threshold length prior to the start of late-deficit treatments thus no effect on return bloom during late water stress was apparent. It has been observed that excessive shading by a dense canopy can also negatively affect return bloom.

In most studies early water deficits (for about 2 months post reproductive cell division) reduced apple fruit size (Naor, 2006 and Rufat *et al.*, 2003). In general, total crop yield increases with both irrigation level and crop load. However, as fruit size is a major attribute of fruit quality, growers are interested in larger fruit up to a certain limit, where oversize apples will fetch a lower price. The yield of large fruit is affected by both irrigation and crop load (Figure 4). At low crop loads, there is no advantage of increasing irrigation, as similar crop yields were obtained in one experiment where irrigation levels between June and harvest ranged from 46 percent to 119 percent of ET_o (Naor *et al.*, 1997).

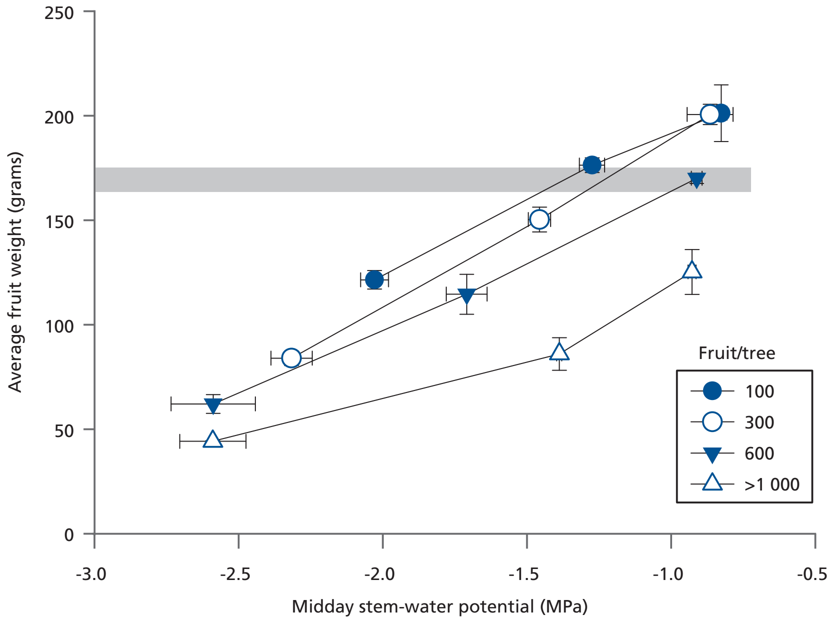
FIGURE 4 Effect of the number of fruit per tree (1 250 trees/ha) on apple yield (>70 mm in diameter) at different irrigation levels (ET_o) from mid-June to harvest. Bars denote Standard Error (Naor *et al.*, 1997).



The water deficits may reduce tree size in the following year, but do not negatively affect flower bud number or fruit load (Girona *et al.*, 2008). As crop load increased (double number of fruit per tree), yield of large fruit increased with increasing irrigation levels. This indicates an increased limitation in assimilate availability that cannot be overcome by supplying additional water above full requirements. At the highest crop load, yield of large fruit did not respond to a seasonal irrigation level above 84 percent of ET_o, which is more or less equivalent to apple ET_c during the irrigation period (see below).

Fruit size increased with increasing midday stem-water potential (SWP: Figure 5) where different response curves were observed for different crop loads. The threshold of midday SWP to reach marketable size fruit shifted to higher stem-water potentials with increasing crop load. For crop loads up to medium levels, maximum fruit size can be achevied by improving tree water status. However, at extremely high crop load, marketable size fruit cannot be reached even under non-stress conditions. Therefore, there is an upper limit of crop load that would enable large fruit size, suggesting that both irrigation and fruit-thinning practices should be employed to maximize crop yield of large, marketable fruit. In some cases, summer pruning can help achieve marketable sizes, as for peach.

FIGURE 5 The effect of midday stem-water potential on average fruit weight at various crop loads 1 250 trees/ha for Golden Delicious apple in Israel (Naschitz, unpublished). The grey rectangle represents the optimal fruit size. The four lower water potentials represent low irrigation rate (1 mm/day) and the four highest water potentials represent high irrigation rate (7 mm/day). The other points represent medium irrigation rate (3 mm/day).



Water deficits and fruit quality in apple

In general, mild water deficits during fruit development advance maturity, increase total soluble solids content and firmness, and may improve red colour and decrease the background colour. It also affects volatile aroma compounds. Many past studies found higher firmness as a result of deficit irrigation. However, it was argued (Behboudian and Mills, 1997) that the increased fruit firmness of stressed trees could be an artifact because fruit size decreases as a direct result of deficit irrigation and the firmness of apples increases with decreasing fruit weight (Ebel *et al.*, 1993). In different studies, water stress after the cell division phase increased (Mpelasoka *et al.*, 2001), did not affect (Ebel *et al.*, 1993), or decreased (Mills *et al.*, 1994) apple firmness at harvest.

The dynamics of fruit firmness in cold storage, as affected by water deficits, were examined in two studies on apple (Mpelasoka *et al.*, 2001. and Kilili *et al.*, 1996). The difference in firmness between fruit from different water-stress treatments remained the same during 10 and 12 weeks in cold storage; they diminished after 10 weeks and reached similar levels by 17 weeks (Mpelasoka *et al.*, 2001). During a shelf-life study (Mpelasoka *et al.*, 2001) the higher firmness imparted by a deficit irrigation treatment was retained for six days, after which the differences diminished and disappeared. Data collected over the past decade suggest that firmness increases in response to post-cell-division water stress, but that the increase is often temporary, around 10 weeks in some studies.

Many studies found that deficit irrigation increased ethylene concentrations in apple, at harvest or during storage (Ebel *et al.*, 1993; Kilili *et al.*, 1996; Behboudian *et al.*, 1998; Mpelasoka *et al.*, 2001 and Mpelasoka *et al.*, 2002). Background colour is an indicator of maturity in apple and it was reported to either decrease or to remain unchanged in response to deficit irrigation. These findings indicate that deficit irrigation advances maturity (and related red colour) in most cases. Studies on the effect of deficit irrigation on aroma volatiles yielded inconsistent results (Behboudian *et al.*, 1998 and Mpelasoka *et al.*, 2002) probably because of a dramatic rise of these compounds at a certain point together with the fact that there is no distinct definition of maturation and the advancement of maturity in response to deficit irrigation. Deficit irrigation increased total soluble solids in apple at harvest (Ebel *et al.*, 1993; Behboudian *et al.*, 1994; Behboudian *et al.*, 1998; Mills *et al.*, 1994; Kilili *et al.*, 1996; Mpelasoka *et al.*, 2001a and Mpelasoka *et al.*, 2002), and the differences were retained during storage. The increased total soluble solids content was accompanied by an increased percentage of dry matter, suggesting part of the increase in soluble solids resulted from to water losses from the fruit. However, deficit irrigation elicited specific metabolic effects that were manifested in changed proportions of specific sugars by increasing fructose or sorbitol content (Mills *et al.*, 1994) compared with unstressed treatments.

Deficit irrigation increased the red colour (Mills *et al.*, 1994 and Kilili *et al.*, 1996) or did not affect it in apple. Enhancement of the red colour could be an indirect effect of deficit irrigation, via a reduction in vegetative growth, which affects light regime within the canopy. It could also be associated with the advancement of maturity induced by the water deficit. More details of the effects of reduced irrigation on fruit quality for important deciduous fruit, including apple, have been recently published (Behboudian *et al.*, 2011).

WATER REQUIREMENTS

Two key factors determining apple tree water consumption are the evaporative demand of the atmosphere and the canopy size that determines the amount of energy intercepted by the canopy. A recent lysimeter study (Girona *et al.*, 2011) showed that the crop coefficient increases from bud break parallel with the development of canopy coverage where canopy coverage reaches a maximum ~60 days after full bloom (Figure 6). A slight increase in K_c was apparent closer to harvest followed by a sharp decline right after harvest. This decline was first probably the result of crop removal, which is known to affect transpiration, while the additional decrease thereafter was related to leaf senescence. The sharp decline in K_c right after harvest, from 1.0 to 0.6 in 2-3 weeks without evidence of leaf senescence (Figure 6) repeats every season (Girona *et al.*, 2011) because fruit is a very important carbon sink and removal feeds back to carbon assimilation and reduces stomatal conductance and transpiration. Trees with very low crop loads therefore use less water than trees with commercial loads, which indicates that the K_c values should be adjusted downward from the values of Figure 6 for low to negligible crop loads. Excessive vegetative growth is expected in the spring in low crop loaded trees and its suppression is difficult because of the low ET in the spring, thus summer pruning should be employed.

Recommended K_c values for various locations in the world are presented in Table 1. The K_c values for apple orchards depend on the intercepted radiation and may vary with different orchard conditions (row and tree spacing, tree age and size, training system, row orientation, etc.). For intensive, hedgerows plantations, a relationship between K_c and midday light interception (Girona *et al.*, 2011) is presented in Figure 7. Given that maximum K_c is around 1.0 (Figure 6), the relationship shown in Figure 7 may be used to determine the specific K_c values for apple orchards that have not achieved maturity.

FIGURE 6 Seasonal reference ET_o crop coefficients for apple. Data from a weighing lysimeter study of commercial size trees within an orchard in Mollerussa (Lleida, Spain) (Girona *et al.*, 2011).

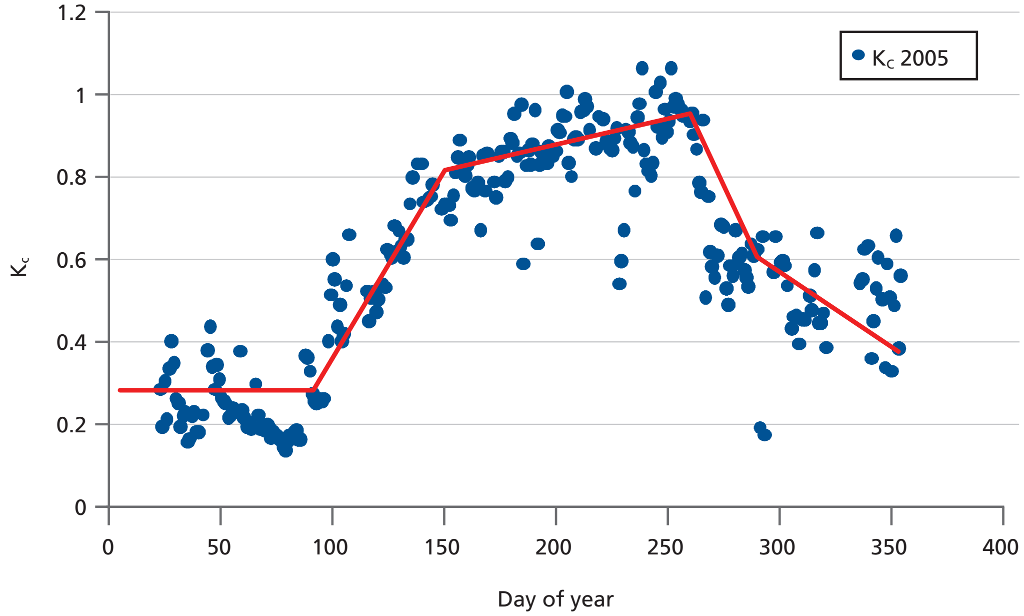


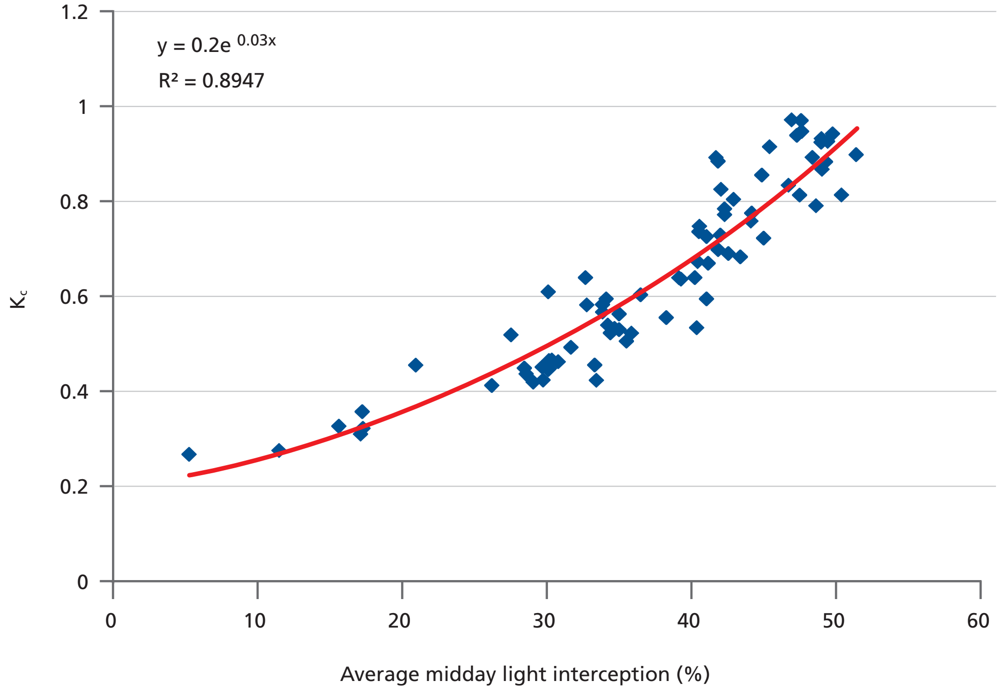
TABLE 1 Common sets of seasonal reference ET_o crop coefficients (monthly averages) from various countries throughout the world (Australia, Israel, and Spain).

Month	Spain (fraction of ET_o)	Israel (fraction of ET_o)	Month	Australia
Mar.	0.30/0.30		Sep.	
Apr.	0.40/0.45	*	Oct.	0.64
May	0.60/0.75	0.42	Nov.	0.64
June	0.82/0.87	0.73	Dec.	0.74
July	0.92/0.93	0.98	Jan.	0.95
Aug.	0.93/0.94	1.05	Feb.	0.95
Sept.	0.95/0.75**	1.05/0.48**	Mar.	0.95/0.42**
Oct.	0.60/0.55	0.32	Apr.	0.42

* *irrigation based on soil moisture measurements*

** *preharvest/postharvest*

FIGURE 7 Effect of midday light interception of apples on their K_c values - data from a weighing lysimeter study of commercial size trees within an orchard in Mollerussa (Lleida, Spain) (Girona *et al*., 2011).



WATER PRODUCTION FUNCTIONS

Water production functions for apple are difficult to generalize because they are affected by many factors such as training system, crop load, pruning and thinning practices, and whether the target is total (as for juice production) or fresh marketable yields.

Figures 8 and 9 present the response of total and marketable yield to a decrease in ET_c determined in Lleida, Spain. In both cases, it seems that relative ET_c may be reduced by about 15- 20 percent without having a negative impact on final yield. Similar results were found in Israel where fruit yield >70 mm was unaffected by increasing K_c above 0.84 (Figure 10).

Water management of fresh market apple production should take into account that: 1) fruit size is highly dependent on crop load thus it should be optimized to maximize yield of marketable size fruit; 2) apples tend to have a biennial bearing pattern in response to high crop load, thus crop load should be optimized to allow stable production for each season. In one specific experiment with Golden Delicious (Figure 10), crop yield of marketable size (>70 mm) increased with both annual irrigation level and crop load, and the maximum crop yield was achieved at the highest load at maximum apple ET_c (equivalent to 84 percent of the seasonal ET_o). It should be emphasized that potential fruit size was high during this season and, although the threshold of maximum commercial crop yield could be higher; optimal crop load that avoids biennial bearing lies between the two highest crop loads (Figure 10) and may change with climatic conditions.

FIGURE 8 Water production function for apple (cv. Golden Smoothee) based on total yield obtained in Lleida, Spain (Girona, unpublished).

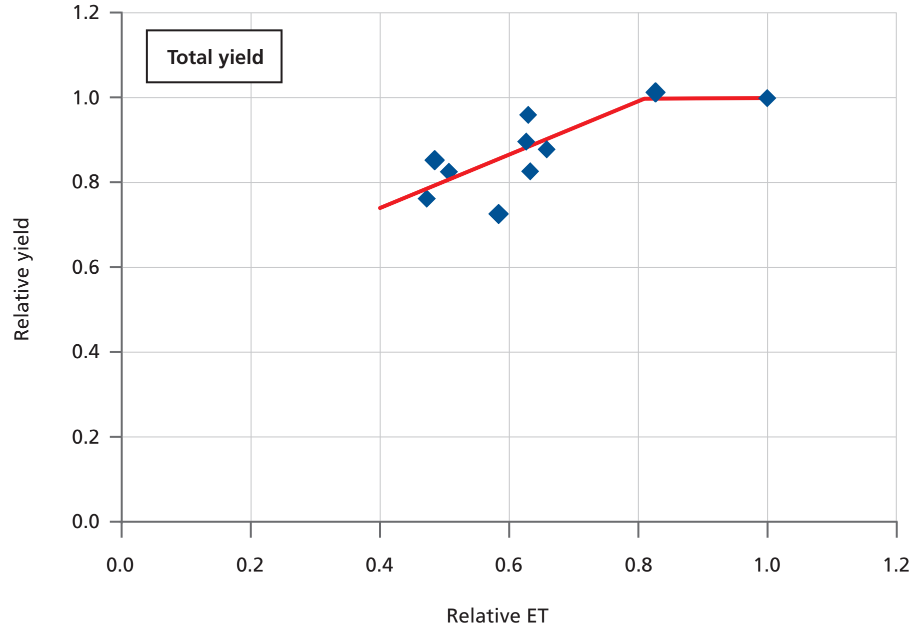


FIGURE 9 Water production function for apple (cv. Golden Smoothee) based on marketable yield obtained in Lleida, Spain (Girona, unpublished).

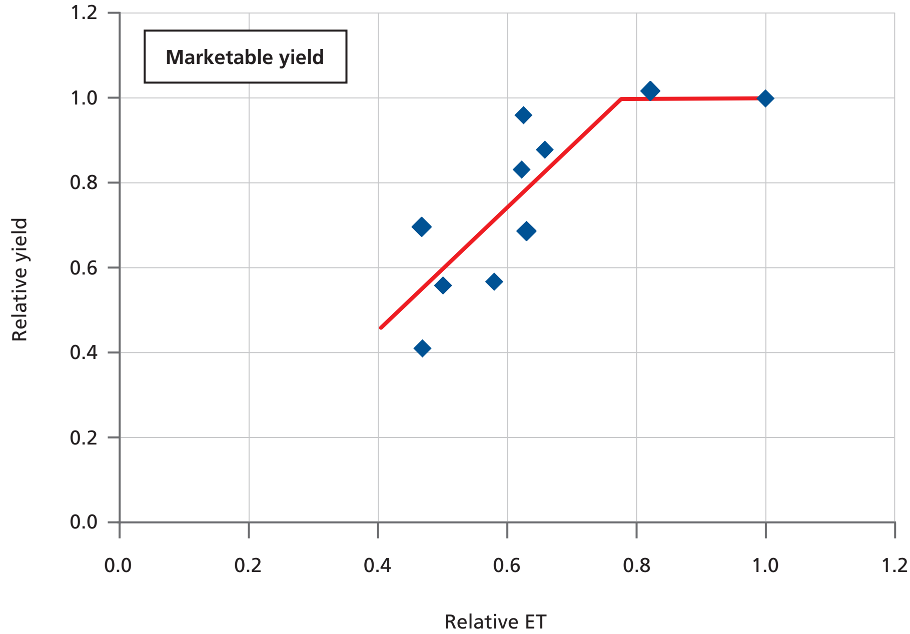
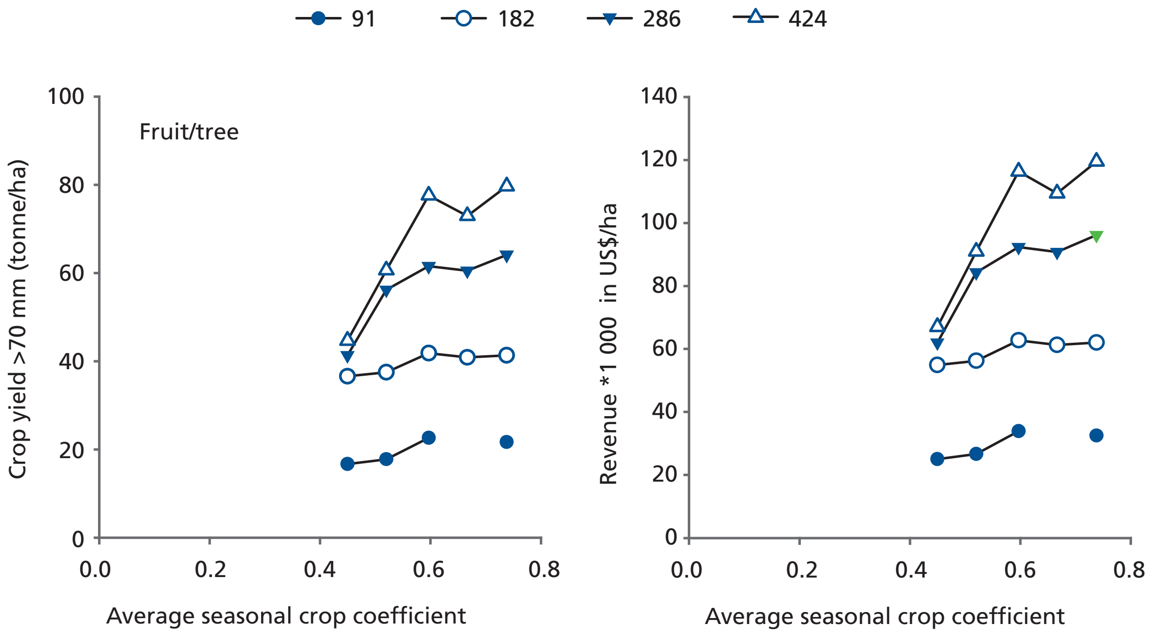


FIGURE 10 Response of marketable fruit yield (>70 mm) and revenue of Golden Delicious apple to irrigation rates (average seasonal reference ET_o K_c) at various crop levels (1 250 tree/ha). Different irrigation rates were applied from mid-June to harvest – K_c values were 0.44, 0.65, 0.84, 1.01, and 1.19; seasonal ET_o (1/5-1/11) was 1 172 mm.



SUGGESTED RDI REGIMES

Given the growth patterns of the apple, and the sensitivity of fruit size to water deficits, it appears that only mild water deficits may be applied to this crop, when grown for fresh market, without impacting negatively on farmers' income. However, RDI has some positive effects on quality that should be exploited, in particular in water scarcity situations. The objective of apple irrigation management under suboptimal water allocation would be to minimize damage and maximize irrigation water productivity. If a small reduction in supply is considered, it should occur preferably during the postharvest period. In common varieties that are harvested in September (Northern Hemisphere) it leaves some period of irrigation up to the start of leaf senescence, a period that will be shorter with increasing latitude. In water shortage conditions one can skip the postharvest irrigation for common varieties but that should not be done in early maturing varieties that have long postharvest period. If water shortages exceed the level equivalent to the amount used for postharvest irrigation, growers should apply the deficit on a continuous basis after the early fruit growth period (avoid stress in the first 30 to 60 days after fruit set, depending on variety), and adjust the crop load by thinning to ensure that the remaining fruit will reach commercial size. A recommendation on irrigation for different water allocations and optimal crop loads for production in warm climates is presented in Table 2.

It is important to monitor soil or tree water status when applying RDI (see Chapter 4). Climate control for apple (frost protection and/or cooling for sunburn protection or to enhance red colour in warm areas) is carried out using sprinkler irrigation and its use, in the case of cooling, may disrupt the RDI programme. Evaporative cooling reduces actual ET on the order of 20 percent, but total seasonal irrigation water requirements would be much higher than the full orchard ET_c, as calculated in Chapter 4.

TABLE 2 Apple orchard water requirements, based on an orchard planted at 4 x 1.6 m, trained with a central leader and with a ground cover about 45-50 percent and tree heights > 3.5 m. Located in Mollerussa (Lleida, Spain). ET_o values used are the average daily data from the last 8 years (2002-2009).

			FULL IRRIGATION		MODERATE RDI		SEVERE RDI	
		ET_o (mm/day)	K_c	ET_c (mm/day)	K_c	ET_c (mm/day)	K_c	ET_c (mm/day)
March	1-15	2.19	0.30	0.66	0.30	0.66	0.30	0.66
March	16-31	2.61	0.30	0.78	0.30	0.78	0.30	0.78
April	1-15	2.70	0.40	1.08	0.40	1.08	0.30	0.81
April	16-30	3.75	0.45	1.69	0.45	1.69	0.30	1.13
May	1-15	3.95	0.60	2.37	0.60	2.37	0.40	1.58
May	16-31	4.64	0.75	3.48	0.75	3.48	0.40	1.86
June	1-15	5.08	0.82	4.17	0.82	4.17	0.50	2.54
June	16-30	5.45	0.87	4.74	0.87	4.74	0.50	2.73
July	1-15	5.40	0.92	4.97	0.90	4.86	0.50	2.70
July	16-31	5.47	0.93	5.09	0.70	2.74	0.45	2.46
August	1-15	4.90	0.93	4.56	0.50	2.45	0.45	2.21
August	16-31	4.45	0.94	4.18	0.50	2.22	0.45	2.00
September	1-15	3.57	0.95	3.39	0.50	1.78	0.45	1.61
September	16-30	3.01	0.75	2.26	0.50	1.51	0.45	1.35
October	1-15	2.44	0.60	1.46	0.50	1.22	0.45	1.10
October	16-31	1.60	0.55	0.88	0.55	0.88	0.55	0.88

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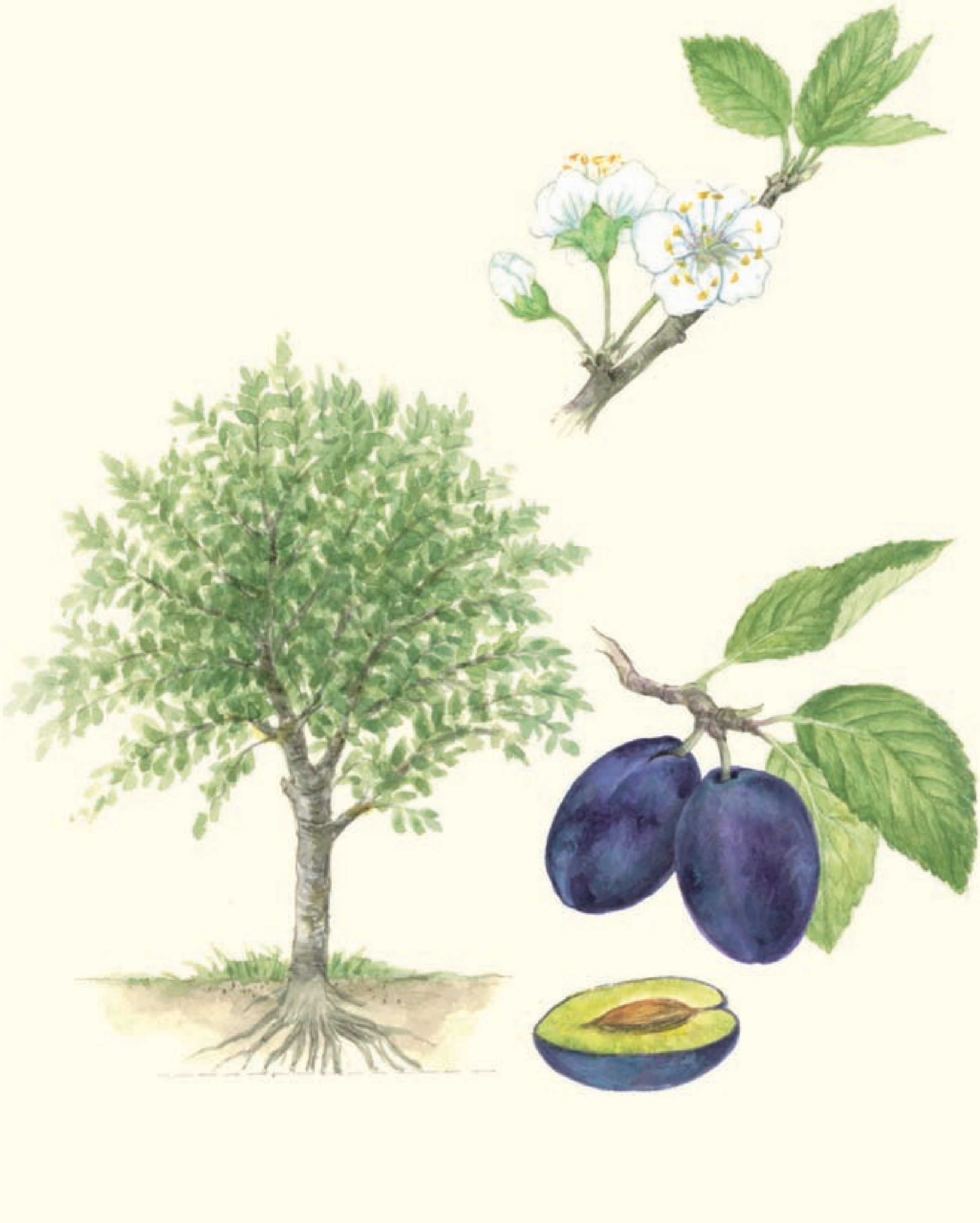

Plum

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Plum

INTRODUCTION AND BACKGROUND

Plum species of commercial importance originated between Eastern Europe and Central Asia. Cultivated plums include two main species, European (*Prunus domestica* L.) or 'prunes' and Japanese plums (*Prunus salicina* L.). Both species are medium-size deciduous stone fruit-trees that differ notably in respect to their climatic requirements. European plums are cultivated in temperate climates to fulfil chilling requirements and to enable proper bud break. They are relatively late flowering, while Japanese plums grow better in temperate-warmer regions, as their chilling requirements are less. Their productive use also differs, as Japanese plums are mainly grown for fresh fruit, while dried fruit (prunes) is mainly obtained from European plum varieties. World acreage was over 2.5 million ha in 2009 with an average yield of 4.3 tonne/ha. China and Serbia are the two main world producers, followed by the United States and Romania (Figure 1). Spain occupies the eighth place with about 191 000 tonne mostly of fresh fruit, but is among the three world highest exporters. France is the main European producer of dried fruit, and Chile is now an important producer and exporter in the Southern Hemisphere (FAO, 2011).

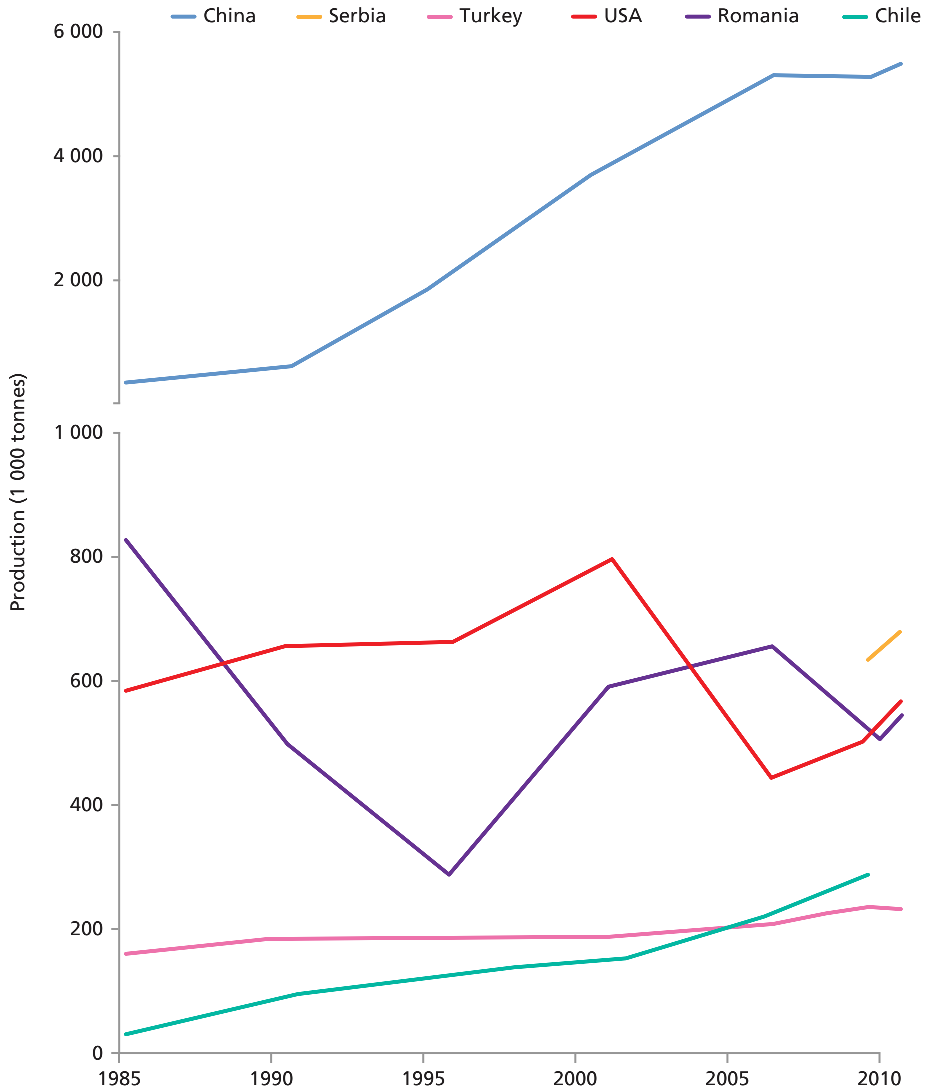
Plum species can adapt to different soil types, although they are sensitive to water-logging, iron chlorosis and salinity. Therefore, the use of rootstocks to cope with these adverse environmental conditions is common. Plum trees generally bear fruit at an early age and the fruiting period lasts 5-35 years. Early varieties can be grown without irrigation in arid climates with rainfall as low as 300 mm/ season, and midseason varieties require at least 400-500 mm/ season. However, productivity and fruit size in these conditions are usually low and, therefore, most plantations are irrigated, especially in arid and semi-arid climates.

The quality features for fresh market include size, colour and a good balance between soluble solids and acidity, while for dry fruit production, soluble solids and size are the two most important quality parameters.

DEVELOPMENTAL STAGES IN RELATION TO YIELD DETERMINATION

Commercial plum tree varieties break dormancy and begin flowering in the Northern Hemisphere between late-February and mid-April, depending on

FIGURE 1 Production trends for plums in the principal countries (FAO, 2011).



the environmental conditions and the cultivar. Bud formation starts with the appearance of the first basal leaves and continues through June on mature trees (Westwood, 1993). Reproductive buds are in a lateral position on terminal shoots or on short shoots called spurs. Flower buds are initiated in the growing season prior to anthesis, and development continues through the dormant season until the following spring just before bud break. The proportion of spur and terminal shoots varies largely with variety and species and so does the proportion of fruit borne on spurs and shoots, which also varies with tree age. Most commercial plum cultivars are not self-pollinating and therefore the use of pollinators is required. Plum trees bloom very profusely and thinning is required, either performed manually, chemically or mechanically to obtain commercial fruit sizes. For example, Black-Gold in Mediterranean conditions may set around 10-40 percent of the flowers produced, but good commercial yields are obtained with only about 5-10 percent of fruit set (Intrigliolo and Castel, 2005). Normally, flowering is completed by late April (Northern Hemisphere) and is followed by rapid fruit expansive growth with concomitant rapid shoot growth.

The fruit with fleshy pericarp is classified as a drupe and is single-seeded. Fruit growth follows the typical double-sigmoid pattern, with rapid exponential growth during the cell division phase (Stage I, ~ 30 days in length), followed by a relatively short period of slow growth during pit hardening and embryo development (lag phase, Stage II). Finally, a second period of rapid cell and fruit enlargement prior to harvest (Stage III), when the fruit can increase in size *ca.* 40-60 percent, although this is linked to accumulated heat units (degree-days) after flowering, in a similar fashion to other *Prunus* species (DeJong and Goudriaan, 1989). Therefore, the length of each stage varies with variety and location. During the postharvest period, some shoot growth and carbohydrate storage for reserves are the primary sinks for carbon assimilation, which continues until leaf fall.

EFFECTS OF WATER DEFICITS

A distinction should be made between plums for fresh fruit production and those for dried fruit production (prunes), as dry matter accumulation is less sensitive to water stress than is the increase in fresh weight, particularly during the last stages of fruit development. In addition, lower fruit hydration rates resulting from water deficits may also offer an advantage for post-harvest fruit processing in the case of prunes for dry fruit production (Lampinen *et al.*, 1995). Thus, prune trees are considered to be moderately resistant to water stress, as indicated by early experiments (Hendrickson and Veihmeyer, 1945) in the deep soils of California's Sacramento Valley, where it took 4 years of no irrigation to detect decreased trunk growth, and 5 years of water deprivation to detect a significant reduction of fruit yields. This is also supported by more recent findings (Goldhamer *et al.*, 1994) where irrigation cutoff, up to 37 days before harvest did not have any negative impact on dry fruit yields of French prune.

Water stress during fruit growth

In Japanese plums for fresh markets, water stress in the final stages of fruit growth significantly decreased fruit size, but accelerate ripening and lead to an increase in fruit sugar concentration (Naor, 2004). Under water stress, average fruit weight and yield were affected by increased tree crop load for Japanese plum (Intrigliolo and Castel, 2005; Naor, 2004) but under minimum stress conditions, the fruit size distribution was unaffected by fruit number per tree, possibly because of low crop yields, which did not introduce significant limitation of assimilates (Naor, 2004). Irrigation of previously water-stressed prune trees has been found to induce fruit-end cracking (Uriu *et al.*, 1962); the formation of cracks was accompanied by increased osmotic potential gradients along the fruit in re-watered trees (Milad and Shackel, 1992).

Water stress during postharvest

The practice of reducing or eliminating irrigation after harvest of an early-maturing plum cultivar (*P. salicina*) irrigated with foggers was studied in California (Johnson *et al.*, 1994), where completely cutting off irrigation led to partial defoliation within a few weeks and loss of yield in the subsequent year. Postharvest midday stem-water potential (SWP) reached ~-3.3 MPa with no symptoms of defoliation in Black Amber (Naor, 2004). For trees that were irrigated daily, but at half the rate of the fully irrigated control, no reduction of yield or fruit quality occurred over a 3-year period, possibly because of the contribution of stored soil water. In young orchards, postharvest water restrictions did not affect yield in the short term (Intrigliolo and Castel, 2005). However, after four seasons of deficit irrigation, there was a 10 percent reduction in yield compared with fully irrigated trees because the stressed trees were smaller. Thus, long-term deficit irrigation of young trees causes a reduction in productivity by reducing tree size. Post harvest water stress, despite its moderate detrimental effect in the long term, should be considered for commercial orchards not only in the case of water scarcity, but also as a tool for controlling vegetative growth in areas where vigorous growth may be a problem.

Plant water stress is known to potentially affect flower bud development for the next season, but there are only a few reports on a decrease in next season crop level because of bud damage (Johnson *et al.*, 1994). Water stress during postharvest, as measured by the SWP, was also correlated with the following season's crop yields.

In some cases, there was even an increase in return bloom leading to larger yield in prune trees where a high crop level was the target (Lampinen *et al.*, 1995). In plum trees, water stress did not appear to be associated with the appearance of fruit disorders such as double fruit formation or fruit deep suture, as occurs in other stone fruit-trees such as peach (Johnson and Handley, 2000).

Plant water stress indicators

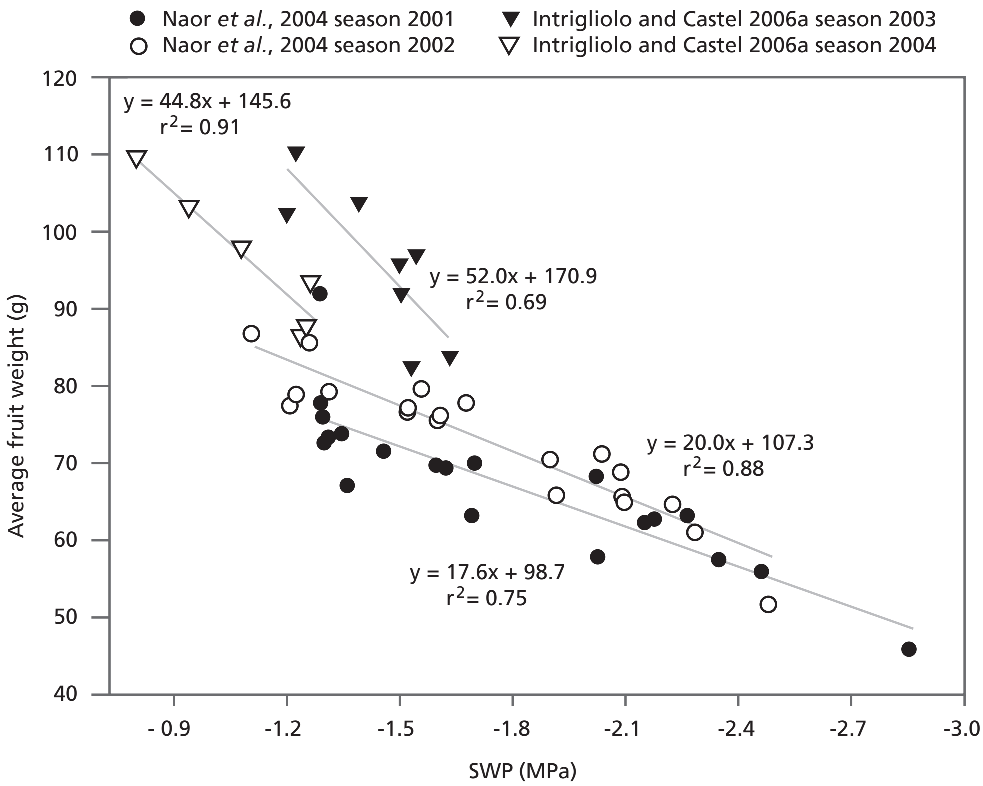
Midday SWP is the most useful indicator of plant water stress in plum trees, since prior to harvest it was highly correlated with tree performance (Naor, 2004; Intrigliolo and Castel, 2005; and Intrigliolo and Castel, 2006a). Figure 2 presents the results of two studies on different varieties of Japanese plums: Black-Gold plums (Intrigliolo and Castel, 2006a) and Black Amber plums (Naor, 2004) in the semi-arid climates of Valencia, Spain and Upper Galilee, Israel, respectively. In each location and season, tree-to tree variations of SWP were well correlated with the average fruit weight at harvest. However, there was no unique relationship relating SWP to fruit weight valid for all data across experiments (Figure 2). The differences in the intercept of the lines reported between seasons and locations indicate that fruit weight is not only a function of plant-water status. In addition, the different slopes of the linear relationships between locations suggest that the effect of plant water stress on fruit growth might change according to different environmental or cultural conditions. Overall these results highlight the importance of conducting local experiments when attempting to predict the effect of plant water stress on fruit weight at harvest.

Studies using other water status indicators for plum trees have also shown that daily trunk contraction, continuously measured with stem dendrometers (Intrigliolo and Castel, 2006b), is highly correlated to SWP, but other factors such as tree age and tree crop load also influence the relationship between trunk contraction and SWP (Intrigliolo and Castel, 2006b; and Intrigliolo and Castel, 2007).

WATER REQUIREMENTS

Only a few early studies quantified the consumptive water use of plum orchards. The recommended crop coefficient values for plum trees are included in the stone fruit tree section together with peach trees in the *FAO I&D No. 56* publication (Allen *et al.*, 1998). A specific study

FIGURE 2 Relationships between average fruit weight at harvest and average midday stem-water potential (SWP) during the last phase of fruit growth. Data correspond to the regulated deficit irrigation experiments carried out with Japanese plum cv. Black-Gold and cv. Black-Amber during different seasons.

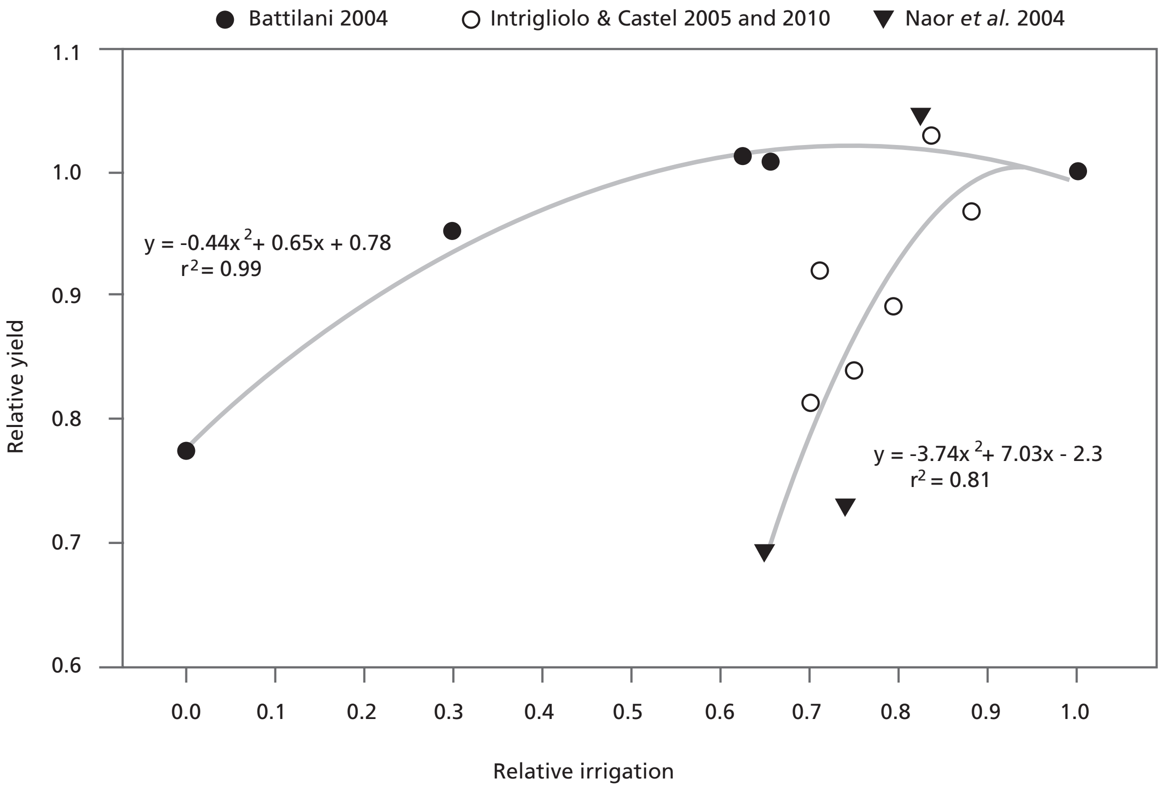


of the water use of plum trees trained to different canopy arrangements (Chootummatat *et al.*, 1990) found that mature trees under a Tatura training system reaching full cover, used 92 percent of class-A pan evaporation in midsummer. Lower water use (82 percent of pan evaporation) was determined for trees trained as vase or palmette systems. As a first approximation, the K_c values for peach (see Peach) should be used for plum orchards.

WATER PRODUCTION FUNCTION

It seems that there are no deficit irrigation trials investigating the relationship between tree water use and yield either for Japanese plums or European prunes. However, from main results reported in the literature it is possible to derive some water productivity functions based on applied water by irrigation. Three studies on different varieties of Japanese plums were included in the analysis: Fortune plums in the humid climate of the Po Valley in Italy (Battilani, 2004), Black-Gold plums (Intrigliolo and Castel, 2006a; Intrigliolo and Castel, 2010) and Black Amber plums (Naor, 2004; Naor *et al.*, 2004) in Valencia, Spain and Upper Galilee, Israel, respectively. In all cases curvilinear functions fit the relationships between relative yield and relative irrigation (Figure 3), but there were differences in the threshold values of relative applied irrigation for no yield reduction. The data from Spain and Israel fell on a single polynomial regression line, which fitted both data set well. In cv. Black-Gold and Black-Amber only 10 percent of reduction in applied water appears to be admissible for no yield penalty,

FIGURE 3 Relationships between relative yield and relative irrigation. Data correspond to regulated deficit irrigation experiments carried out with Japanese plum cvs. Fortune, Black-Gold and Black-Amber. The data from cvs. Black-Gold and Black-Amber were pooled together. All values are calculated relative to the fully-irrigated control plots.



whereas in the study in Italy with the cv. Fortune, it was possible to reduce irrigation by 20-25 percent without any yield reduction. In addition, the response of Black-Gold and Black-Amber plums showed a much sharper decrease in relative yield with irrigation deprivation relative to Fortune plums. The differences in the relationships between applied water and yield are related to the unknown contribution of stored soil water and of in-season precipitation to the crop ET_c under water deficits. The similarity in the response of two different varieties in Spain and Israel probably reflect the limited contribution of soil storage in both studies (hence the sharp decline in relative yield when irrigation decreases). Additionally, the differences between the study in Italy and the other two might be the result of climatic conditions, with higher winter and growing season precipitation in the Po Valley and tree age; mature trees in Italy and younger orchards in the studies in Spain and Israel.

The patterns obtained in the above-mentioned studies are in line with general tree responses to water supply, where yield increases with increasing water application but up to a point where further increases in water application do not produce any increase in yield. Since there are no studies relating yield to ET_c in plum trees, overall data reported in Figure 3 showed that for plum trees deficit irrigation could save around 10-20 percent of applied water with minimum or no yield loss.

SUGGESTED DEFICIT IRRIGATION STRATEGIES

The suggested deficit irrigation strategy may greatly vary depending on the final market product, dried fruit or fresh fruit, and on specific phenological aspects of each variety affecting bloom intensity and fruit set levels and particularly, earliness. The general strategy used to impose the water deficits for French prune was to limit water deficits during early stages of tree and crop development, imposing more severe stress during mid and late season. In this sense, in a clay loam soil in California, allowing a progressive decline in midday SWP to approximately -1.5 MPa by harvest, e.g. irrigating at about 50-60 percent ET_c from spring, resulted in an effective way to reduce irrigation and maintain an economic return over a 3-year period (Lampinen *et al.*, 2001a).

For early season fresh market varieties it can be concluded that water stress after harvest that limits the decline in SWP below -2.0 MPa, despite some possible slight detrimental effect in the long term, should be considered in commercial orchards not only for water scarcity, but also as a tool to control vegetative growth. In young orchards, postharvest deficit irrigation may be combined with closer tree spacing, a feature very common in modern fruit tree plantations where new cultivars and orchards have a short life.

For fresh market varieties water stress, if applied during fruit growth, should be concentrated during pit hardening. The length of this phase depends on the harvest date. Hence, in early and even midseason maturing cultivars there is a risk of extending the water stress into the final fruit growth stage with detrimental effects on fruit size. Recent results (Intrigliolo and Castel, 2010) suggest that some degree of water stress can be applied during the early stage of fruit growth, providing that plant-water stress is mild (SWP > -1.4 MPa) and trees return to optimum water status at least one month before harvest. The convenience of water stress applied during fruit growth would indeed depend upon price market values of different fruit size categories and fruit quality effects of water restrictions. In this sense it should be considered that deficit irrigation during fruit growth advances maturity, increases total soluble solids content and firmness, and may improve fruit colour. The effects of water restrictions on volatile aroma compounds and particularly fibre and other fruit quality components related with human health have not been extensively studied and could be of great importance for plum growers if the consumption of plums is promoted.

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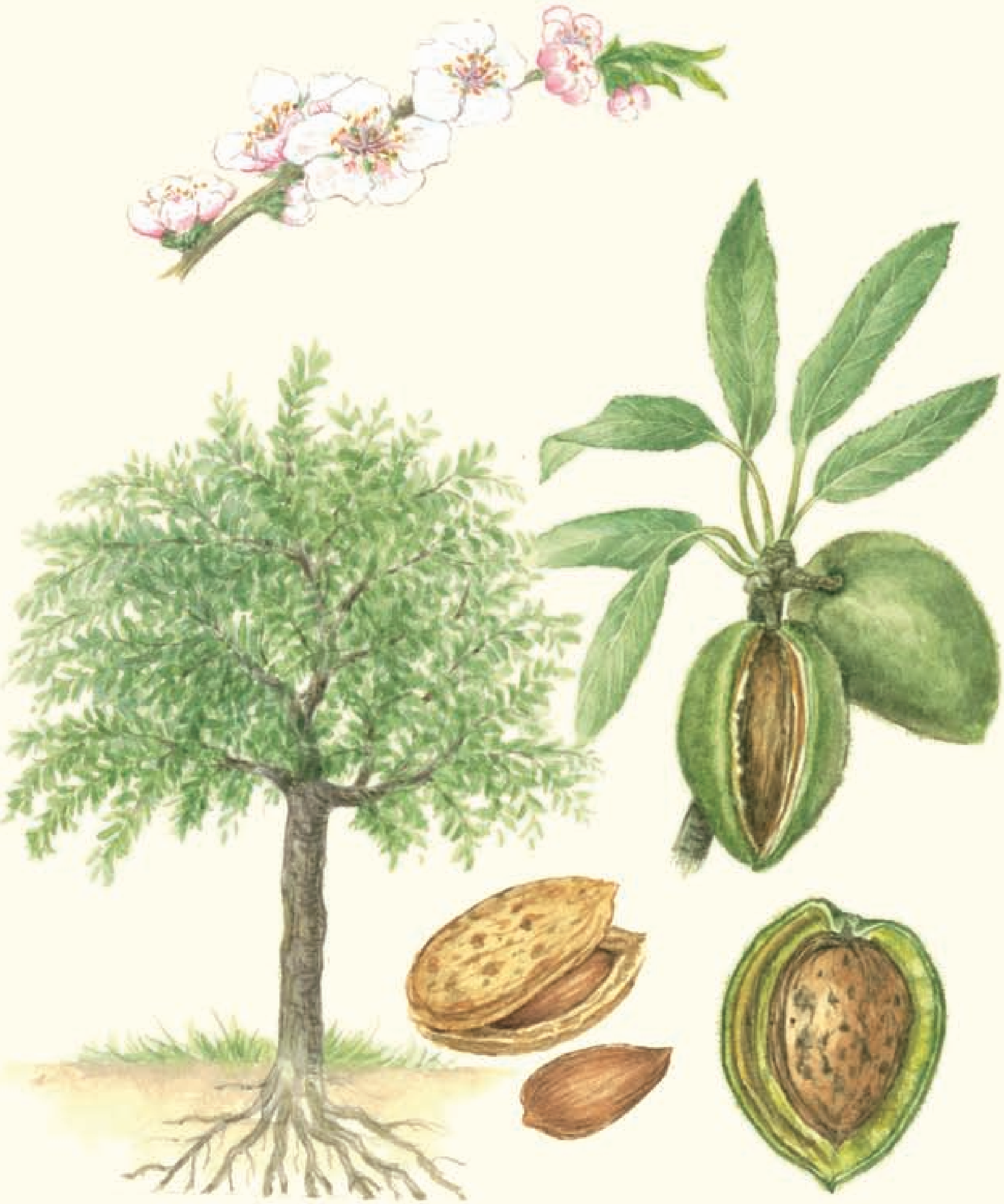

Almond

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Almond

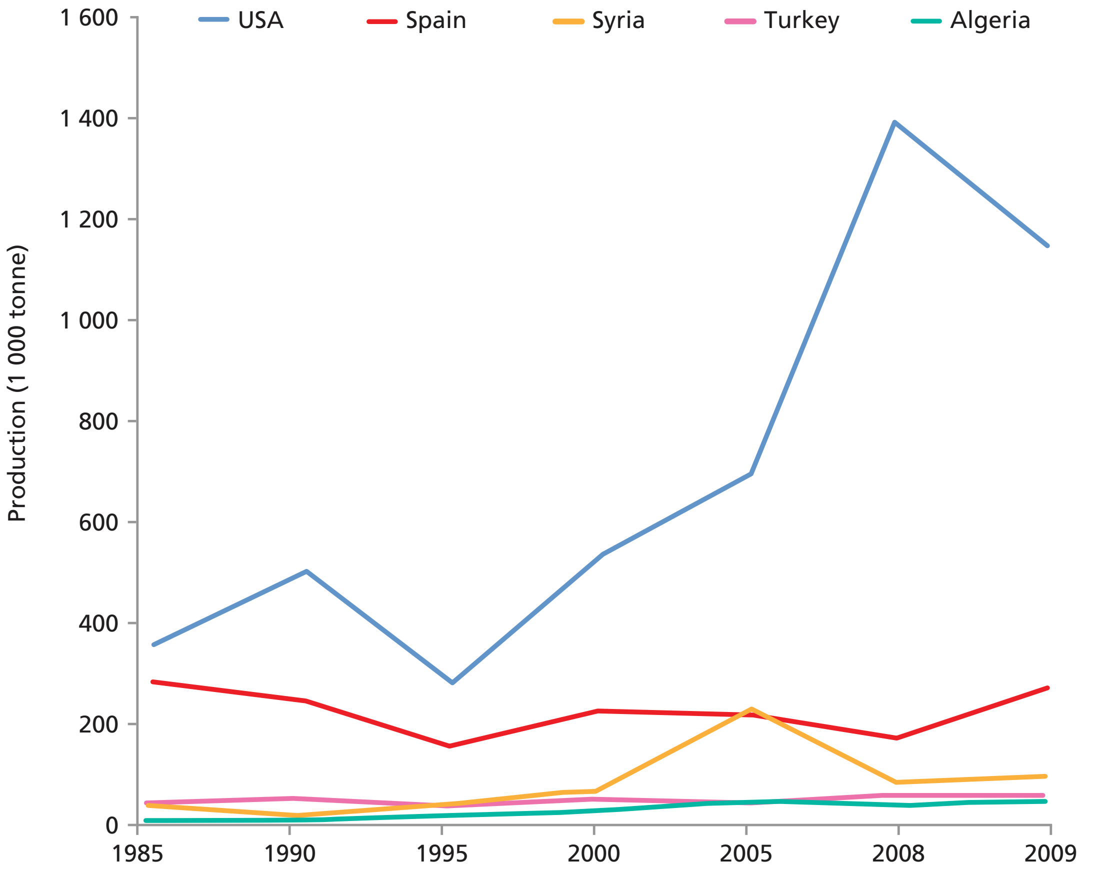
INTRODUCTION AND BACKGROUND

Almonds are grown under both rainfed and irrigated conditions; production in semi-arid zones, such as the western United States and Spain, reflects the drought tolerance of the tree. In many areas of the Mediterranean Basin, almond trees are grown on marginal soils in areas where annual rainfall does not exceed 300 mm, being important for erosion control and to prevent desertification. As a result of the limited water supply and poor soil conditions of the rainfed areas, tree densities are quite low and yields are also low and variable from year-to-year. However, they can be much higher when the water-use requirements of the trees are fully met and, in most areas of the world, this requires irrigation. New irrigated almond plantations have expanded in recent decades in many areas and are highly productive. Nevertheless, almonds are an important crop in very diverse agricultural systems, from very marginal to highly intensive. In 2009, the cultivated area worldwide amounted to 1.8 million ha with an average yield (with shell) of 1.3 tonne/ha (FAO, 2011). Figure 1 shows the recent trends in production of the major producing countries.

Modern almond cultivation presents unique challenges to irrigation in general and regulated deficit irrigation (RDI) in particular. These include dealing with multiple cultivars in each orchard, a long period between flowering and fruit maturity the need to dry the soil prior to harvest in order to mechanically shake nuts from the trees, and a relatively late reproductive bud morphogenesis period. On the other hand, since the fruit is sold dry, many of the problems associated with fresh fruit production, including physical appearance, handling and storage are absent.

The almond flower of most varieties is self-infertile; it cannot pollinate itself. Even for cultivars that are self-compatible, production is enhanced by cross-pollination. Thus, each orchard normally contains at least two different cultivars with overlapping bloom periods to help the process of cross-pollination; the transfer of pollen from the anthers of a flower from one cultivar to the stigma of a flower from another cultivar. This transfer is facilitated by the introduction of honey bees into the orchard during flowering. To maximize pollen exchange, a common arrangement is single, alternating rows of each cultivar. The fact that two or more cultivars exist in a field complicates irrigation management in that the different harvest periods usually result in harvest-related water deprivation for one cultivar, while kernel filling is occurring in the other cultivar. Further, there is some evidence that different cultivars have different stress sensitivities.

FIGURE 1 Production trends for almonds in the principal countries (FAO, 2011).



Quality considerations

Insect damage, shrivel, kernel colour, and broken kernels are quality criteria worldwide. Additionally, marketplace differences result in cultivar-dependent crop values. Some markets also place a premium value on larger nuts; the United States, for example.

DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Almond trees require very low chilling and thus, vegetative growth and flowering begin very early in the season relative to other deciduous tree species; although plant breeders aim to develop cultivars that bloom late to avoid chilling injuries. This earliness feature relates to the evolution of almonds in mild, subtropical climates with prolonged summer drought. The period from flowering to fruit maturation of almond is relatively long, depending on climate and cultivar; from late January-March to August-September in the Northern. Hemisphere, and the sensitivity of each of the physiological processes during this time to water deficits must be considered to assess the impact of stress on the yield and quality of the fruit at harvest. Not only current season impacts but those of subsequent seasons must be taken into account.

EARLY VEGETATIVE AND REPRODUCTIVE GROWTH

Flowering and initial leaf development occur almost simultaneously from late January in the Northern. Hemisphere for the earliest blooming cultivars until the end of March for the late blooming. Fertilization of the flower is followed by growth of the pollen tube into the ovary, which will evolve into the marketable kernel. The maximum potential fruit production is determined during this early period. It is established by the number of flowers produced (flower set) and the percentage of these that are successfully pollinated (fruit set). Early fruit development is largely the result of cell division. The early stages of fruit growth occur at the same time as most of the leaf expansion and shoot growth. This results in considerable competition for tree resources, principally carbohydrates. Thus, if flowering and fruit set are high, shoot growth may be lower. Since fruit are borne on spurs, this may reduce the number of new reproductive buds produced and, in turn, reduce the crop potential for the following year. In addition to its impact on fruiting positions, this carbohydrate competition can influence fruit set. If carbohydrate reserves from the previous year are low, the current year fruit set may be reduced (Esparza *et al.*, 2001). This effect may enhance alternate bearing in almonds, especially under rainfed conditions.

Stages of fruit growth

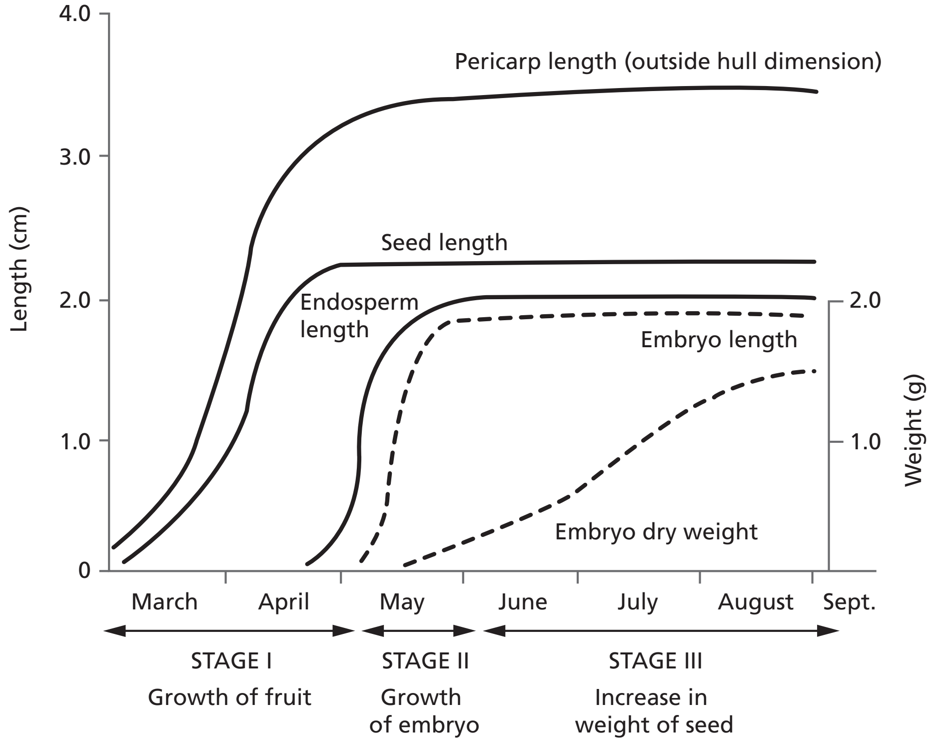
Figure 2 shows the pattern of fruit growth where three stages may be defined:

Stage I is one of rapid growth of the hull, shell, and integuments. The entire fruit remains soft and reaches its maximum size. Cell division is completed in a few weeks; the major part of growth thereafter is expansion. At this point, the kernel is a white structure filled with watery, translucent tissue. The time between fertilization of the flower to the end of fruit development is about two months. The end of Stage I is marked by the attainment of the maximum external dimensions of the hull, shell, and kernel.

Stage II is characterized by shell hardening and kernel expansion. There are two types of almond varieties: hard and soft shelled. Hard shelled, which are many of the Mediterranean varieties, have shelling percentages of 25-35 percent, while soft shelled have 70 percent. They completely harden in Stage II while the soft shelled remain soft. The growth of the embryo involves clear watery tissue becoming translucent, starting at the apical end. This white, opaque embryo rapidly expands during this period. Toward the end of Stage II, kernel dry weight begins to increase.

In Stage III, the major event is the steady dry matter accumulation in the kernel. The morphological differentiation of the hull, shell and kernel are complete. Dry matter accumulation of assimilates continues at a steady rate until maturity, as long as the vascular connections remain intact. Two events signal the approach of maturity: hull split (endocarp dehiscence) and the formation of an abscission layer at the nut-peduncle connection. Complete dehiscence requires an adequate tree-water status because the sides of the hull must be turgid to separate properly. Excessive stress may cause the hulls to adhere to the shells (hull-tights), which complicates processing. Maturity is also characterized by a sharp slowing in the rate of kernel dry matter accumulation. In some areas, commercial harvests occur prior to kernel maturation to avoid insect navel orange worm (NOW) damage.

FIGURE 2 The three stages of almond fruit development and the typical length and weight of the fruit at each stage. Adapted from the UC Almond Production Manual, 1996.



Bud development

The reproductive buds are borne on spurs and are initiated in the spring as the spurs develop. There are three subsequent stages of flower-bud development. The first is induction where the internal physiology of the growing point changes. This occurs in mid-August and the vegetative and reproductive buds are indistinguishable. Second are the morphological-anatomical changes in the internal structure, which are readily observable in September. Third is gradual growth of the reproductive parts during the autumn and winter, i.e. development of the sepals, petals, stamens and ovaries.

RESPONSES TO WATER DEFICITS

As for most crop plants, vegetative growth of almonds is very sensitive to water deficits. Avoidance of water deficits throughout the season in young trees is critical to reach full production in the shortest time period (Fereres *et al.*, 1981). In mature plantations, responses to water deficits depend on the timing of the stress.

In areas that receive substantial winter rainfall, tree processes that occur very early in the season, such as leaf out, flowering, pollination and fruit set, will be under non-limiting soil water levels. However, as the season progresses and evaporative demand increases, shoot, spur, and fruit growth will be subjected to water deficits without irrigation or in-season rainfall. Several reports state almond vegetative growth is very sensitive and directly affected by tree-water deficits.

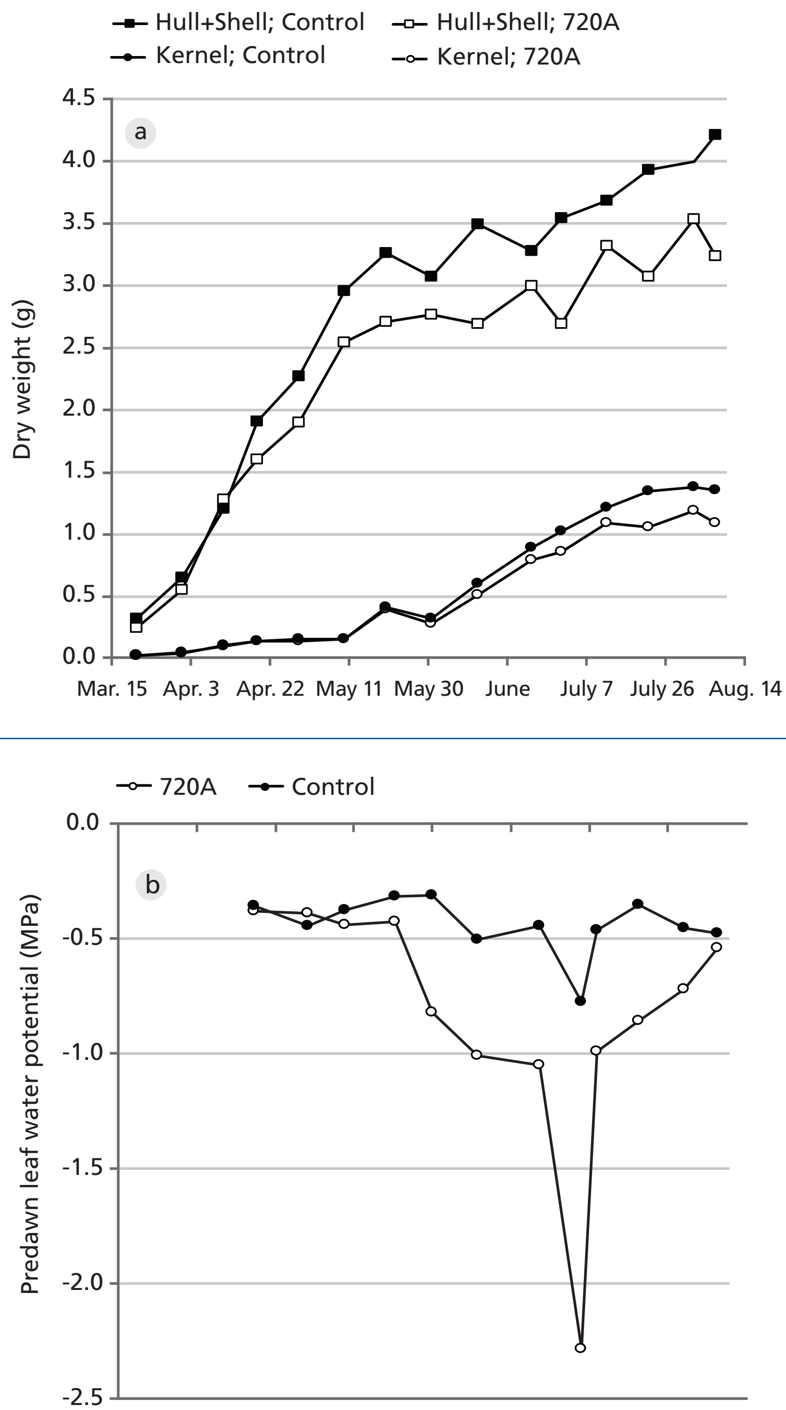
The research results on preharvest impacts of stress on kernel filling are seemingly contradictory and may reflect the importance of stress timing and cultivar differences. A study in Spain (Girona *et al*., 2005) with cv. Ferragnes, reported that kernel dry weight accumulation was not influenced during the first two seasons of an RDI regime that irrigated at 20 percent of ET_c during late June through the mid-September harvest (minimum predawn leaf water potential of -1.7 MPa in August) but was lower during the final two seasons of the study, which was attributed to the cumulative impacts of stress reducing the reserves of carbohydrates available for kernel filling and to relatively low soil water levels during those years. However, a California study (Goldhamer and Viveros, 2000) with higher evaporative demand (minimum predawn leaf water potential of -3.5 MPa) and earlier stress reported significant reductions in kernel dry matter accumulation with cv. Non Pareil in all experimental years. Dry matter accumulation in the hull and shell after three successive years of preharvest stress, diverged from the fully irrigated in late April, well before there were differences in tree stress, as shown in Figure 3. This was likely because of early season competition for carbohydrates. A study (Romero *et al.,* 2004) with cv. 'Cartagenera' that imposed an RDI regime that resulted in a minimum predawn leaf water potential of -2.5 MPa in late July found no reduction in dry kernel weight at the mid-August harvest.

A recent study with cv. Non Pareil in California showed that imposing water deficits primarily from early July through an early September harvest over a four-year period did not reduce kernel weight or nut load (Stewart *et al.*, 2011). These workers attempted to maintain midday stem-water potential between -1.4 and -1.8 MPa during this period. The objective was reduced hull rot, a disease that damages the fruit (Teviotdale *et al.*, 2001), while reducing consumptive use. Other efforts using this same philosophy have achieved positive results and this practice is now being widely adopted by California almond growers with trees afflicted by severe hull rot. However, it should be noted that detailed analysis of the fruit components (hull, shell, and kernel) suggests that the impact of preharvest stress on hull splitting may impact kernel weights. In numerous studies, California researchers found that slight reductions of kernel dry matter accumulation occurred concomitant with the onset of hull split, while at the same time, there were slight increases in the rate of dry matter accumulation in the hulls. The net result was slightly lighter kernels (generally 2-3 percent relative to full irrigation) but no difference in the dry weight of the entire nut. They hypothesized that hull split resulted in some physical disruption in assimilate transport in the pathway leading to the kernel.

It appears that there are two factors involving early season stress timing that can contribute to reduced kernel size: lower cell division and/or expansion, which is enhanced by carbohydrate competition, and the disruption in assimilate transport to the kernels because of accelerated hull split. These stress impacts may well be cultivar-dependent although comparative research studies are lacking.

Of the two primary yield components of almond, fruit load appears to be the most sensitive in terms of water stress impacts on yield. A study in Spain found that fruit loads were reduced in the final two years of a four-year RDI treatment and attributed this to the cumulative impacts of stress on the bearing surface, and thus fruiting positions, of the tree. Another study in California also reported that yield reductions associated with water deprivation in August and September (minimum midday stem-water potential of -2.5 MPa) were the result of a reduced bearing surface resulting from less shoot and spur growth. This study found that yields were reduced only after two years of stress. Other studies have found little impact of preharvest stress on fruit load.

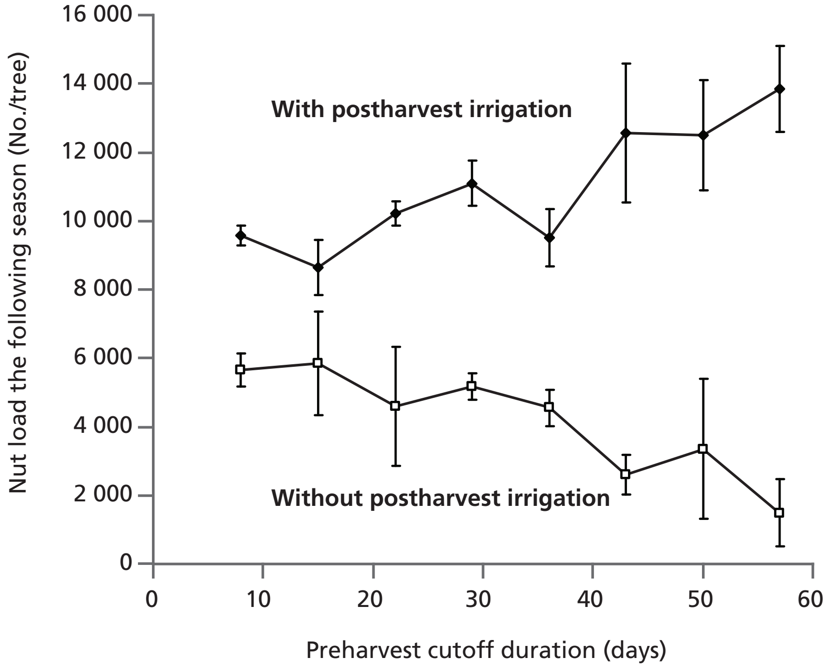
FIGURE 3 Differences in the cultivar Non Pareil trees subjected to preharvest water deficits (720A) and those fully irrigated (Control) in: **(a)** dry matter accumulation in the hulls+shells and kernels with time in the third year of the stress treatments, and **(b)** corresponding predawn leaf water potentials. Adapted from Goldhamer *et al*. (2006).



Much less work has been done on the impacts of postharvest stress on almond production, in part, because in many parts of the world, autumn rains eliminate this possibility. However, a dramatic impact of the presence or absence of postharvest irrigation on the following season's fruit load has been detected (Goldhamer and Viveros, 2000) (Figure 4). Even when the trees were near fully irrigated prior to harvest, postharvest water deprivation resulted in 40 percent reduction in fruit load the following season, relative to trees that received postharvest irrigation. It should be emphasized that this was with a mid-August harvest under high evaporative demand; predawn leaf water potential was below -4.0 MPa in mid September. For this same stress level at preharvest, there was near complete defoliation but after the reintroduction of full irrigation postharvest, there was vegetative bud break and new leaf growth, alleviation of the stress, and no reduction in fruit load the following season (Goldhamer and Viveros, 2000).

The dramatic impact of postharvest water deprivation on fruit load was attributed to stress impacts on reproductive bud development. Early work (Tufts and Morrow, 1925) showed that bud differentiation in almond occurred from late August through early September, and this has been confirmed by more recent work. The timing of bud development showed no clear pattern between cultivars or locations within California, spanning a distance of more than 500 km (Lamp *et al.*, 2001). Thus, bud development can occur both after and before harvest, depending on the cultivar and geographic location. Moreover, bud development is not related to hull split: it occurred three weeks after hull split in Non Pareil but prior to hull split in 'Butte' and 'Carmel.' Stresses that occur during flower development are likely to adversely affect flower quality to the extent that the next season's crop load, and thus yield, would be reduced.

FIGURE 4 Relationships between fruit load in the season following the imposition of different preharvest irrigation cutoff regimes for conditions with and without postharvest irrigation. Vertical lines are plus and minus one standard error. Adapted from Goldhamer and Viveros (2000).



Indicators of tree water status

To precisely schedule irrigation, it may be necessary to monitor a given soil and/or plant parameter and make decisions according to some pre-established criteria. Also, implementing an RDI regime may have to be based on estimates of tree water status, such as the stem-water potential (SWP). The SWP values of well-irrigated almond trees in mid-summer range from -0.5 to -1.0 MPa at midday, depending on the evaporative demand and the time of the year. In one study, there was a 0.2 MPa decrease in the SWP of fully irrigated trees on different days (from -0.7 to -0.9 MPa) when the air temperature increased from 25 to 40 °C. The SWP values decrease as stress increases but in almond, it seldom exceeds -4.0 MPa even under very severe stress (Castel and Fereres, 1982). The tree will shed its leaves before reaching the extreme dehydration levels that would induce lower water potential, as measured in other fruit tree species.

WATER REQUIREMENTS

Most of the almond water use estimates in the literature were developed using soil water balance approaches rather than from more accurate weighing lysimeters. The monthly crop coefficient values (K_c) for clean cultivated, weed free, high evaporative demand conditions published by several authors are shown in Table 1. Because almond ET has often been grouped with peach, apricot, and plum, weighing lysimeter K_c data for peach determined in California are also shown in Table 1 for comparison (Ayars, 2003). Early season crop K_c values for the peach used in their work are relatively low owing primarily to the slow canopy development of this cultivar. Maximum K_c values (July-August) for all the presented data range from 0.95 to 1.08. Recent data from California suggests that almond peak K_c values of an intensive, mature orchard irrigated with microsprinklers may reach as high as 1.17 (Goldhamer, unpublished), which is considerably higher than previously reported. Similar high K_c values have been recently reported in Australia (Stevens *et al.*, 2011). It should be noted that when the early ET data were developed, surface irrigation (border strip) was the primary irrigation method, whereas drip or microsprinklers were used in the more recent studies. The higher K_c values are likely due to the increase in tree densities in recent plantations, larger tree canopies (there is much less annual pruning now than previously), and higher fruit loads. Also, the more frequent wetting of the orchard floor with microirrigation and thus, higher surface evaporation may be another factor for the higher K_c values.

WATER PRODUCTION FUNCTION

Relative yield versus relative applied water data derived from fourteen irrigation studies are presented in Figure 5. It was not possible to estimate ET_c in many of the studies and therefore, the actual production function based on consumptive use could not be drawn. These studies were done over a wide range of evaporative demands, cultivars, and soils with various deficit irrigation regimes; different timing and magnitudes of stress. The correlation coefficients of the linear regressions for these studies ranged from 0.87 to 0.98, indicating a strong functional relationship between yield and applied water. Some of these studies had similar slopes ranging from 0.7 to 0.9, whereas others had a milder slope above 0.3. The lower yield sensitivity of these studies is likely due to a combination of deep soils, relatively low crop loads, and relatively wide tree spacing. Thus, the impact of instantaneous stresses was buffered by the high potential rate of water supply to the trees. It should be noted that these studies generally had consumptive use rates that deprived the trees of up to 30-50 percent of maximum ET_c. Close inspection of

Figure 5 shows that with mild deficit irrigation that would reduce relative ET_c by only 10-15 percent, the impact on production is negligible.

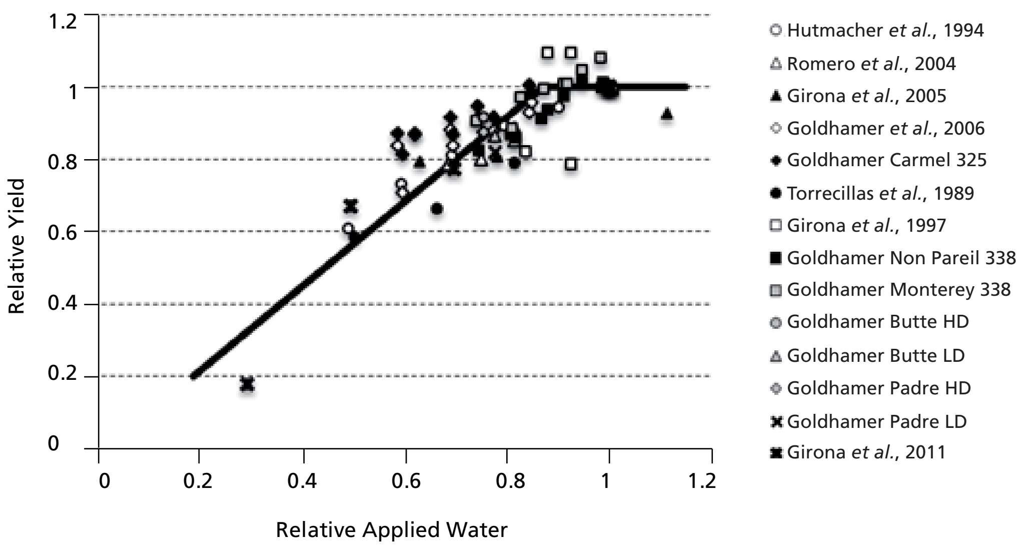
SUGGESTED RDI REGIMES

Growers with limited water supplies must make a decision on when to stress trees. Based on research results, we believe the two most stress sensitive periods are in the Spring when the

TABLE 1 Estimates of the monthly crop coefficient (K_c) values for mature deciduous trees (first column), almond (columns two-five) and peach trees (last column).

	Doorenbos and Pruitt (1977)	Fereres and Puech (1981)	Sanden (2007)	Goldhamer (unpublished)	Girona (2006)	Ayars *et al.* (2003)
March	0.50	0.60	0.59	0.20	0.40	0.28
April	0.75	0.71	0.78	0.67	0.65	0.48
May	0.90	0.84	0.92	0.95	0.80	0.68
June	0.95	0.92	1.01	1.09	0.92	0.88
July	0.95	0.96	1.08	1.15	0.96	1.06
Aug.	0.95	0.96	1.08	1.17	1.05	1.06
Sept.	0.85	0.91	1.02	1.12	0.85(*)	1.06
Oct.	0.80	0.79	0.89	0.85	0.60	0.90
Nov.	0.70		0.69		0.40	

FIGURE 5 Relationships between relative yield and relative applied water for 14 deficit irrigation studies on almond with a wide variety of cultivars, locations, soils, rainfall, stress timing patterns, and evaporative demand.



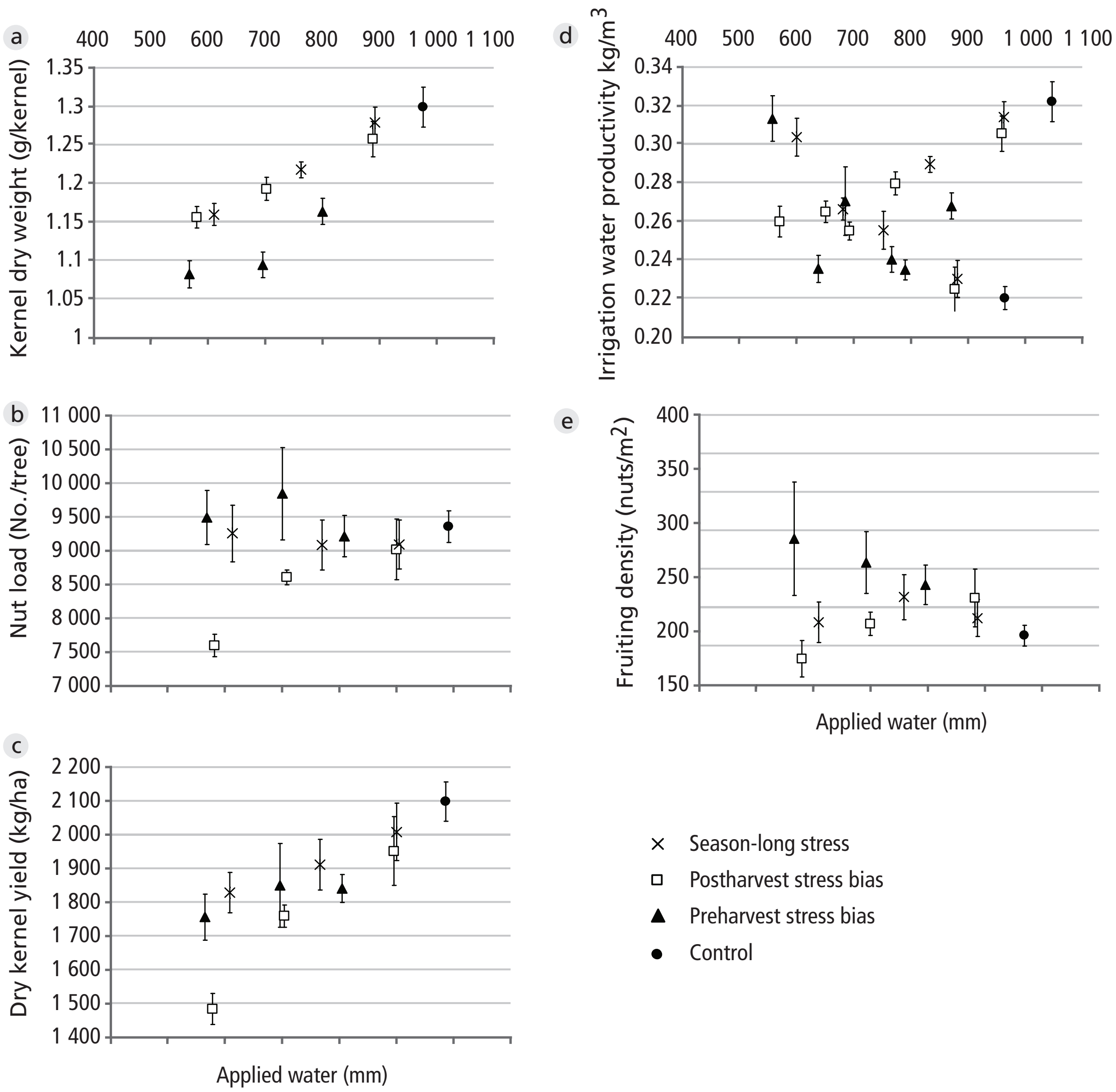
nuts are rapidly expanding and late summer/autumn when bud morphogenesis is occurring. This second stress-sensitive period is usually postharvest for early harvest cultivars but prior to harvest with later maturing cultivars. The results of an experiment (Goldhamer *et al.*, 2006) provide useful information on the relative sensitivity of pre and postharvest stress to aid RDI decision making. It was found that the greater the preharvest water deprivation, the greater was the reduction in kernel dry weight at harvest (Figure 6a). However, minimizing preharvest stress at the expense of postharvest irrigation resulted in significantly lower fruit loads in subsequent seasons (Figure 6b). Yield, the integrator of fruit weight and fruit load, was least affected by minimizing stress after harvest (Figure 6c). These regimes also resulted in the highest irrigation water productivity (Figure 6d).

Water supply constraints may be temporary, as a result of one year drought. Single season drought RDI strategies were tested (Goldhamer and Smith, 1995) where they applied less than 40 percent (400 mm) of potential seasonal ET_c with different timing regimes: irrigating at 100 percent, 75 percent, and 50 percent ET_c until the 400 mm was exhausted, which occurred in early June, mid July, and late August, respectively. They found that full irrigation early in the season limited reductions in fruit size but resulted in dramatic reductions in the following seasons' fruit load (Table 2) (Goldhamer and Smith, 1995). They attributed this to the negative impact of stress on reproductive bud differentiation. The treatment that irrigated at 50 percent ET_c, which applied water longer (through August; two weeks after harvest), did not suffer any significant decrease in fruit load the following season. When they averaged the drought year and the following two fully irrigated recovery years, they found that the 50 percent ET_c treatment had higher yields that the other two RDI regimes; those that applied their available water supply all preharvest. Nevertheless, none of the RDI regimes achieved complete production recovery even after two seasons of full irrigation following the single drought year, suggesting that impacts of reduced shoot and spur growth may have also been a factor (Goldhamer and Smith, 1995).

Suggested RDI regimes for five different levels of available water supply (300, 450, 600, 750, and 900 mm where full ET_c is 1250 mm) expressing irrigation rates as percentages of ET_c are presented in Table 3. To show how these regimes would affect applied water, we used as an example long term values of ET_o from western Fresno County, California and bimonthly crop coefficients (K_c) from Goldhamer (unpublished) for 'Non Pareil' almonds. When the water supply was relatively high, the stress is biased to the preharvest period, saving as much water as possible for the most stress sensitive period; from mid August through the end of September. With a severely restricted water supply, the concern is about tree survival and general health in addition to maximizing stress impacts on time-averaged yields. It must be emphasized that when applying very low amounts of potential seasonal water supply, surface evaporation, and thus, the number of irrigations, should be minimized. Therefore, the duration (amount of applied water) of each irrigation should be maintained as normal but the frequency of irrigation should be changed. For example, if microsprinkler irrigation is normally operated every three days, an RDI strategy that applies 25 percent ET_c would extend the frequency to every 12 days.

Since RDI reduces vegetative growth, it should not be used on young trees where the objective is to grow the canopy to full size, and thus attain maximum yields, as fast as possible. It has been confirmed (Girona *et al.*, 2005) that RDI imposed too early in the life of the orchard can reduce potential yields.

FIGURE 6 Relationships between applied water and a) kernel dry weight, b) fruit load, c) kernel yield, d) irrigation water productivity, and e) fruit density. Vertical lines are plus and minus one standard error. Data are mean values from four experimental years with Non Pareil. Adapted from Goldhamer *et al.* (2006).



Additional considerations

Water stress in almonds has been known to increase spider mite levels (Youngman and Barnes, 1986) and the navel orangeworm (Goldhamer, unpublished data). The latter becomes more of a problem when the onset of hull split is accelerated by preharvest stress and/or the nuts remain longer on the tree before shaking. Hull rot can be dramatically reduced by imposing water deficits during the first two weeks of July (Teviotdale *et al.*, 2001). Their target predawn leaf water potential value was -1.6 MPa.

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TABLE 2 Irrigation management, yield, and nut quality data for a single year drought irrigation study conducted in western Fresno County, California.

Year	Treatment	Water applied through	Water allotment applied ** (mm)	Total kernel yield (lbs/acre)	Individual kernel weight (grams)	Tree nut load (No./tree)	Hull splitting		
							Full hull split	Partial hull split	Hull tight
							(- - - - - % of tree nut load - - - - -)		
Drought	Full irrigation control	Full season	1 024	1 653 a***	1.24 a	7 100 a	98.9 a	0.4 a	0.7 a
Year	100%DY ET_c*	June 19	409	1 362 b	0.97 b	8 160 a	38.2 b	48.1 b	13.7 b
	75%DY ET_c	July 11	411	1 236 b	1.10 bc	6 340 a	85.3 a	11.4 a	3.3 a
	50%DY ET_c	August 28	414	1 448 ab	1.03 bc	7 000 a	99.0 a	0.6 a	0.4 a
Recovery	Full irrigation control	Full season	843	2 730 a	1.04 a	1 2850 a	99.7 a	0.0 a	0.3 a
Year 1	100%DY ET_c*	Full season	836	911 b	1.03 a	4 770 b	99.7 a	0.1 a	0.2 a
	75%DY ET_c	Full season	836	1 493 c	0.99 ab	8250 c	99.9 a	0.0 a	0.1 a
	50%DY ET_c	Full season	846	2 010 d	0.89 b	1 1690 a d	99.6 a	0.0 a	0.4 a
Recovery	Full irrigation control	Full season	838	2 358 a	0.97 a	9 890 a	98.3 a	1.3 a	0.4 a

TABLE 2 (CONTINUED)

Year	Treatment	Water applied through	Water allotment applied ** (mm)	Total kernel yield (lbs/acre)	Individual kernel weight (grams)	Tree nut load (No./tree)	Hull splitting: Full hull split	Hull splitting: Partial hull split	Hull splitting: Hull tight
							(- - - - - % of tree nut load	- - - - -)	
Year 2	100%DY ET_c*	Full season	838	2 327 a	1.02 a	9 200 a	98.8 a	0.7 a	0.5 ab
	75%DY ET_c	Full season	838	1 975 b	1.02 a	7 900 b	97.9 a	1.2 a	0.9 b
	50%DY ET_c	Full season	838	1 949 b	1.13 b	7 050 b	98.5 a	1.0 a	0.5 ab
Year 3	Full irrigation control		902	2 247 a	1.08 a	9 948 a	99.0 a	0.5 a	0.5 a
Mean	100%DY ET_c*		693	1 534 b	1.01 a	7 378 b	78.9 b	16.3 b	4.8 b
	75%DY ET_c		696	1 568 b	1.04 a	7 498 b	94.4 a	4.2 a	1.5 a
	50%DY ET_c		**699**	**1 802 c**	**1.02 a**	**8 581 b**	**99.0 a**	**0.5 a**	**0.5 a**

* Irrigation rate until allotment applied; no additional irrigation for the remainder of the season.

** Does not include 100 mm pre-season irrigation applied each year.

*** Numbers for each year followed by a different letter are significantly different at the 5% confidence level using Duncan's New Multiple Range Test.

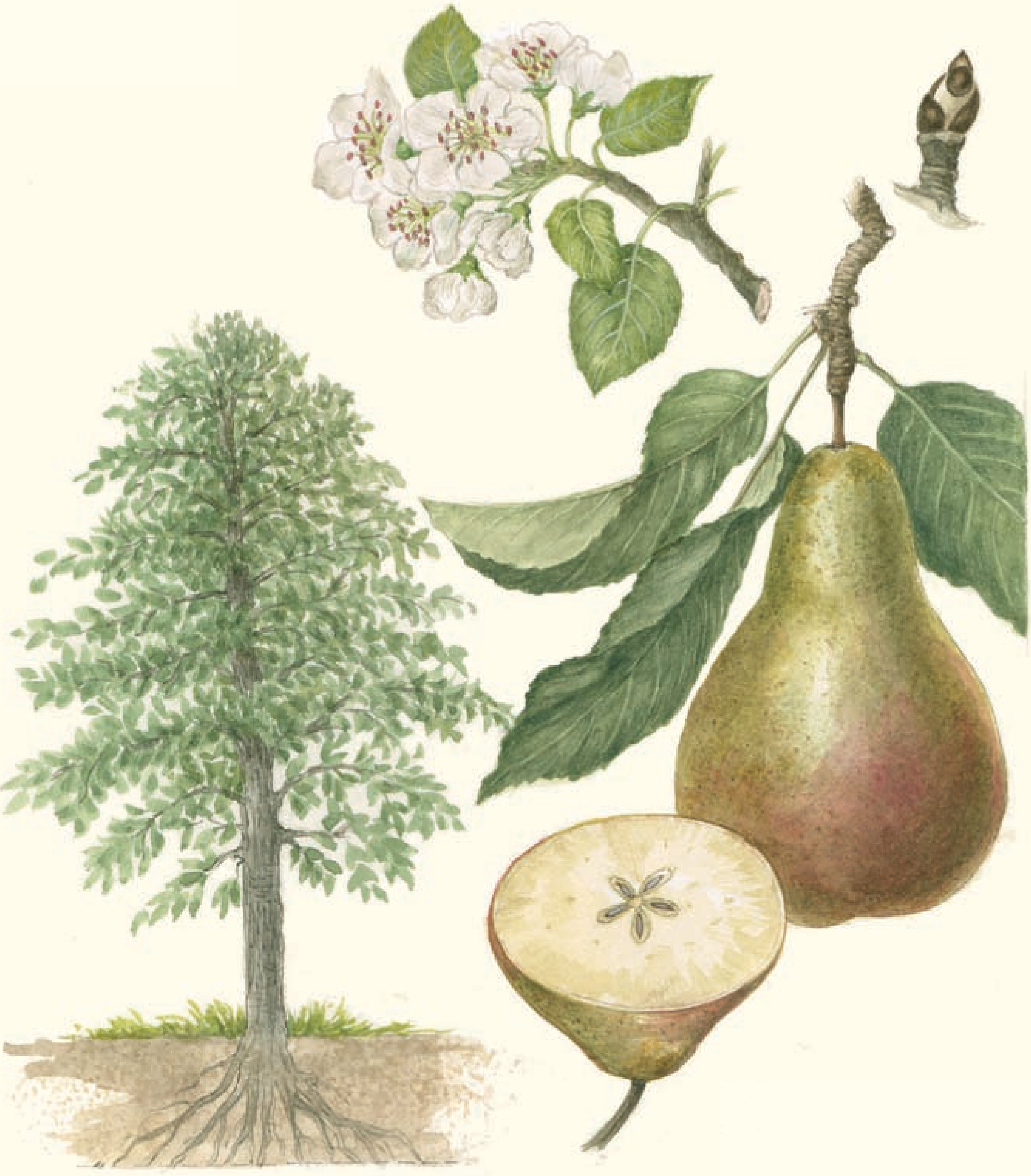
TABLE 3 Suggested RDI strategies for different available water supply scenarios from 900 to 300 mm when potential ETc is 1250 mm.

	Potential	900 mm available case		750 mm available case		600 mm available case		450 mm available case		300 mm available case	
	ET_c in	Irrigation	Applied	Irrigation	Applied	Irrigation	Applied	Irrigation	Applied	Irrigation	Applied
Date	Period	Rate	Amount	Rate	Amount	Rate	Amount	Rate	Amount	Rate	Amount
	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)
Mar. 16-31	12	75	9	70	9	60	7	40	5	25	3
April 1-15	35	75	27	70	25	60	21	40	14	25	9
April 16-30	57	75	43	70	40	60	34	40	23	25	14
May 1-15	82	75	61	50	41	30	25	25	20	25	20
May 16-31	106	75	80	50	53	30	32	25	27	25	27
June 1-15	114	75	86	50	57	30	34	25	29	25	29
June 16-30	120	75	90	50	60	30	36	25	30	25	30
July 1-15	121	50	60	25	30	25	30	25	30	20	24
July 16-31	125	100	125	100	125	90	112	75	93	25	31

TABLE 3 (CONTINUED)

	Potential	900 mm Available Case		750 mm Available Case		600 mm Available Case		450 mm Available Case		300 mm Available Case	
	ET_c in	Irri.	Applied	Irri.	Applied	Irri.	Applied	Irri.	Applied	Irri.	Applied
Date	Period	Rate	Amount	Rate	Amount	Rate	Amount	Rate	Amount	Rate	Amount
	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)
Aug. 1-15	111	100	111	100	111	90	100	60	67	25	28
Aug. 16-31	109	75	82	60	65	50	54	60	65	50	54
Sept. 1-15	90	75	67	60	54	50	45	25	22	25	22
Sept. 16-30	72	75	54	60	43	50	36	25	18	25	18
Oct. 1-15	55	25	14	60	33	50	27	25	14	0	0
Oct. 16-31	32	0	0	0	0	0	0	0	0	0	0
Total	**1242**		**909**		**746**		**595**		**458**		**298**
Irrigations	33*		24		20		16		12		8

* The grower would keep track of cumulative amounts to be applied with RDI scenarios. When they total 37 mm (the amount applied by the microsprinklers in 24 hrs in this example), he irrigates. Thus, there would be one irrigation in the first week of April with full water supply but with 300 mm available case, first irrigation would not be until the first week of May.



Pear

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Pear

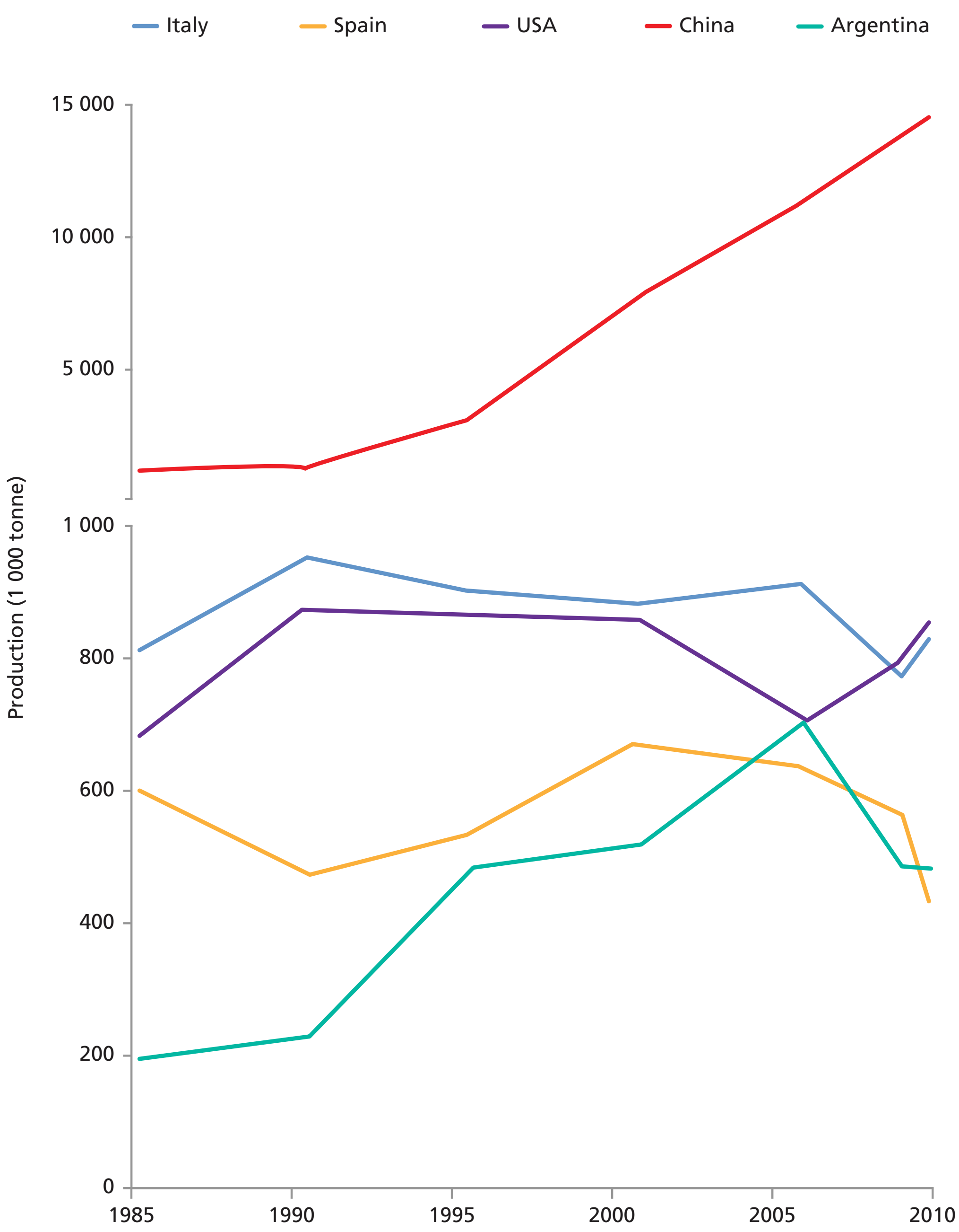
INTRODUCTION AND BACKGROUND

Pears, along with peaches, are the second deciduous fruit tree species in economical importance after apples. The genus *Pyrus* includes about 20 wild species and its primary centre of origin is Europe, and regions in temperate Asia. Two main species are cultivated. European pear (*Pyrus communis* L.) is grown in Europe, United States, South Africa and Oceania, and the Asian pear or Nashi (*Pyrus pyrifolia* Burm.) (syn. *Pyrus serotina*) is traditionally grown in Asia. Other species of the genus have been used as rootstocks such as *Pyrus calleryana* Dcne. Today the most widespread rootstock is clonal quince (*Cydonia oblonga* L.), though its graft compatibility is not good for all cultivars.

The cultivated pear is self-incompatible, and cross-pollination with other cultivars is required for optimum fruit production, with the exception of some varieties such as Bartlett and to some extent Conference. Pears typically bear fruit on spurs in terminal buds. Flower buds are initiated at the end of shoot development during the preceding season, and the formation of these flowers depends on the light received by spurs in the previous season. An open canopy is thus required for full fruitfulness by training branches and pruning to specific shapes.

Other factors that influence flower bud initiation are previous crop load and water stress. Water stress, to a certain extent, can be a positive stimulus for bud initiation, but a high crop load has a negative influence in the next season. For this reason pears often exhibit biennial alternate bearing. Another key issue in pear orchards is growth control to prevent decreased light penetration into the canopy. Water stress, vigour controlling rootstocks, and growth regulators are means available to reduce vigour in pear orchards. Pears are grown in a wide-range of climates, from cool to warm and from humid to arid-areas. In 2009, there were 1.58 million ha of pear orchards globally with an average yield of 14.2 tonne/ha (FAO, 2011). Figure 1 presents the production trends of the major producing countries. The major factors limiting for the expansion of pear production in warm regions are insufficient chilling temperatures during winter and the occurrence of diseases such as fireblight. Pear trees are not a drought resistant species and its commercial production in areas with dry seasons depends entirely on irrigation. As far as irrigation is concerned, pear orchards may benefit from judicial use of deficit irrigation because it can have positive effects by controlling tree vigour during current season and on flowering in the following season.

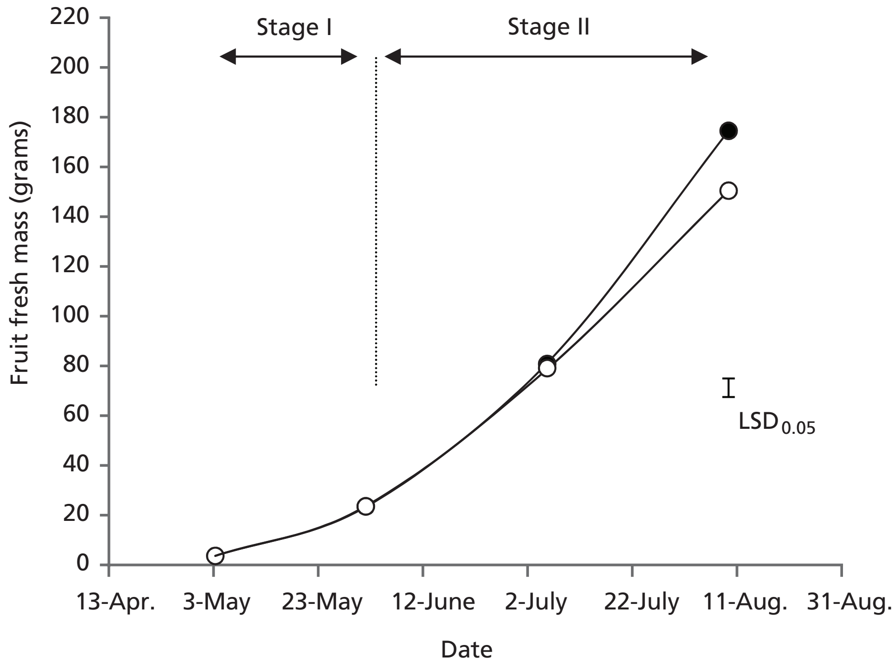
FIGURE 1 Production trends for pears in the principal countries (FAO, 2011).



DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

The reproductive growth of pear trees can be divided into two stages based on the growth rate of the fruit (Figure 2). Stage I of pear fruit development, corresponds to the initial slow growth phase, and Stage II corresponds to the rapid growth phase (Mitchell *et al.*, 1989) which in the cultivar Bartlett the second stage could be differentiated when growth (volume increase) surpasses the rate of 1.5 $cm^3 \cdot day^{-1}$.

FIGURE 2 Reproductive growth of pear trees.



Early vegetative and reproductive growth; growth Stage I

Pear flowers commonly open almost synchronously with leaf appearance. Shoot growth starts after first leaf appearance and occurs concomitantly with the current season reproductive growth. Vigour-conditions will determine the extent and the timing of shoot growth enlargement. In trees grafted on vigour controlling rootstocks such as quince, shoot development occurs in one-to-two flushes during spring (April and May in the Northern Hemisphere). Under more vigorous conditions shoot growth extends into early summer throughout all Stage I. At this time, vegetative growth of the scion is a stronger sink than fruit, and fruit growth is quite slow in terms of dry mass accumulation. Root growth in spring is also relevant and occurs concomitantly with shoot development and ceases near the end of May. Root growth, however, depends on inter-organ competition and availability of carbohydrates. The end of rapid shoot growth is signalled by the appearance of a terminal bud.

Fruit growth starts right after ovary fertilization and this can be measured in the field at about one month after full bloom. Physiological fruit drop, however, lasts longer and can extend until the end of Stage I or onset of Stage II (in midseason cultivars). Stage I corresponds to the fruit main cell-division period, and takes place during the first 7 to 8 weeks after bloom (Bain, 1961). The remainder of fruit development constitutes Stage II when the major increase in cell volume occurs (Bain, 1961). Cell expansion, however, is also active during Stage I, but its effect is masked by the simultaneous occurrence of cell division.

Fruit growth during Stage II

Expansive fruit growth is the main growth event for the tree during Stage II. Stage II corresponds to the period of rapid fruit cell enlargement. Nevertheless, bud development also becomes relevant after cessation of shoot enlargement. Differentiation of buds into flower buds usually occurs at the beginning of Stage II in midseason cultivars (early to mid-June)

(Elkins *et al.*, 2007). The appearance of flower structures takes place during Stage II. However, this process is influenced and modified by climatic conditions and a number of factors that are not yet well understood. Although shoot extension growth is minimal during that time, branch thickening may occur if fruit load is low and water status is optimal.

Postharvest

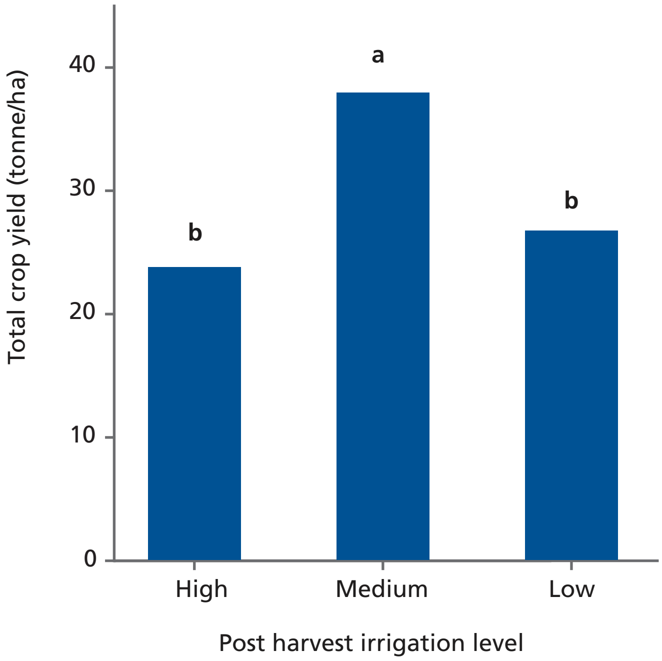
Bud will continue to develop during postharvest and at a slower rate throughout winter. During this period, buds will increase in size by 25 percent, which mainly corresponds with the elongation of the carpels. During the postharvest period, there is a second peak of root growth activity, and this period is also important for reserve accumulation in roots and stems before the start of defoliation. This tends to occur somewhat sooner than in apple and other deciduous species and it is accelerated by low temperatures. Anomalous postharvest flowering can occur in autumn after a period of severe postharvest water stress, if this stress is relieved by irrigation or rainfall a month before leaf die back (Naor *et al.*, 2006).

RESPONSES TO WATER STRESS

Although pear is not considered drought resistant, its organs and tissues can withstand a certain degree of dehydration, which surpasses the capacity of other deciduous fruit trees such as peach, plum or apple. During summer, leaf turgor loss occurs in the cv. 'Barlett' at values of midday stem-water potential (SWP) close to -3.1 MPa (Marsal and Girona, 1997), which is quite low relative to the other deciduous fruit trees. It has also been reported that recovery from water deficits is delayed if SWP reaches values below -3.5 MPa, suggesting this threshold as a limit for the occurrence of vascular embolism (Marsal *et al.*, 2002b). Stomatal conductance and leaf photosynthesis decrease linearly with midday SWP in response to irrigation reductions. For European pear, nearly zero values in both stomatal conductance and leaf photosynthesis have been reported at SWP values of -2.5 MPa (Naor *et al.*, 2000; and Marsal *et al.*, 2002b). Trunk growth ceases at SWP below -2.2 MPa, but shoot extension growth stops sooner, at about -1.7 MPa in the case of moderately low vigour conditions. For more vigorous conditions (i.e. young, defruited trees) extension growth precedes up to -2.0 MPa of SWP. Fruit growth (fresh weight) is somewhat less sensitive to water deficits, stopping at about -2.5 MPa, either during Stage I or Stage II (Marsal *et al.*, 2002b). The SWP values discussed above are indicative of full impairment, but the processes, whether fruit or vegetative growth, are affected by much milder water deficits. For instance, for cv. 'Conference' it was found that to achieve fresh market standards of fruit size for at least 50 percent of harvested fruit, SWP values below -1.1 MPa should be avoided during the Stage II of fruit growing period.

In terms of flowering, moderate water stress during the fruit-growing season (Marsal *et al.*, 2002a) or postharvest (Naor *et al.*, 2006) increases bloom the following season as compared to fully irrigated trees. This behaviour is attributed to the fact that moderate water stress levels hasten development of flower organs (Forshey and Elfving, 1989). However, severe water stress (SWP values below -2.8 MPa) can induce cropping deficiencies next season (Naor *et al.*, 2006). The data in Figure 3 shows that moderate water stress was the best postharvest strategy in terms of subsequent season productivity (Naor *et al.*, 2006). Contrary to European pear, Asian pear seems to have a differential flowering response to water deficit the previous year. In general, water stress reduced return bloom in Asian pears (Caspari *et al.*, 1994).

FIGURE 3 Effects of postharvest irrigation levels on next season crop yield (cumulative of two years). Midday stem-water potential was -2.8 MPa, -2.4 MPa, and -1.5 MPa in the Low, Medium and High irrigation levels, respectively (source*:* Naor *et al.,* 2006).



In general terms it can be stated that for favourable growing conditions reference midday SWP values for unstressed pear trees oscillate between -0.65 and -0.95 MPa depending on evaporative demand; values below -1.1 MPa are indicative of water stress conditions. On the other hand, it is difficult to diagnose early waterlogging effects from SWP values.

Water stress responses during Stage I

Pear trees are highly responsive to seasonal water stress. Water stress during Stage I decreases shoot growth, fruit growth, final fruit size at harvest, and can increase fruit drop (Marsal *et al.*, 2000*;* and Naor *et al.*, 2000). Water stress during Stage I can potentially affect fruit cell division, cell enlargement or both processes (Marsal *et al.*, 2000). Only in few cases and under moderate water stress conditions (LWP above -2.5 MPa), final fruit size was not impaired or favoured by the application of early water stress (Behboudian *et al.*, 1994*;* and Mitchell *et al.*, 1989). These authors argued that such responses were achieved by the occurrence of fruit osmotic adjustment that increased fruit growth after the early water stress. However, other interpretations of these positive effects, such as the different conditions in the timing and duration of the applied water stress, are also possible (Naor *et al.*, 2006). Other factors such as vigour and tree-to tree shading conditions can also be added to this controversy. The early literature from Australia described the application of water deficits to cv. 'Barlett' pear trees in high density orchards (from 2 500 to 5 000 plant/ha) growing on largely vigorous rootstocks (*Pyrus calleriana*). In those experiments, fruit under RDI during Stage I sized larger than Control fruit at harvest, and water stress during Stage I helped reduce vegetative growth that was considered excessive. The growing conditions in these studies were site-specific and do not represent the typical pear-growing conditions around the world where canopy shading is optimized by the introduction of new vigour controlling rootstocks. Experiments carried out in Spain under more common growing conditions including moderate density orchards (1 100-1 600 plant/ha), and using vigour-reducing rootstocks such as clonal quince (BA-29 or M-C) indicated no significant effect on fruit size at harvest in response to RDI Stage I as compared to Control irrigated trees (Marsal *et al.*, 2002a; and Asin *et al.*, 2007). In one case, where trees grew in isolated large containers of 120 litre, deficit irrigation during Stage I actually reduced final fruit size at harvest (Marsal *et al.*, 2000). Furthermore, several attempts in Spain during the nineties to use RDI during Stage I in commercial orchards aimed to increase fruit size above that of fully-irrigated trees, proved unsuccessful.

Water stress responses during Stage II

Water stress during Stage II of fruit development decreased final fruit weight and lower fruit diameter (Behboudian *et al.*, 1994; Marsal *et al.*, 2000; Naor, 2001; Marsal *et al.*, 2002a; and O'Connel and Goodwin, 2007). Water stress at this time mainly reduces fruit cell size (Marsal *et al.*, 2000) and, as a consequence, final fruit size at harvest.

Water stress responses during postharvest

There are few studies available on this topic. One study attempted to use RDI in postharvest for Spadona European pear where the elapsed time for deficit irrigation was three months (from August to the end of October) (Naor *et al.*, 2006). The results of the experiment indicated that water could be saved, provided midday SWP did not surpass the threshold of -2.2 MPa. A positive effect related to moderate postharvest water stress (i.e. SWP >-2.2 MPa) was that, during the following season, return bloom and fruit yield increased significantly compared to fully irrigated and severely stressed trees (Naor *et al.,* 2006).

Similar results regarding increased return bloom have been found by Marsal in Spain for the cultivar Conference. However, in his study fruit set was lower for these trees with higher bloom and this ended up reducing yield but increasing fruit size.

WATER REQUIREMENTS

There are only a few reports available on ET_c information for pear trees. One study used drainage lysimeters of 105 litre capacity and conditions close to hydroponics with the soil surface covered to avoid soil evaporation (Buwalda and Lenz, 1995). The study considered three different cultivars, two training systems and presence or absence of fruit. The effect of both cultivar and training system on tree water consumption was significant; although the differences can be explained by differences in leaf area. However, the presence of fruit increased tree water consumption by 36 percent as compared to de-fruited trees, independently of leaf area (Buwalda and Lenz, 1995). These differences were probably related to increases in stomatal conductance and therefore leaf photosynthesis and transpiration which are frequently observed under higher cropping conditions of pear (Marsal *et al.*, 2008).

The crop coefficients obtained in the lysimeter study (Buwalda and Lenz, 1995) were referred to the Priestley and Taylor ET_o equation, and did not consider a soil evaporation component. Nevertheless, the reported values were quite low, with maximum values of 0.38 for cv. Conference with a leaf area index (LAI) of 2.0. Water use in this study must have been restricted

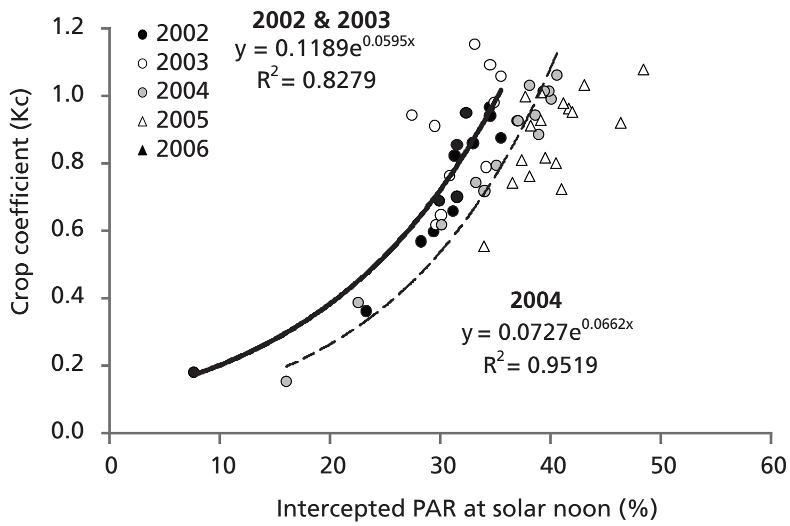
TABLE 1 Crop coefficients relative to grass reference crop (ET_o) for mature pear trees (Conference on quince) grown in a central leader training system and measured using a lysimeter located in an experimental orchard at Lleida, EEL (Spain) by Girona *et al.* (unpublished).

Date	Crop coefficient (K_c)	Ground cover (%)
Apr. 1-15	0.30	23
Apr. 16-30	0.48	30
May 1-15	0.70	36
May 16-31	0.80	39
June 1-15	0.85	40
June 16-30	0.90	40
July 1-15	0.90	40
July 16-31	0.90	40
Aug. 1-15	0.90	40
Aug. 16-31	0.70	40
Sept. 1-15	0.60	40
Sept. 16-30	0.50	40
Oct. 1-15	0.40	40
Oct. 16-31	0.35	36
Nov. 1-15	0.35	25

by the size of the containers because a field study found a midsummer K_c of 0.9 for a pear orchard of the cv. Blanquilla with trees trained to a palmete system (Marsal *et al.*, 2002a). This K_c value is slightly lower than the 0.95-1.0 value that has been traditionally recommended (Allen *et al.*, 1998). A weighing lysimeter study within a pear orchard, measured the ET_c of three pear trees, cv. Conference, trained to a central leader (Girona *et al.*, 2010). Values for crop coefficients (ET_o calculated according to FAO *I&D Paper No. 56* Penman-Monteith equation) in midsummer were around 0.9 with a LAI of 1.4. The seasonal changes in K_c values for Conference trees are presented in Table 1.

It must be emphasized that K_c values in Table 1 are only indicative, and that they may require adjustment to each specific training system and growing conditions. In fact, in the lysimeter study (Girona *et al.*, 2010), K_c showed ample variation over the years (see Figure 4), and there were variations even within the same season after full canopy development. It appears that, at least for the cv. Conference in a semi-arid climate, pear K_c increases under high air vapour pressure deficits (Girona *et al.*, 2010), suggesting that transpiration (Tr) in pears is enhanced relatively more than grass Tr, which is the reference crop for ET_o. This effect makes the use of

FIGURE 4 Relationships between the percentage of photosynthetically active radiation (PAR) intercepted at solar noon and daily crop coefficients (K_c) for individual lysimeter-grown apple and pear trees from bud-break until harvest. The relationships between the percentage of PAR intercepted and daily K_c were fitted to exponential equations. Each K_c value represents the average K_c calculated three days before and after the PAR measurements (*source: Girona et al., 2010*).



a relationship between K_c and the fraction of midday crop intercepted radiation less useful in pear than in peach or apple (see both Sections). Nevertheless, the use of the midday fraction of crop intercepted radiation (or, if midday intercepted radiation data is unavailable, the percent ground cover may be used as a surrogate; see Chapter 4) provides a first approximation for adjusting the K_c values for pear trees.

A water-use study of Asian pear measured the water consumption of trees planted in 12 medium-large drainage lysimeters (9 100 litre) and with a soil surface covered with reflective net (Chalmers *et al.*, 1992). Trees were trained to a Tatura trellis and ET was determined from pan evaporation. This and another study of Asian pears (Caspari *et al.*, 1993; and Caspari *et al.*, 1994), reported their K_c values on a per tree canopy area basis instead of ground area, and thus cannot be compared with the standard K_c values. Nevertheless, the conclusion of the Asian pear studies is that their water requirements are somewhat lower than the values recommended in FAO *I&D Paper No. 56* for this crop.

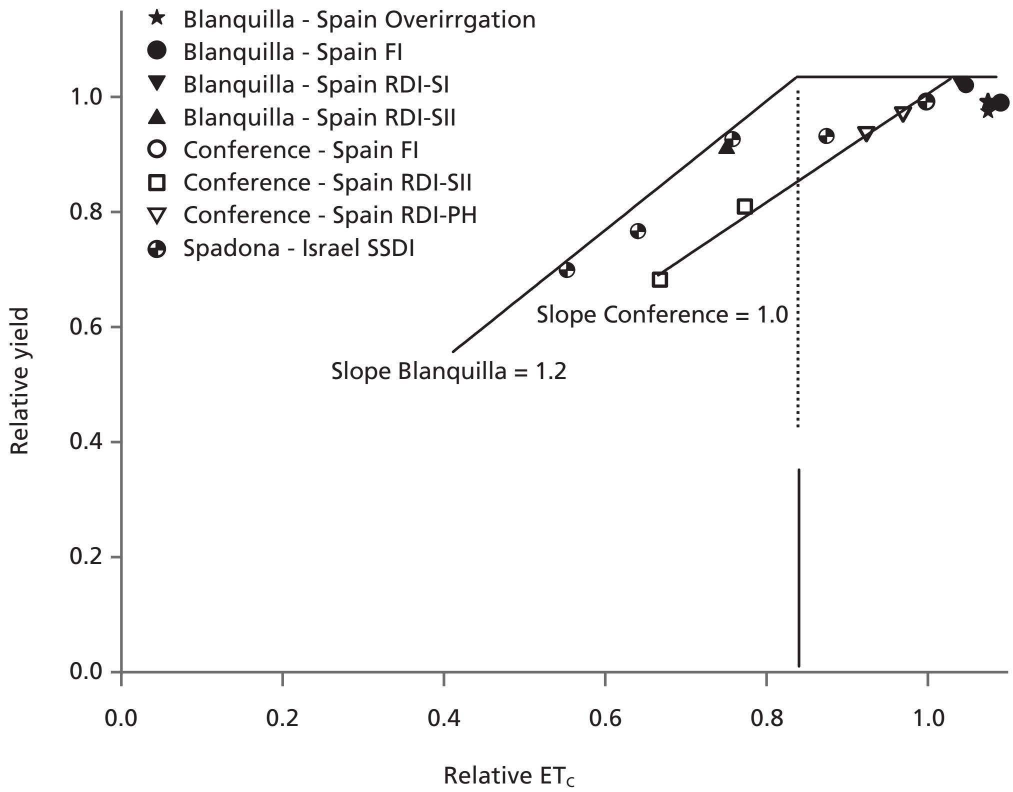
An inherent risk of calculating orchard water requirements is irrigation overestimation. In the case of pears, over-irrigation can have a remarkable negative impact on flowering during subsequent seasons (Marsal *et al.*, 2002a). To avoid this negative impact, accurate determination of crop-water requirements is essential in pear irrigation. One useful strategy could be to apply a mild deficit irrigation programme and monitor the level of stress with soil or plant measurements.

WATER PRODUCTION FUNCTIONS

Water production functions have been derived from four studies: Two of them for the cvs. Blanquilla and Spadona (Spadona and Blanquilla are denominations corresponding to the same cultivar but used in Italy and Spain, respectively); (Naor *et al.*, 2000; and Marsal *et al.*, 2002a), and two other studies on the cv. Conference; the latter dealing with postharvest deficit irrigation (Marsal *et al.*, 2008; and Marsal *et al.*, 2010). In these four studies it has been considered that: i) annual ET_o and effective rainfall were known, ii) ET_c was estimated from soil-water content variation and applied water, and iii) the effects of irrigation on fruit yield were considered for two consecutive years. Figure 5 shows the relation between relative fruit yield and relative ET_c. Relative yield is unaffected by ET_c deficits of 15-20 percent and then declines more or less linearly as ET_c deficits become more severe.

Figure 6 shows the water production function considering relative gross revenue instead of yield as a productive parameter. The relative gross revenue penalizes fruit with cheek diameters of less than 65 mm. The prevailing market conditions are very different between these two cultivars, since Conference pears commonly receive a better price than Blanquilla. Prices may change from country-to-country. For the sake of a fair cultivar comparison and to avoid the specificity of country market effects on gross revenues, the pricing criterion of Conference in Spain was applied to all reported experiments.

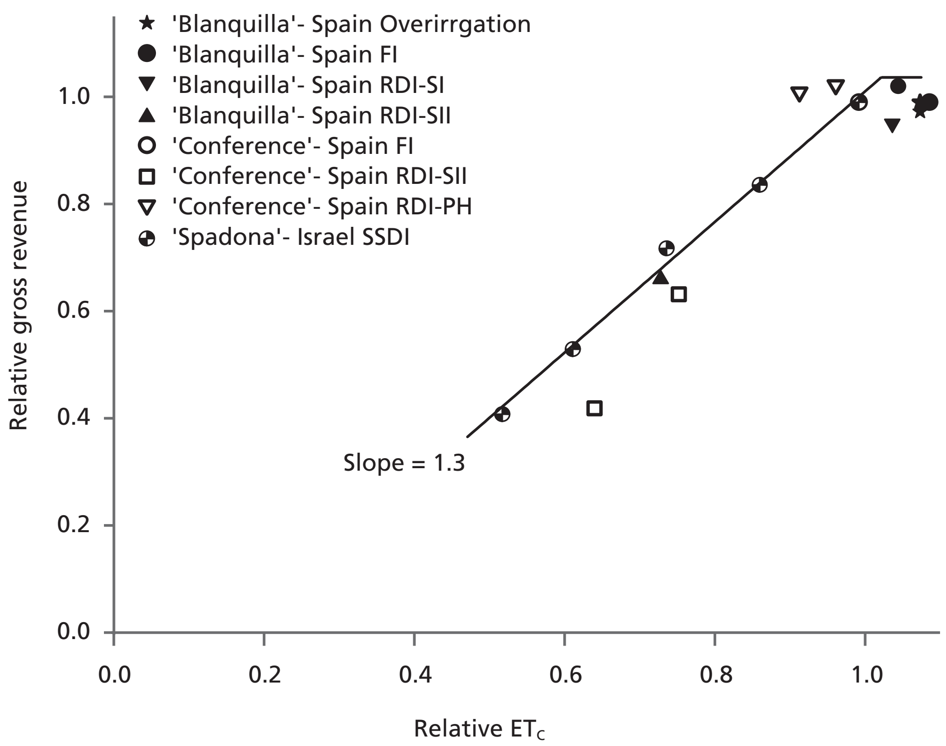
FIGURE 5 Production function developed for RDI strategies that imposed stress during Stages I and II. Data points were obtained from studies of at least two-year duration. Three studies from Spain and one from Israel were used for the relationship (Source: Marsal *et al*., 2002a in Blanquilla; Marsal *et al*., 2008 in Conference; Marsal *et al*., unpublished in Conference; and Naor *et al*., 2000 in Spadona). Linear boundary lines consider separate cultivar fitting through linear regression from the observations defining an upper boundary. FI, RDI-SI, RDI-SII, RDI-PH and SSDI stand for full irrigation, RDI during Stage I of fruit growth, RDI during SII of fruit growth, RDI during postharvest and seasonal sustained deficit irrigation, respectively.



Data in Figure 5 suggest that there are cultivar differences in the response to ET_c deficits, cv. Conference being more sensitive than Blanquilla (or Spadona). A 30 percent reduction in ET_c caused only a 12 percent yield reduction in Blanquilla-Spadona but a 22 percent decrease in Conference. However, cultivar yield sensitivity to ET_c deficits was similar once they showed a response to decreasing relative ET_c; their sensitivity remained similar with a slope for the yield response to ET_c of 1.2 and 1.0 for Blanquilla and Conference, respectively (Figure 5).

An explanation of the differences between cultivars in the yield-response threshold to reduction in ET_c may be related to a complex interaction between three factors: i) the positive effect of moderate water stress on increasing return bloom in the next season, ii) the limited use of fruit thinning as a commercial practice for pear, and iii) the possible fruit-set response to previous season water stress. In other words, changes in return bloom as a consequence of incipient ET_c reductions in the previous season, may produce higher cropping next season, provided fruit set is unaffected. Under these circumstances, increases in crop load leads to the production of smaller fruit, but the smaller fruit size at harvest is often more than compensated by the positive impact of higher fruit number on yield. It is interesting to

FIGURE 6 Relative revenue function developed for RDI strategies that imposed stress during Stages I and II. Data points obtained from studies of at least two year duration. Three studies from Spain and one from Israel were used for the relationship (Source: Marsal *et al*., 2002a in Blanquilla; Marsal *et al*., 2008 in Conference; Marsal *et al*., unpublished in Conference; and Naor *et al*., 2000 in Spadona). Linear boundary lines consider no differences in cultivar response and fitting is performed through linear regression from the observations defining an upper boundary. Note the greater sensitivity to ET deficits in terms of revenue than in yield terms. FI, RDI-SI, RDI-SII, RDI-PH and SSDI stands for full irrigation, RDI during Stage I of fruit growth, RDI during SII of fruit growth, RDI during postharvest and seasonal sustained deficit irrigation, respectively.



notice that this was the case for Blanquilla for RDI-SII in Spain and also for the mild irrigation reductions in the Spadona experiment in Israel (Figure 3). However, this was not found to be so Conference, because RDI-SII, besides increasing blooming return, it also reduced fruit set the next season so that competition between fruit was lowered. Specificity of cultivar yield response to ET deficits could be explained by a different sensitivity of fruit set to current bloom density and past history of water stress. On the other hand, the advantageous yield response observed in Blanquilla was lost when analysed in terms of relative revenue (Figure 6). This was because of the price penalty related to the production of smaller fruit under deficit with high cropping conditions (Figure 6). Therefore Conference and Blanquilla revenue responses were approximated by only one boundary line, which corresponded to the conditions of deficit irrigation applied during the fruit-growing season (Figure 6).

In the case of postharvest deficit irrigation for Conference, it was found that relative revenues rose above the boundary line (Figure 6). Curiously, postharvest water deficit produced yield reductions that were accompanied by reductions in fruit set and associated with increased fruit size. Accordingly, postharvest RDI fruit received a higher price and relative gross revenue was not reduced by the slight ET_c reductions attained in the above-mentioned experiment (Figures 5 and 6). However, under more significant stress during Stage II, which caused a 30 percent reduction in ET_c, the decrease in gross revenue of the cv. Conference reached 60 percent (Figure 6), a response that is substantially more negative than what could be predicted from the yield-ET_c relationship (Figure 5).

SUGGESTED RDI REGIMES

Consistency of results across the different experiments on RDI suggests that this technique may be safely used for pear production. However, the myriad of possible combinations of pear growing conditions (cv. x rootstock x planting density x fruit load x soil type x climate) offer a wide spectrum of possibilities that have not been fully investigated in relation to RDI. Nevertheless, there is no doubt that, in climates having low rainfall during the hot season, reducing irrigation during Stage II should be avoided to guarantee maximum fruit size at harvest (Figure 6). Early water stress should also be avoided in most cases, except for high-density orchards growing under vigorous conditions. The period in which RDI could be applied to save water is postharvest, provided excessive water stress is not achieved. This risk of applying too much water stress during postharvest may depend on each specific situation. Risks increase where growing conditions are suboptimal. Bad weather can affect pollination and fruit set, and fruit drop can occur especially during late spring. Postharvest water stress has been hypothesized to reduce winter reserves in the tree (no data available on pear) and subsequently impair fruit set and yield following season.

The data available on responses to RDI make it difficult to propose a strategy that is applicable to all possible combinations of management practices. Nevertheless, the postharvest period is the safest to apply RDI, but water savings can be short if a late maturing cultivar is used. Therefore, if water shortages have to be more severe, RDI could be applied in combination with other periods. Table 2 presents various RDI strategies for different water allocations that are simulated for specific experimental and environmental conditions (Marsal *et al.*, 2008; and Marsal *et al.*, 2010). Water deficit in Stage I (RDI-SI), only allows a 6 percent reduction of the annual applied water. By using RDI in Stage II (RDI-SII), 33 percent of applied water can be saved, but this causes a reduction in growers' gross revenues (Table 2). A more sensible approach would be to use a combination of deficit irrigation during Stage I and postharvest, in combination with a slight reduction during the first part of Stage II fruit growth (Table 2). The latter strategy would reduce the annual water use by 33 percent (from 600 mm to 400 mm) and probably would have less negative impact on fruit growth than an RDI-SII strategy.

TABLE 2 Suggested RDI strategies for different available water supply scenarios from 600 to 400 mm when potential ET_c is 600 mm. Weather data corresponds to Ebro valley Northeast Spain and K_c corresponds to those presented in Table 1.

Date	Potential ET_c (mm)	Water req. (mm)	RDI-SI (560 mm)		RDI-SII (400 mm)		RDI-Postharvest (460 mm)		RDI-Combined (400 mm)	
			Irri. rate (%)	(mm)	Irri. rate (%)	(mm)	Irri. rate (%)	(mm)	Irri. rate (%)	(mm)
March 15-30	9	10	100	10	100	10	100	10	100	10
Apr. 1-15	13	14	100	14	100	14	100	14	100	14
Apr. 16-30	15	10	100	10	100	10	100	10	100	10
May 1-15	28	17	40	7	100	17	100	17	40	7
May 16-31	37	28	40	11	100	28	100	28	40	11
June 1-15	56	62	100	62	50	31	100	62	80	49
June 16-30	71	79	100	79	50	39	100	79	80	63
July 1-15	72	74	100	74	50	37	100	74	80	59
July 16-31	77	84	100	84	50	42	100	84	100	84
Aug. 1-15	67	73	100	73	50	37	100	73	100	73
Aug 16-31	65	71	100	71	100	71	10	7	10	7
Sept. 1-15	36	39	100	39	100	39	10	4	10	4
Sept. 16-30	27	30	100	30	100	30	10	3	10	3
Oct. 1-15	16	1	100	1	100	1	10	0	10	0
Oct. 16-31	9	0	100	0	100	0	10	0	10	0
Nov. 1-15	5	0	100	0	100	0	10	0	10	0
Total	**602**	**591**	-	**564**	-	**405**	-	**464**	-	**395**

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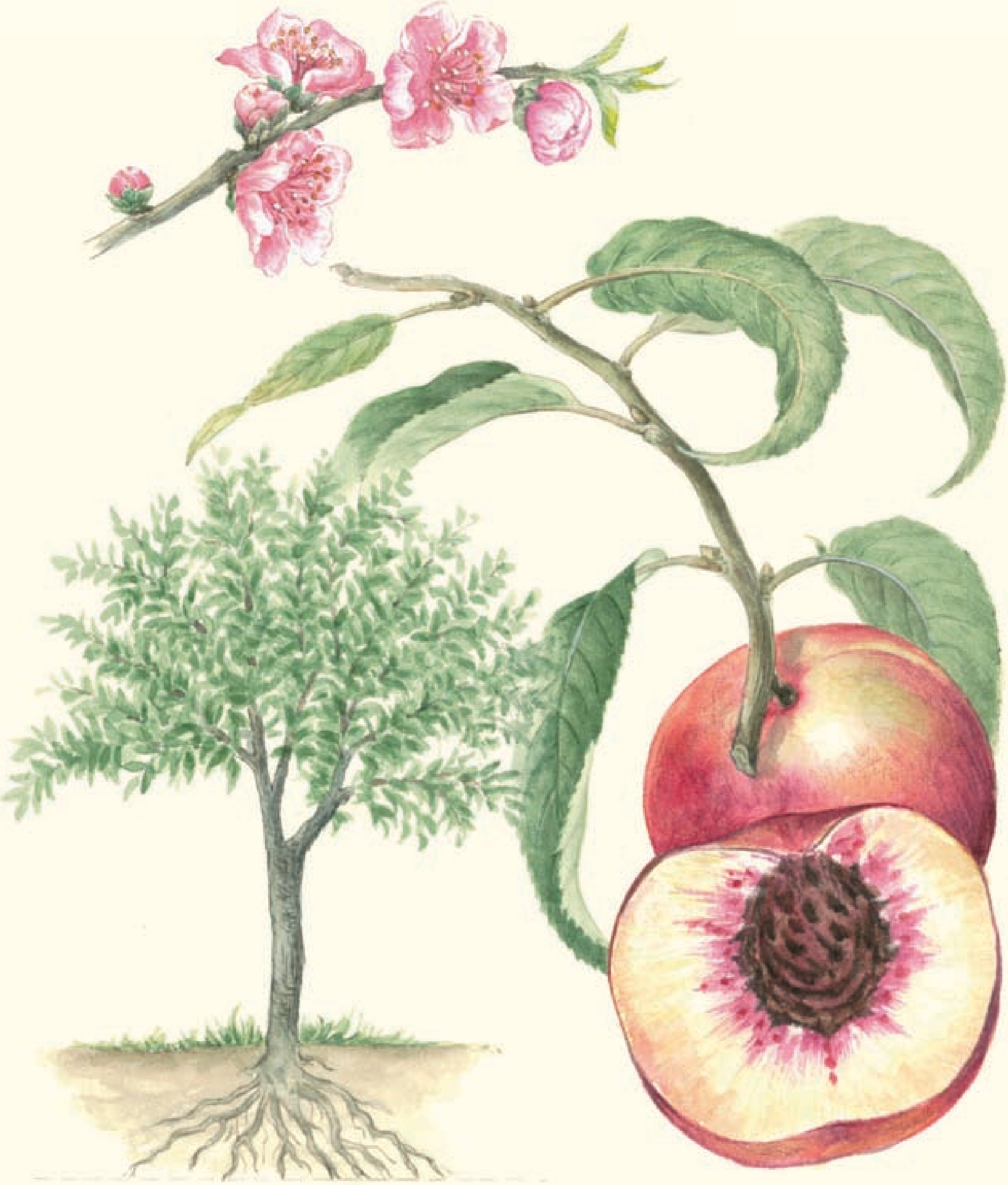

Peach

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Peach

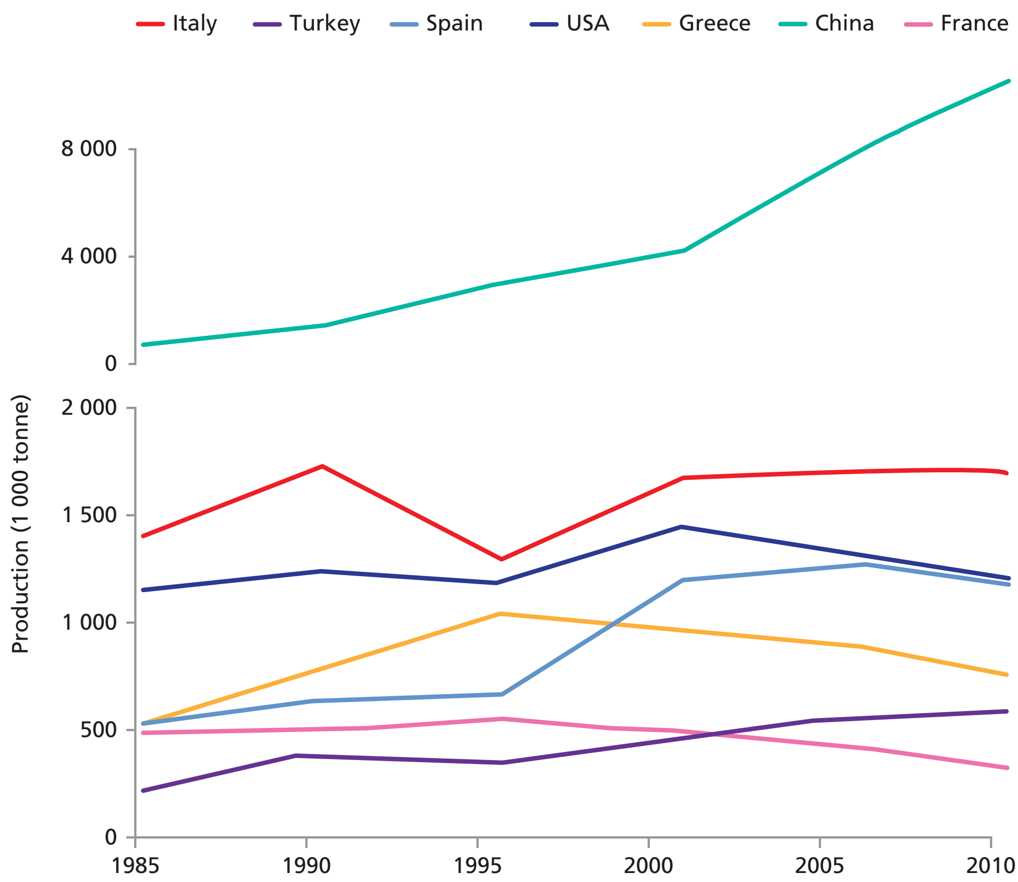
INTRODUCTION AND BACKGROUND

Peach *(Prunus Persica* L.*)*, was originally from China, but in ancient Greece and Rome it was thought to have originated in Persia, is a stone fruit tree that exhibits ample diversity in terms of fruit types: freestone or cling; round or flat shape; hairy or smooth skins; flesh that is either firm or soft and white or yellow. There is also a wide-range of maturity dates for the peach cultivars; from very early where the fruit matures at the end of spring, to very late that reach maturity at the end of summer, as much as four months after the earliest varieties arrive at the market. The tree is vigourous and can reach more than 5 m in height, but peach production is limited worldwide by its relatively narrow range of climatic adaptation. On the one hand, it flowers early and is quite sensitive to frost–particularly at flowering- but on the other, it has chilling requirements that are not met in some of the frost-free areas of the temperate zones and the subtropics.

The evolution of peach production in selected countries in the last ten years is shown in Figure 1. In 2009 there were over 1.5 million ha of peach and nectarine globally with an average yield of 13.0 tonne/ha (FAO, 2011). The main producing country is China, which represents 50 percent of the world peach production. Production in China rose spectacularly over the last decades from 380 000 tonne in 1970 and an average yield of 3.6 tonne/ha to over 10 million tonne in 2009 with an average yield of 14.4 tonne/ha, followed by Italy (FAO, 2011). Other major commercial production areas are located in southern Europe (Spain, Greece, and France), United States (California, Georgia), Chile, and Australia. Highest yields are obtained in United States with almost 20 tonne/ha.

The fruit is usually consumed fresh and, because consumers in many world areas prefer large-size fruit, peach is grown mostly under irrigation even in many subhumid areas. There, the most important role of irrigation is to stabilize production in years of below-normal rainfall, and to guarantee adequate soil moisture during the critical fruit enlarging period, just prior to harvest. In more arid areas where rainfall is only a fraction of ET_c, irrigation is essential for commercial production, as the period of fruit growth can span all summer in the late maturing varieties. Most peach production systems are quite intensive, with orchards planted at high densities (from 400 up to 1 000 tree/ha); the highest densities are normally for peach production used in industry (canning and food processing). A wide-variety of training systems are used, designed to maximize the distribution of solar radiation to all tree parts in order to achieve good fruit colour, and to promote fruiting

FIGURE 1 Production trends for peaches in the principal countries (FAO, 2011).



Fruit quality

There are many factors determining peach fruit quality and some of them have a significant influence in the crop value, particularly, fruit size. Fresh market peaches are valued for their size, and large sizes fetch premium prices in many markets. Fruit size depends on tree fruit numbers and is affected by environmental factors such as water deficits. Colour and lack of visual defects are also important quality aspects; the colour is determined by light exposure during fruit growth that, in turn depends, on tree configuration, degree of vegetative growth and fruit position on the tree. Other quality factors include firmness, concentrations of total soluble solids (*TSS*), soluble sugars, titratable acidity (*TA*), sugar to acid ratio, aroma volatiles, enhanced maturity and better storability (shelf-life). All of these parameters respond to variations in the tree water supply that affect tree water status.

branches throughout the tree canopy. Sometimes, trellises are used with the trees shaped in a horizontal plane, or in a V shape. For the very intensive plantations, low tree vigour is favoured to reduce mutual shading and harvest costs. Some dwarf tree cultivars have been bred in the past, but have had little commercial success.

DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Vegetative and reproductive growth

As with other stone fruit, peach flowering is immediately followed by vegetative growth in early spring. Peach chilling requirements, usually computed during dormancy as hours above 7 °C, vary widely among varieties, but in some may be substantial. During the canopy development period, fruit set and initial fruit growth take place simultaneously. Figure 2a depicts the patterns of fruit growth for three cultivars differing in maturity and the relative rate of vegetative growth for the late-maturing cultivar. Although early maturing cultivars bloom earlier than the late, initial fruit growth is very similar for the three types. In the early cultivar, such initial growth is directly followed by a fast fruit enlargement phase (Figure 2a) that ends with fruit ripening. In the other cultivars, there is a slowdown in growth rate of the fruit, coinciding with the acceleration of vegetative growth (Figure 2a). Vegetative growth, measured as seasonal shoot length or the increase in trunk diameter, has similar trends for the different cultivars. Extension of primary shoots occurs first followed by the growth of secondary shoots. In the early cultivars there are two peaks of rapid extension growth, the second one taking place after fruit harvest. In the medium and late-maturing cultivars, there is normally only one peak of fast shoot growth, but there may be another one after harvest in some cultivars and environments. At some point in the season, shoot growth slows and the rapid fruit expansion rate period begins (Figure 2b). This last fruit enlargement phase extends until the fruit matures prior to harvest, and the longer this period, the greater is the accumulation of dry matter in the fruit and the larger is the final potential fruit size (Figures 2a and 2b).

Because bud emergence usually occurs with a fully charged soil profile, water deficits affecting the early growth stages of fruit and canopies are uncommon. When they occur, tree leaf area and final fruit size will be reduced, because in the latter case, initial growth is mostly caused at cell division stage that sets the final number of cells that a fruit will have.

FIGURE 2a Evolution of fruit fresh weight for early (A), medium (B) and late (C) maturing peach cultivars. Stages I, II, and III of fruit growth and postharvest (PH) maturing peach cultivars. Stages I, II, and III of fruit growth and postharvest (PH) for a medium cultivar grown in the Northern Hemisphere are shown.

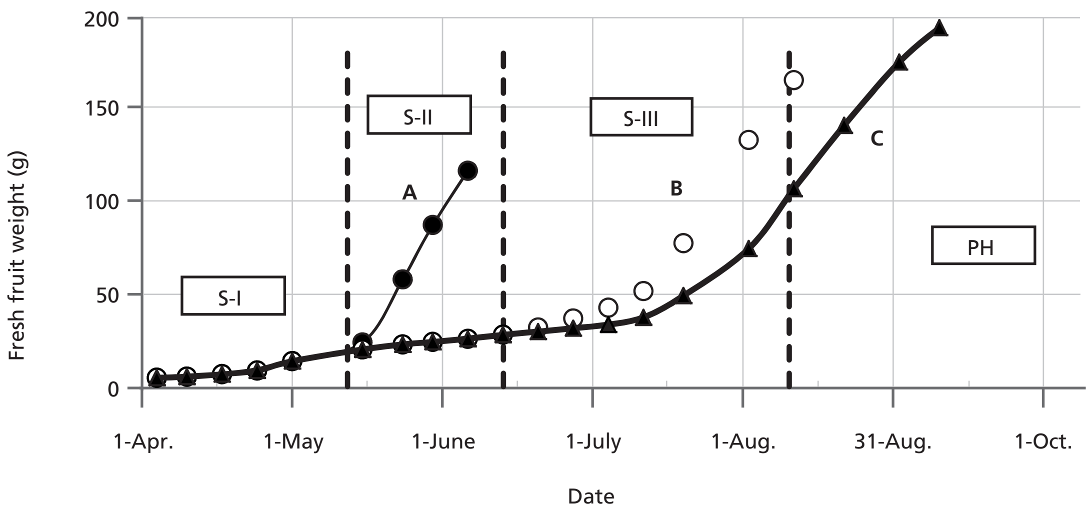
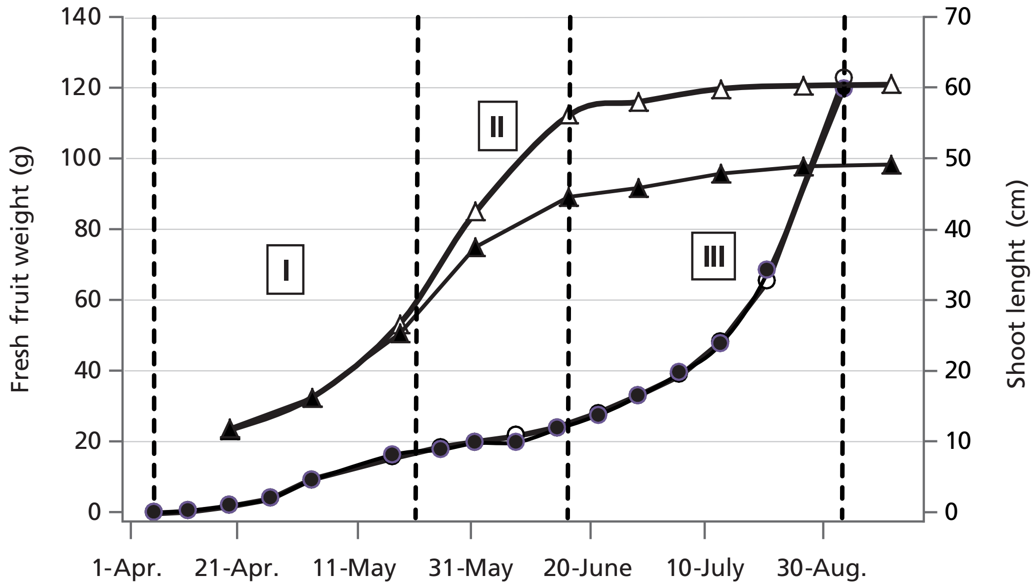


FIGURE 2b Evolution of vegetative (shoot) growth (triangles) and of fruit growth (circles) in peach trees under RDI (closed symbols) and under a fully-irrigated control (open symbols) at Lleida, Spain.



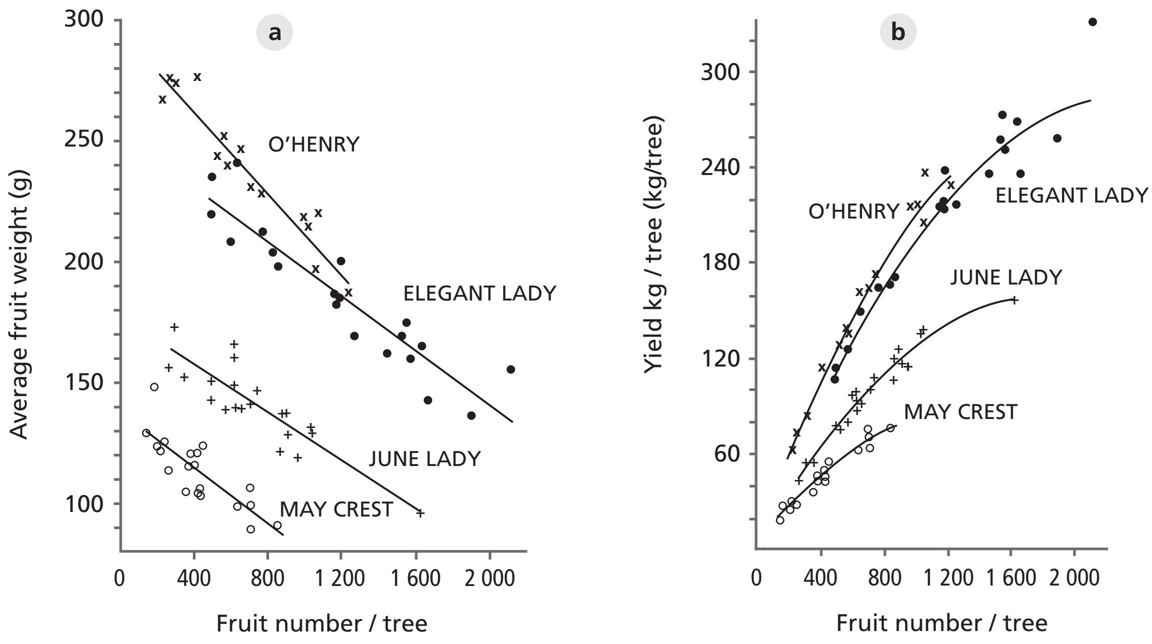
While flower buds are quite resistant to freezing temperatures above -7 to -10 °C during dormancy, flowers and recently formed fruit are very sensitive to mild frosts, with minimum temperatures below -2 to -3 °C. Thus, peaches are very sensitive to spring frosts that can completely wipe out fruit production.

Stages of fruit growth

As discussed above, fruit growth, measured by either increase in fruit volume or in dry weight, follows a double sigmoid curve in peach. From Figure 2 it can be seen that there are three apparent stages of fruit growth, although in early varieties, it is difficult to detect more than two from periodic measurements of fruit volume. The first stage, defined as Stage I, starts soon after pollination and is a period of active cell division that ends around pit hardening, when the fruit has reached about 20 to 25 percent of its final size. Fruit growth slows in the second stage and this coincides with a period of active shoot extension and leaf development (Figure 2b). The duration of this second phase (Stage II) varies; in early varieties, it is hardly detectable, while in very late varieties it can lasts for more than 40 days. Following Stage II, fruit enlargement resumes at a very high rate in what is called Stage III, proceeding more or less in an exponential fashion until harvest (Figure 2b). Dry matter accumulation in the fruit lags behind fruit enlargement, but also follows a double sigmoid pattern, less marked than for the accumulation of fresh weight, and more evident in late varieties but hardly detectable in medium and early varieties. The most relevant difference among cultivars varying in season length, from early to late maturity, is the duration of Stage II (Figure 2a).

Final fruit size is determined primarily by fruit load (number of fruit per tree), but tree size, canopy configuration and pruning, water and nutrient status are also important factors. The relationship between final fruit size and fruit load is cultivar dependent as shown on Figure 3 (Johnson and Handley, 1989) where these relationships are shown for several early

FIGURE 3 (a): Relationship between average fruit weight and number of fruit per tree of four peach cultivars (b): Relationship between yield per tree and number of fruit per tree of four peach cultivars (Johnson and Handley, 1989).



and midseason cultivars. Both final fruit size (Figure 3a) and total yield per tree (Figure 3b) are fruit load dependent. Fruit size increases as fruit load decreases (Figure 3a), while final yield increases with increases in fruit load (Figure 3b) For each cultivar, and depending on market prices, the total number of fruit per tree that are left after thinning should be chosen to optimize profits by obtaining a maximum yield with a minimum fruit load. Final fruit size depends also on the timing of hand thinning. Early hand thinning reduces fruit competition and allows larger fruit.

Bud development

The terminal peach bud at the end of a shoot is always vegetative and produces a leafy shoot. Auxiliary buds develop during the summer at the base of leaves on the current season's shoots and can be either leaf or flower buds. A flower bud produces a single flower that can set one fruit. Each node on a vegetative shoot may have from zero to three buds. The buds that generate vegetative growth are small and pointed while flower buds are larger, rounder, and more hairy. Many of the nodes on the lower two-thirds of a shoot have two or three buds arranged side by side. Most often a leaf bud is flanked by flower buds. The number and distribution of flower buds on a shoot varies with tree vigour, cultivar, and the radiation environment that the shoot experiences. Short shoots generally have the most fruit buds per unit length. Moderately vigorous shoots have a high proportion of nodes with two flower buds. The leaf buds at most nodes develop into lateral shoots that may be fruitful in subsequent years. In the very vigorous current season's shoots, a number of auxiliary buds produce secondary shoots that are not desirable because fruit buds do not develop at many of their nodes. Ideal shoots (between 30 and 50 cm long) have enough growth to produce sufficient fruit buds for the following season but do not have secondary shoots.

The postharvest period is important for peach trees, as it is during this period when next season's flower buds are initiated (usually around August) and when these buds are clearly differentiate from vegetative buds they start to develop floral organs (Handley and Johnson, 2000). Another important feature of the period between harvest and leaf fall is the accumulation of carbohydrate reserves, needed for continuous bud development processes until bloom, and also because fruit set is highly dependent upon carbohydrate availability (Arbeloa and Herrero, 1991). Heat and water stress during post harvest enhances the formation of abnormal fruit (Naor *et al.,* 2005).

RESPONSES TO WATER DEFICITS

Peach water relations have been studied in more detail than most other deciduous fruit tree species. As for most plants, vegetative growth is extremely sensitive to water deficits, and several studies have shown that leaf and young shoot expansive growth are slowed by mild water deficits that are difficult to detect.

Peach trees are mostly grown to produce fresh fruit, where both size and some quality characteristics are important. However, while there is a premium paid for large fruit size in most markets (or a penalty for the small sizes), quality features, other than size, do not generally influence growers' revenue, although many consumers are well aware of the important differences in quality among and within peach and nectarine varieties.

Final fruit size depends directly on the number of cells and the average cell size of the mesocarp. The number of cells is primarily determined during Stage I and several experiments (some in container-grown trees) have demonstrated that this is a very sensitive period for water deficits in terms of final yield and revenue. One field study (Girona *et al.,* 2004) with mild to moderate stress at Stage I demonstrated that fruit dry matter was affected at high fruit loads, but that fresh weight could recover if the water supply during Stages II and III was adequate. Nevertheless, risks of inducing damaging stress levels at Stage I are low because the initial soil profile is usually full, evaporative demand is low and the canopy development process has not been completed (and thus the crop coefficient, K_c, is below the maximum that will be achieved when canopy growth is near completion). Thus, peach transpiration (Tr) is relatively low at this time, which also coincides with seasonal spring rains in many peach growing regions. It is therefore not difficult to avoid water deficits in Stage I, even inadvertently. Nevertheless, in shallow soils and/or very dry environments, or in drought years when the soil profile is dry, it is possible to induce significant levels of water stress that will impact negatively on fruit size and yield (Girona *et al.,* 2004).

As the fruit continue to grow and the pit starts to harden, the rate of vegetative growth accelerates and fruit growth slows at the onset of Stage II. The duration of this phase varies from only a few days in early varieties (and thus is almost impossible to detect) to about 60 days in the very late varieties. Water deficits during Stage II affect primarily lateral shoot expansion and trunk growth while having minimal or no impact on fruit growth. Figure 2b shows the impact of water deficits in shoot extension growth and the negligible influence that it has on fruit growth and final fruit size (Girona *et al.*, 2003). This differential sensitivity between vegetative and fruit growth formed the basis for the successful application of water stress in Stage II in peach first described by Mitchell and Chalmers (*1982*). These authors and several others since that time have found that Stage II is not sensitive to water deficits in terms of negatively impacting yield. It has been shown (Girona *et al.,* 2003) that significant water deficits applied during Stage II may induce some dehydration of the fruit, but that subsequent recovery of fruit growth is usually complete after the water stress is relieved at the onset of Stage III, and that Stage II water deficits have no impact on final yield.

Even though there has been an initial report showing (Chalmers *et al.,* 1981) increased fruit size, relative to fully irrigated controls, when applying RDI in Stage II, no other published papers reported such results, with one exception (Girona *et al.,* 2003) for a single season in a three-year study, where low temperatures at blooming time damaged many fruit and the final fruit load was very low. A comprehensive analysis of the effect of fruit load on the response to RDI at Stage II (Girona *et al.,* 2004), detected larger fruit in the RDI treatment compared with an unstressed control only with low fruit loads, and as the fruit load increased, no effects were detected and in some cases, even a reduction in fruit size was observed. Presumably the RDI in Stage II enhances fruit growth relative to unstressed controls by directing more carbohydrates to fruit growth, but this phenomenon apparently occurs only with low fruit loads (Girona *et al.,* 2004). There have been reports of less fruit drop before harvest under RDI (Girona *et al.,* 2003), and this could explain the few observations where water deficits during Stage II had positive effects on yield, relative to fully-irrigated treatments.

Vigorous fruit expansion takes place during Stage III when the rate of fruit expansion is highest and most sensitive to water deficits. Fruit water content is more sensitive to water deficits than fruit dry weight during this period. A reduction of 25 percent in fruit water content occurred with Stage III water deficits in a medium peach cultivar (Girona *et al.,* 2004). Water deficits that affect fruit dry matter accumulation must be quite severe because, not only must they decrease photosynthesis but they must also counterbalance the tendency of many fruit trees, including peach, where assimilate allocation to fruit has higher priority relative to its distribution to other tree parts (DeJong *et al.*, 1987). Leaf photosynthesis and tree transpiration in peach are not affected by water deficits until more than 50 percent of the available water in the root zone is depleted (Girona *et al.*, 2002). When water deficits occur under these conditions, the peak of daily Tr moves from a plateau between noon and 14:00 hours towards the morning hours, and by the time Tr was reduced by 70 percent, the maximum Tr rate occurred at 9:00 am hours (Girona *et al.*, 2002).

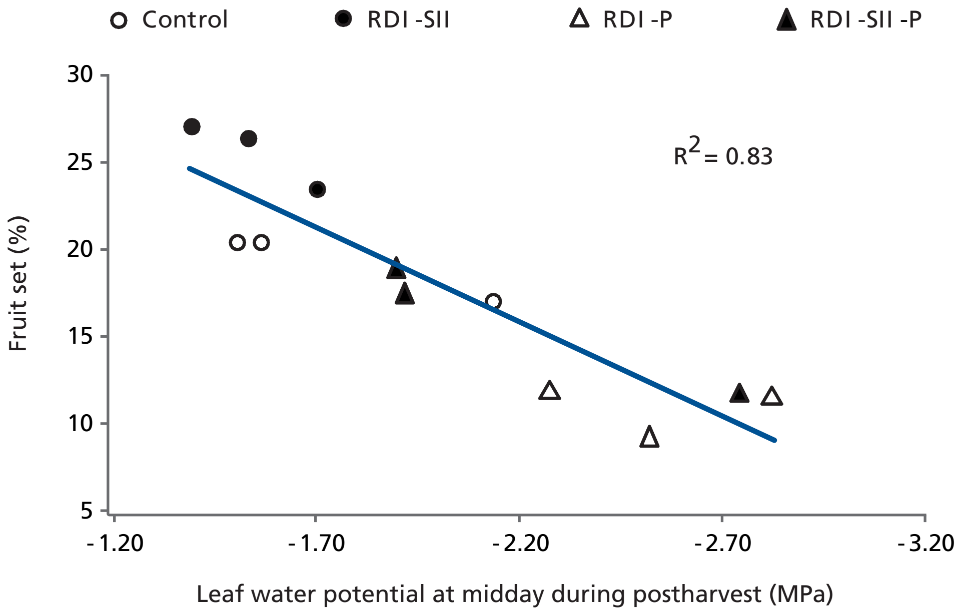
Indicators of peach tree water status are used to quantify the water stress levels. A comparative study among different indicators (Goldhamer *et al.*, 1999) found that indices derived from micrometric measurements of trunk diameter fluctuations were the most sensitive for water stress detection, followed by stem-water potential. Other indicators such as stomatal conductance, leaf photosynthesis, and leaf temperature were less sensitive (Goldhamer *et al.*, 1999).

Water deficits may have a negative impact on fruit appearance in the next season. An increased frequency of fruit doubles and deep sutures have been observed in water-stressed peach trees (Johnson and Phene, 2008). These problems have been overcome by relieving the water stress shortly before and during carpel differentiation (Johnson *et al.,* 1992). With early-season cultivars, this stress-sensitive period is in August and September and suggests avoidance of water deficits during these months (Johnson and Phene, 2008). For a midseason cultivar, the increase in occurrence of double and deep suture fruit is highly correlated with the midday stem-water potential in August of the previous year, i.e. during the initial stages of flower bud development (Naor *et al.,* 2005). The occurrence of double fruit was observed to increase sharply as the midday stem-water potentials fell below -2.0 MPa, suggesting that a midday stem-water potential of -2.0 MPa could serve as threshold for postharvest irrigation scheduling (Naor *et al.,* 2005).

Fruit set can also be influenced by postharvest stress. Both early season (Johnson and Phene, 2008) and midseason (Goodwin and Bruce, 2011) cultivars found that fruit set was moderately sensitive to the degree of water stress during the previous season's postharvest period. In late season-cultivars, fruit set was highly affected by the level of water stress during postharvest, as shown by the strong correlation between the average leaf water potential during the postharvest period and the fruit set (Girona *et al.,* 2004) (Figure 4). The negative impact of water deficits on fruit set in the next year may not be important as thinning is a common practice in peach, but severe impacts on fruit set cannot be corrected by thinning (Goodwin and Bruce, 2011).

Moderate water deficits applied during Stage II improved fruit quality (firmness, colour, improved TSS) without affecting yield (Gelly *et al.*, 2003 *and* Gelly *et al.*, 2004). Moderate water stress in Stage III also improves fruit quality, but a negative impact on fruit size and yield is very likely. The trade-offs between quality and size must be resolved bearing in mind the market where the produce will be sold.

FIGURE 4 Relationship between fruit set 2 months after full bloom in 1996 and seasonal average midday leaf water potential experienced under several irrigation treatments during the previous year at postharvest (Girona *et al.*, 2004).

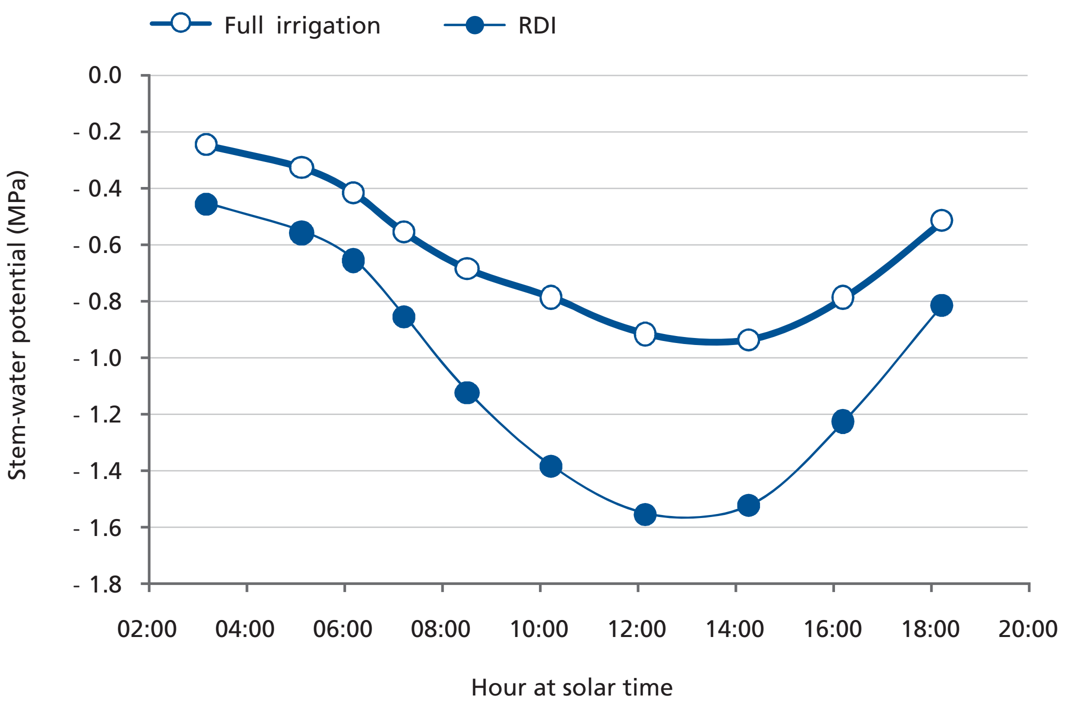


BOX Detecting water stress in peach

Although the established method of detecting tree water stress in peach is the leaf or stem-water potential (Goldhamer *et al.*, 1999), visual indicators may be used to estimate stem-water potential when it is not possible to take actual SWP measurements.

In a normal summer day, typical stem-water potential patterns are shown in the figure below.

FIGURE Diurnal patterns of stem-water potential for fully irrigated (control) and RDI for peach, Lleida, Spain. In both cases, midday stem-water potential values are the lowest and values at predawn (before sunrise) are the least negative, for both well-irrigated and RDI peach trees.



Visually, it is possible to differentiate a leaf that has a water potential of -0.9 MPa from one that has a value of -1.9 MPa. The first is fully expanded and usually oriented towards the sun (Photo D), while the second is partially rolled and droops (Photo A).

For the optimal RDI regime that applies stress on Stage II, it is good practise to arrive at midday SWP values close to -1.5 MPa. At that SWP level, some leaf-rolling symptoms may be observed, but without leaf drop or yellowing, which will indicate excessive water stress. In the morning, growers should observe expanded leaves. A lead rolling symptom of water stress in the morning will indicate excessive stress, while no symptoms at midday will indicate lack of the desired level of stress during Stage II.

PHOTO Peach leaf appearance under three different levels of plant water status.
A: Severe stress (stem-water potential (SWP) = -1.9 MPa); **B**: Very mild stress (SWP = -0.9 MPa); **C**: Moderate stress (SWP = -1.1 MPa); **D**: Well irrigated (-0.8 MPa).

WATER REQUIREMENTS

The water use rates of peach trees are similar to other *Prunus* species, such as nectarines or plums. Table 1 lists the crop coefficients for mature peach trees, and an estimation of the water use at Lleida, Spain. The crop coefficients were obtained from lysimeter studies (Ayars *et al.*, 2003). In one study, the ET_c of a peach tree in a weighing lysimeter was followed for several years since its planting until it reached maturity. This study has provided data on the evolution of K_c for a peach orchard, as the canopy expands (Ayars *et al.*, 2003), and the results are shown in Figure 5. The lysimeter studies have shown that Tr in peach does not decrease much from peak values until soon before leaf fall, unless the water deficits imposed by restricting irrigation in the postharvest period induced stomatal control of Tr and early leaf senescence.

WATER PRODUCTION FUNCTIONS

A number of experiments have been conducted to quantify the relation between yield and applied irrigation water for peach (Girona *et al.*, 2002). A summary of some of the experiments

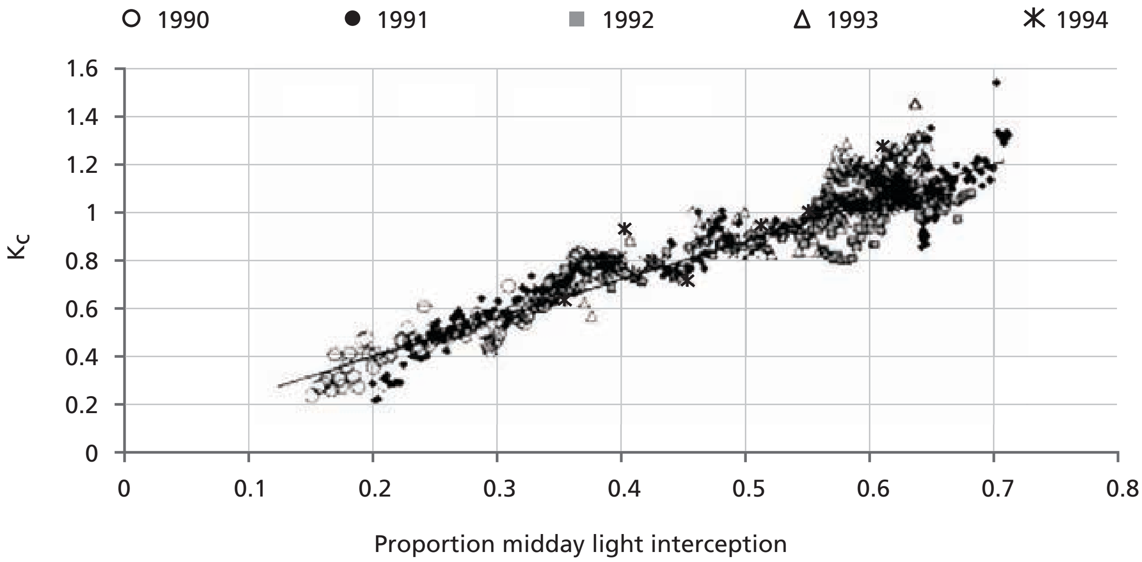
TABLE 1 Crop coefficients relative to grass reference crop (ET_o) for mature peach trees (Phenological stages for midseason cultivar at Lleida, Spain).

Date	Crop Coefficient (K_c)	Growth Stage
Mar. 1-15	0.25	
Mar.16-31	0.30	Bloom
Apr. 1-15	0.45	
Apr. 16-30	0.60	
May 1-15	0.70	
May 16-31	0.80	End of FGS I *
June 1-15	0.90	
June 16-30	0.95	Beginning of FGS III *
July 1-15	1.05	
July 16-31	1.05	
Aug. 1-15	1.05	Harvest
Aug. 16-31	1.00**	
Sept. 1-15	1.00**	
Sept. 16-30	1.00**	
Oct. 1-15	0.75	
Oct. 16-31	0.55	
Nov. 1-15	0.45	

* FGS = Fruit growth stage

** Management reductions in postharvest irrigation may lower these K_c values

FIGURE 5 Relation between the crop coefficient (K_c) for drip-irrigated peach trees measured in a weighing lysimeter in central California and the proportion of light interception by the trees. The linear equation approximation to calculate the K_c is:
$K_c = 0.082 + 1.59$ (PMLI) (Ayars *et al.*, 2003)



concluded that applied water may be reduced by 10- 20 percent below the maximum needs without a negative impact on yield. However, the analyses have very seldom included revenue considerations, relative to the price differential that different sized peach fruit fetches in the market. The response to applied water depends on the water storage capacity of the soil, and thus cannot be generalized. Figure 6 shows the relation between yield and ET_c in relative terms for different irrigations strategies, full irrigation (Control), RDI, and sustained DI (SDI). For the optimal RDI regime, it is possible to reduce the ET_c by 15-20 percent without a detrimental impact on yield. However, when the water deficits were imposed on sensitive stages or throughout the season (SDI), a reduction in ET_c was accompanied by a yield reduction (Figure 6). The differences in the responses to the various DI regimes illustrate the benefits of stress management when planning deficit irrigation programmes.

SUGGESTED RDI REGIMES

Based on the results shown above, it can be concluded that RDI strategies applied during Stage II in peach, especially when a fast recovery at the beginning of Stage III can be achieved, has proved to be very effective in controlling excessive vegetative growth and improving fruit quality without a yield penalty. For early season cultivars, RDI that concentrates the water deficits in the postharvest period is an effective strategy, provided severe water stress is avoided (Tables 2 and 3). Given the impact that different root zone water storage capacities have to the response to RDI, Tables 2 and 3 present different RDI schedules for two types of soils (shallow and deep), also giving indications of the minimum stem-water potential trees can withstand without having a detrimental effect on yield.

FIGURE 6 Relation between relative yield and relative ET_c for peach. The black continuous line represents the production function under no effective RDI irrigation strategies and the dotted black line represents the possible production function under effective RDI (data from Girona *et al*., 2002; Girona *et al*., 2005; Fereres, unpublished; and, Rufat and Villar, unpublished).

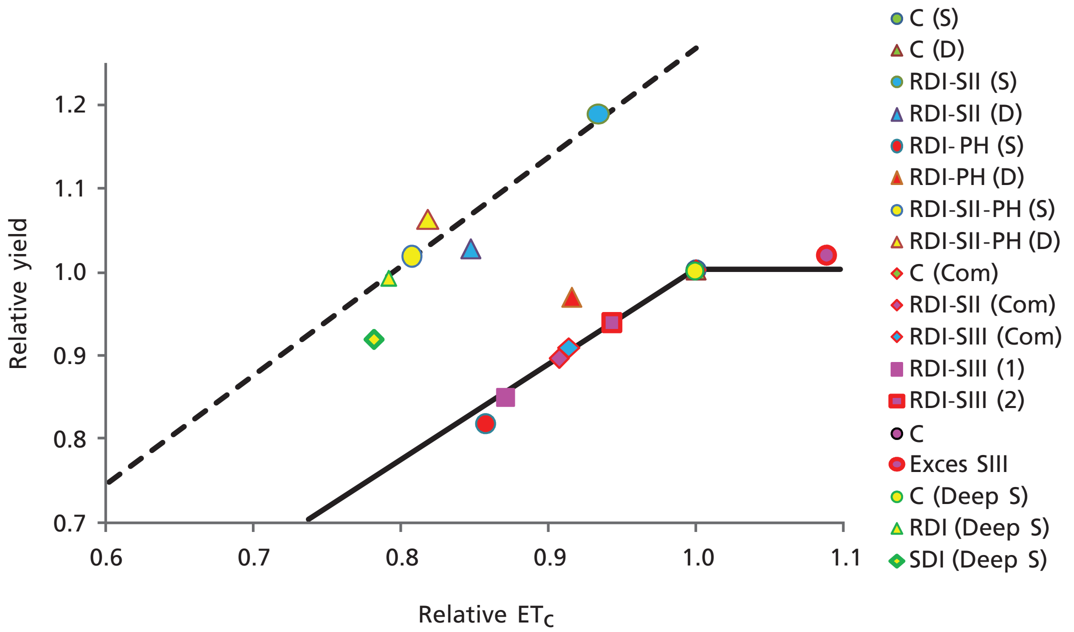


TABLE 2 Suggested limits of midday stem-water potential for late-season cultivars.

Fruit growth stage	Late-season cultivar		
	% of ET_c		Suggested limits of stem-water potential at midday
	Shallow soils (%)	Deep soils (%)	
I	100	100	-0.9 MPa
II	65	35	-1.8 MPa
III	100	100	-1.1 MPa
Ph	80	50	-1.8 MPa

TABLE 3 Suggested limits of midday stem-water potential for early-season cultivars (PH: post-harvest stage).

Fruit growth stage	Early-season cultivar		
	% of ET_c		Suggested limits of stem-water potential at midday
	Shallow soils (%)	Deep soils (%)	
I	100	100	-0.9 MPa
III	100	100	-1.0 MPa
Early Ph	50	35	-1.8 MPa
Late Ph	80	80	-1.2 MPa *

* *To prevent next year crop failure*

In applying RDI strategies an important factor is fruit load, and to manage the degree of plant water stress according to the number of fruit per tree. As has been discussed previously, the fruit load *per se* has a strong influence on the final size of the fruit (Naor *et al.*, 1999). If fruit numbers are very high and water is limited, there is a risk that imposing an RDI regime would induce a fruit size reduction. In that case it would be better to reduce fruit load by thinning to achieve the fruit size distribution of the crop that economically provides the highest net profit to the grower. If fruit load is low, RDI may even increase fruit size above that of full irrigation and will decrease vegetative growth and summer pruning costs. With medium fruit loads, optimal RDI that reduce ET_c by 15-20 percent would not have a negative impact on yield in most cases.

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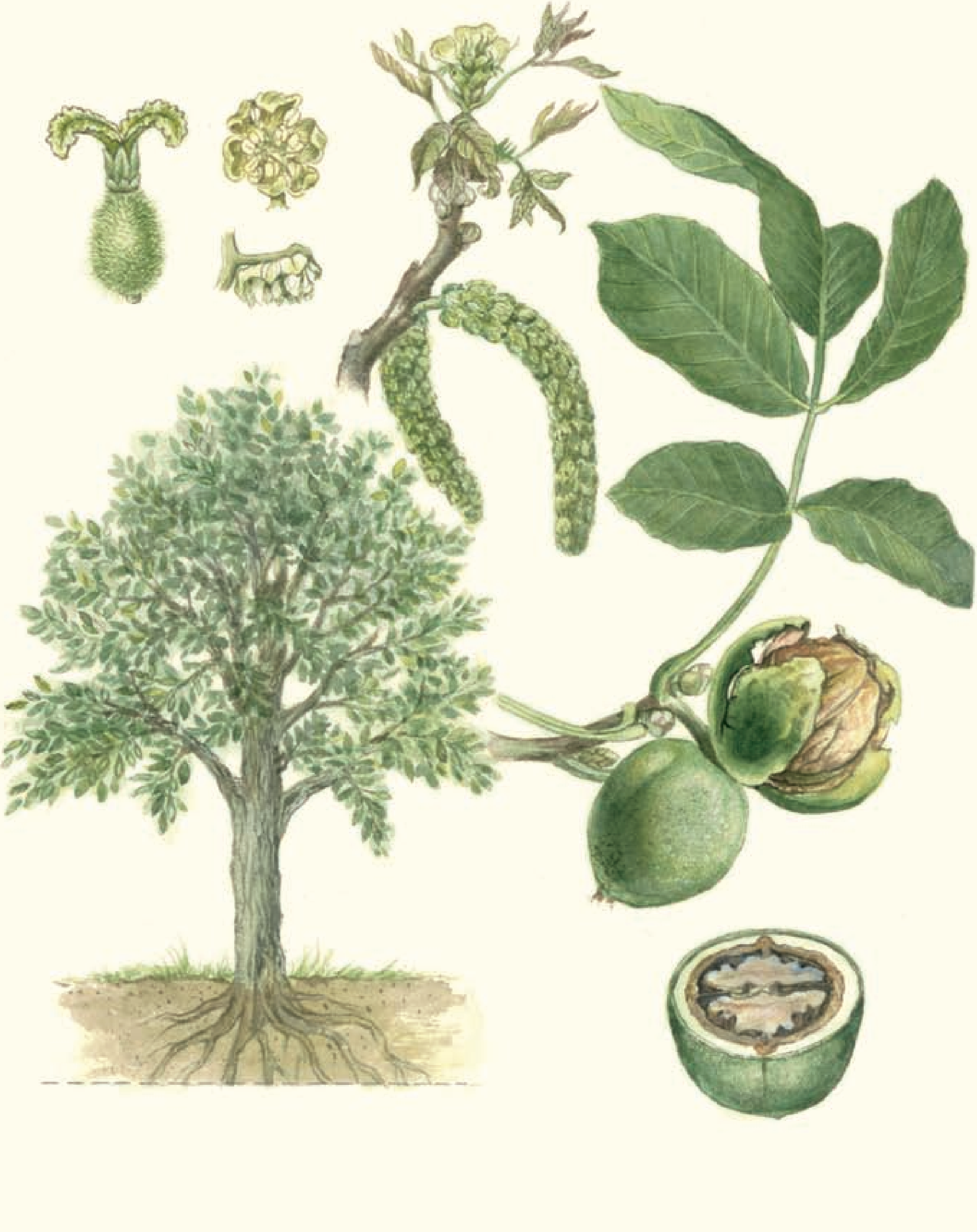

Walnut

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Walnut

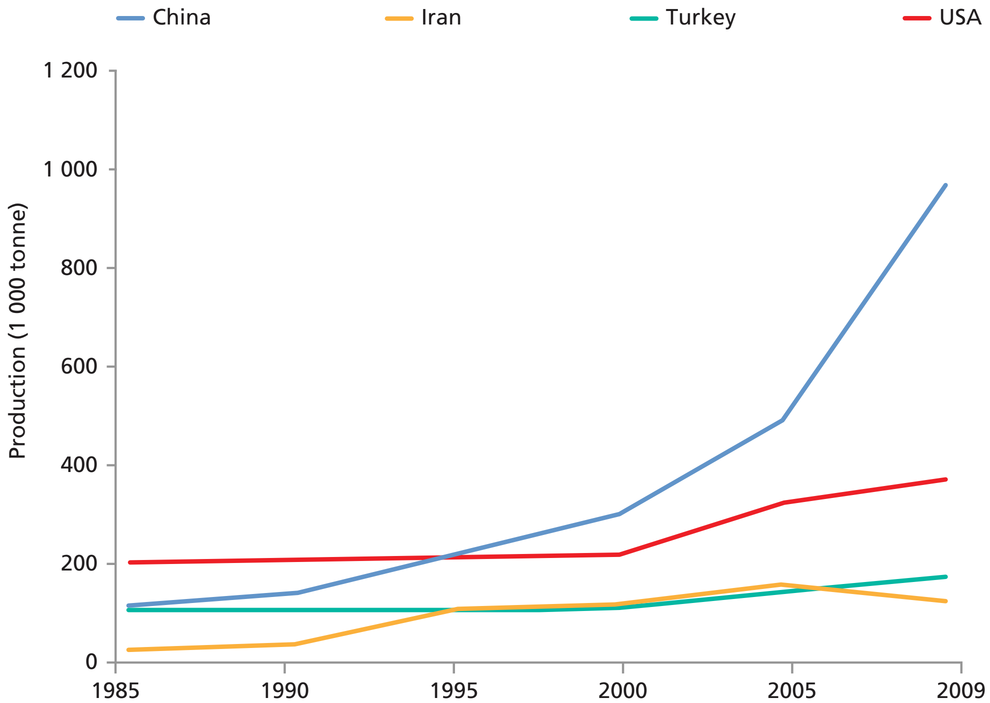
INTRODUCTION AND BACKGROUND

Walnuts *(Juglans regia* L.*)* are large trees that are cultivated in temperate climates for their nuts, rich in oil, and for their wood. Plantations are relatively widely spaced as this species does not tolerate mutual shading well. Common spacing of vigorous varieties varies between 8 x 8 and 10 x 10 m, while the less vigorous cultivars may be planted at 7 x 7 m spacing. Experiments that have increased tree density above the spacing mentioned have resulted in higher yields during the first years of the orchard but this may be at the expense of reduced orchard longevity. In 2009, world acreage was 843 000 ha and average global yield (with shell) was 2.7 tonne/ha (FAO, 2011). Figure 1 presents the production trends of the main producing countries. China and the United States are the two main world producers, followed by Iran, Turkey, and Ukraine. France is the main European producer and Chile is now an important producer in the Southern Hemisphere.

VEGETATIVE AND REPRODUCTIVE DEVELOPMENT

Commercial varieties of walnut trees break dormancy and begin to leaf out in the Northern Hemisphere between mid-March and mid-April, depending on the environmental conditions and the cultivar. This is followed by flowering, both the emergence of pollen-producing male flowers and the female flowers that evolve into the nut after pollination. Normally, flowering is completed by late April and is followed by rapid fruit expansive growth with concomitant rapid shoot growth. Bud formation occurs from leaf out through June on mature trees. By early June, the fruit has reached its full size and this is followed immediately by the internal development of the nut. At this time, shoot growth slows. The internal nut development sequence begins with shell expansion and hardening and dry matter accumulation in the kernel that continues through harvest. The indicator for physiological maturity is the development of 'packing tissue brown' which occurs before hull split. This can be identified by cracking open the nuts and observing the colour of the tissue surrounding the kernel inside the shell. If this tissue is white, the nuts have not reached maturity and there will likely be continued dry matter accumulation in the kernel. A brown colour indicates the nuts have matured and kernel development has ceased. Hull split generally follows closely after walnuts have reached physiological maturity. After splitting, the hulls break down rapidly. During the postharvest period, some shoot growth and carbohydrate storage are the primary sinks of photosynthesis products.

FIGURE 1 Production trends of walnuts in the principal countries (FAO, 2011).



EFFECTS OF WATER DEFICITS

Water stress can decrease nut size and quality (kernel colour and shrivel). Stress-related reductions in shoot growth can reduce fruiting wood for the following season(s). There is some evidence that not only are the number of reproductive buds less because of lower vegetative growth but that some flower buds are not viable, resulting in fewer flowers and ultimately less fruit. Further, the reduction of shoot growth causes higher fruit temperatures as a result of both more sunlight penetration into the canopy and thus, more direct solar radiation on a higher percentage of the fruit, and higher canopy temperatures because of less transpiration, that can darken kernel colour, reducing crop value. This temperature effect is very cultivar dependent.

As walnut fruit load is very dependent on the previous year's shoot growth, the impact of water deficits is much more severe in the season following the imposition of water deficits. The primary impact in the year that stress is imposed is on fruit size and quality while in the following season, the impact is on fruit load, regardless of the irrigation regime used in the following season. One California study found that hedgerow walnuts (cv. Chico) irrigated at 33 and 66 percent ET_c suffered marketable nut yield reductions of 32 and 50 percent, respectively, after three years because of reduced nut size, fruit load, and crop quality (Goldhamer, 1997). Upon returning these trees to full irrigation, tree growth and gas exchange immediately recovered but yields were little changed the first recovery year, even though shoot growth dramatically increased. It wasn't until the second recovery year that harvest yields completely recovered as a result of the fruiting positions created by the first recovery year's shoot growth. Similar stress impacts and recovery results have been obtained from other studies in California (cv. Chandler) (Lampinen *et al.*, 2004). The rapid production recovery from severe water stress was possible because of the absence of stress-induced disease or insect pressures. Trunk diseases such as deep bark canker that often occur in water stressed orchards were not evident in these studies.

WATER USE

Walnut orchards have high water use rates as because of the high leaf, tall tree stature, and near full ground cover when the trees are fully mature. Table 1 provides the crop coefficients for mature walnut orchards obtained from studies in California (Goldhamer, 1997).

TABLE 1 Crop coefficients for mature walnut trees (Goldhamer, 1997).

Date	Crop coefficient (K_c)
Mar. 16-31	0.12
Apr. 1-15	0.53
Apr. 16-30	0.68
May 1-15	0.79
May 16-31	0.86
June 1-15	0.93
June 16-30	1.00
July 1-15	1.14
July 16-31	1.14
Aug. 1-15	1.14
Aug. 16-31	1.14
Sept. 1-15	1.08
Sept. 16-30	0.97
Oct. 1-15	0.88
Oct. 16-31	0.51
Nov. 1-15	0.28

DEFICIT IRRIGATION STRATEGIES

The general strategy followed experimentally for reducing irrigation in walnut orchards has been to limit water deficits during early stages of tree and crop development in favour of imposing them during mid and late season. One study in northern California used midday stem-water potential to impose the 'low' and 'moderate' stress treatments. The target midday stem-water potential values were -0.5 to -0.7 MPa and -1.2 to -1.4 MPa during the bulk of the season for these two regimes with corresponding reductions in applied water of 30 and 50 percent of potential ET_c, respectively (Fulton *et al.*, 2002). It should be noted that the water potential values of fully irrigated walnut trees are much less negative then the two primary nut crops, almond and pistachio. Walnut predawn leaf water potential values for fully irrigated trees range between -0.15 and -0.2 MPa and midday stem-water potential between -0.40 to -0.60 MPa. After three seasons, yields in these stress treatments had declined by 26 and 40 percent, respectively, relative to fully irrigated trees (Lampinen *et al.*, 2004). Full recovery was achieved after two years of full irrigation. A companion study was conducted on deeper soils with older trees with a lower tree density. Yield reductions were appreciably lower at this site, which was attributed to the stress development being relatively slow because of the larger soil moisture reservoir and possibly the larger carbohydrate reserves of the bigger trees.

To simulate a one-year drought with a water supply of 400 mm where potential ET_c was

1 100 mm, a team in California applied 85 percent of ET_c through April to mature cv. Chico trees and then progressively lower percentages of ET_c as the season progressed (25 percent was the minimum from early July through the early September harvest) and no postharvest irrigation (Goldhamer *et al.*, 1989). Fruit yields in the drought year were about 10 percent lower than the fully irrigated control (not statistically significant). However in the following recovery year, when full irrigation was applied to all trees, the drought year trees had about 80 percent lower yields almost entirely the result of a lower fruit load. Yields returned to near full levels during the second recovery year (Goldhamer *et al.*, 1990).

It appears that walnut trees do not respond well to water deficits, regardless of the deficit irrigation strategy, in terms of nut yield. This is probably because of the high sensitivity of shoot growth to water deficits and, in turn, to the heavy dependence of fruit load on the shoot growth of the previous year in walnuts.

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Pistachio

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Pistachio

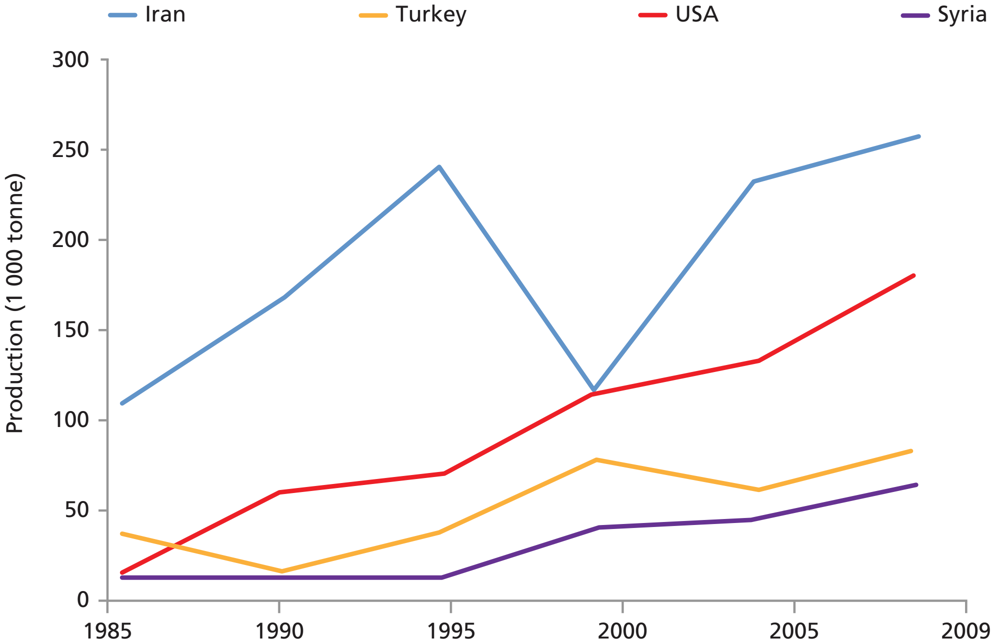
INTRODUCTION AND BACKGROUND

Pistachio *(Pistacia vera* L.*)*, is native to the Near East, primarily Syria and Iran, with large areas planted just recently in the United States. In 2009, there were 586 000 ha globally with an average yield of 1.1 tonne/ha (FAO, 2011). Figure 1 presents the production trends of the main producing countries since 1985. The bulk of Near East production is dryland as the pistachio tree is very drought tolerant. Most of the production in the United States is in California, which is irrigated. There is a huge difference in productivity between dryland and irrigated trees. For example, the average dryland yield in Turkey is only 1.4 kg per tree compared with 16-18 kg per tree under irrigation in California (Tekin *et al.,* 1990). While the value of irrigation for pistachio production is currently unchallenged, there are still some growers in rainfed areas who have the misconception that irrigation is harmful (Kanber *et al.*, 1993). Much of the Near East production is on marginal soils because the tree is perceived to be drought tolerant and good soils are scarce. This is not the case in California where irrigated orchards have been planted on productive valley soils.

The pistachio tree is dioecious; the male flowers are borne on one tree and female flowers on another. The male trees do not produce nuts. However, a certain percentage of the orchard, generally around 4 percent in commercial orchards, must be planted with male trees to ensure adequate pollination.

Among fruit and nut trees, pistachio has one of the highest degrees of alternate bearing. Crop yields can show up to a 90 percent year-to-year reduction. The physiological mechanisms of alternate bearing in pistachio are not well understood. It is likely to involve carbohydrate levels and/or competition with hormonal activity also being a possible factor. Alternate bearing is first manifested during nut filling in early July when the fruit buds (for next year) die and abscise. The heavier the crop, the greater is the bud abscission. The alternate bearing cycle is expressed not only for individual trees but for entire growing regions. It is thought that low production resulting from poor weather in a given year puts the entire region on the same alternate bearing cycle. Excessive alternate bearing in a region can cause a marketing problem for the industry. The current state of the art control of alternate bearing is pruning; heavily prior to an ‘on’ year and minimally going into an ‘off’ alternate bearing year. The fact that pistachio fruit are borne on year-old wood dictate the location and severity of pruning practices designed to mitigate alternate bearing. Moreover, pistachio shoot growth can be characterized as either preformed or neoformed, which is based on when

FIGURE 1 Production trends for pistachios in the principal countries (FAO, 2011).



Quality considerations

Pistachio is distinguished by having more quality components than other nut crops. These include not only the alternate bearing feature that affects nut size but also embryo abortion; nuts that have full size hulls and shells but where the kernels die prematurely or don't fill at all. Also, endocarp dehiscence (shell splitting) is required to produce the highest value nuts. Closed nuts shell at harvest cannot be marketed as snack food, which is the largest market for pistachios. Another type of fruit that is not commercially viable are early splits; nuts that split well before the onset of normal shell splitting. Not only are these nuts worthless but they are prone to fungal disease infection that can lead to the formation of Aflatoxin. Finally, the percentage removal of filled nuts by mechanical shaking also impacts harvest yields.

the tissue was differentiated. Virtually, all the crop is borne on the preformed growth and this has implications for irrigation management.

Although pistachios have been cultivated for centuries in countries of the Near East and West Asia, the industry is relatively young in California compared with the other nut crops grown there. The California pistachio industry is dominated by one variety, Kerman, and large growers and processors have readily embraced advanced practices, including drip or microsprinkler irrigation. In the main producing countries of the Near East, there is a wide-range of varieties and irrigation is being introduced, even though much production is still rainfed. California pistachio growers were very quick to adopt useful research results on water requirements and the impact of water stress on yield and crop quality partly because much of the acreage is located in high water cost and/or low availability areas.

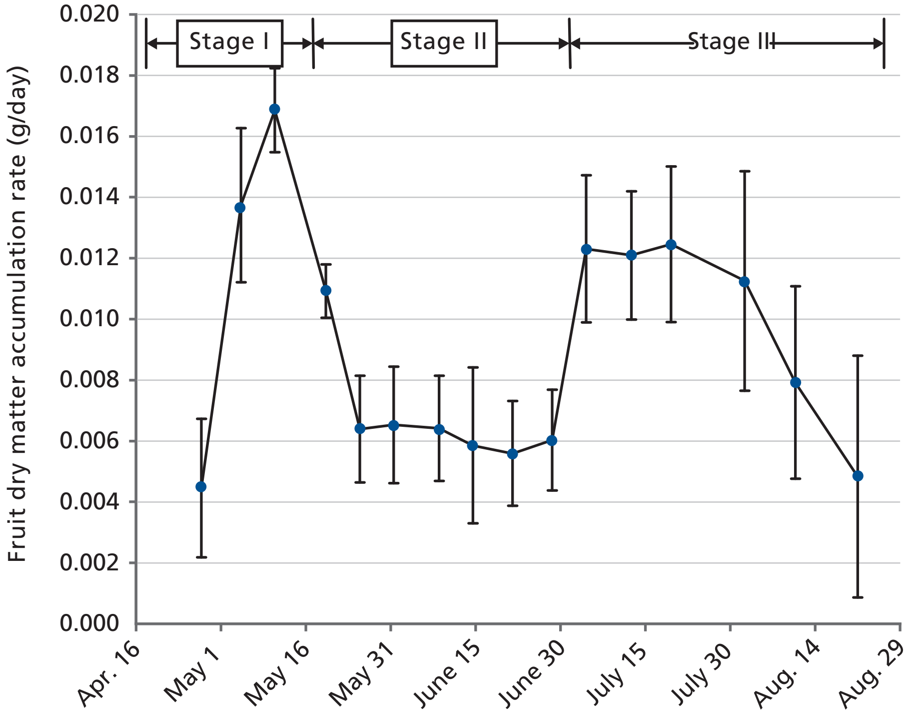
DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

The reproductive growth of pistachio trees can be divided into three stages based upon the development of the nut component parts: the hull+shell and the kernel. The development patterns of the nut components are shown in Figure 2. The hull+shell grows rapidly from late April through mid-May (Northern Hemisphere), after which full size is attained. This period is referred to as Stage I. However, the feniculous (embryo), which will eventually evolve into the kernel, normally does not begin to grow until early July. From mid-May through early July, the nut's primary growth activity is thickening of the shell. This period, characterized by a relatively low rate of dry matter accumulation in the nut, is known as Stage II. Rapid growth of the kernel begins in early July and remains so as harvest is approached. The biofix for this period, which is known as Stage III, is the appearance of a distinct green colour in the feniculous. Research (Spann *et al.*, 2009) has identified the concomitant vegetative growth associated with these stages and their eventual importance as locations for fruiting positions.

Early vegetative and reproductive growth; growth Stage 1

Shoot growth occurs simultaneously with the current season reproductive growth (swelling buds that will form the crop) as well as with embryonic (inflorescence primordia) bud development for the following season's crop from late April through mid May. Lateral inflorescences in the leaf axils are borne on shoots with, generally, a single apical vegetative bud. Buds differentiate in April, May and June, remain quiescent from July to September, and resume differentiation in October.

FIGURE 2 Time course development of dry matter accumulation in pistachio nuts illustrating the three growth stages. Vertical bars are plus and minus one standard error of the mean.



There are two types of shoot growth; the above-mentioned preformed or neoformed. All components of a preformed shoot are differentiated in the dormant bud whereas in neoformed growth, some differentiation of its component parts can occur during the growing season. Most of the buds found on preformed growth are reproductive; there are very few lateral vegetative buds on preformed shoots. Most of the vegetative growth occurs from terminal buds. Preformed shoots tend to be short compared with neoformed shoots which are longer. This longer shoot growth is undesirable because it tends to be weak and hangs down in the orchard rows, making management and harvest difficult. For these reasons, growers typically remove these shoots on mature trees by pruning during the dormant season. However, long shoot growth may be desirable in young, developing trees to ensure the most rapid development of the tree canopy.

Reproductive bud swelling begins in March. By mid-April, there are 100-300 flowers per rachis. Pollination and fruit set occur at this time. There are generally 20-25 developing fruit per rachis and they grow rapidly, with the hull+shell attaining full size by about mid-May. This event also coincides with a hardening of the shell.

Lag phase of reproductive growth: growth Stage II

From mid-May through early July, the primary activity in the nut is thickening and hardening of the shells, a process called lignification. However, dry matter accumulation in the fruit during this growth phase is low relative to the preceding (Stage I) and succeeding (Stage III) periods. There may also be some additional shoot growth in late May. Reproductive buds that will form the following season's fruit continue to differentiate through June. Sometimes there is an additional vegetative flush of growth in late June.

Rapid kernel development: growth Stage III

This phase is characterized by the resumption of a high rate of dry matter accumulation in the nut almost entirely results from the rapid growth of the kernel. Within a matter of a few weeks, the kernel will entirely fill the nut cavity and begin to exert pressure on the shell. Shell splitting is primarily because of this expansion of the kernel (Polito and Pinney, 1999). Shell splitting generally begins in early August. At this time, the hull begins to breakdown, changing from turgid tissue that is tightly bound to the shell with a papery, loosely connected covering that can easily be peeled from the shell. During Stage III, leaves on the same shoot as developing fruit sometimes become yellow and defoliate. This is thought to be the consequence of translocation of resources from the leaves to the fruit.

A certain percentage of the nuts, generally from 10 to 30 percent, do not fill. These are known as 'blanks' or 'aborted' nuts. With the former, there is no evidence of any development of the embryo whereas with the latter, the embryo development is aborted. The term 'blanking' is sometimes used to describe both phenomena. The hulls of these nuts do not breakdown as with the filled nuts. Also they are much more difficult to remove from the tree with mechanical shaking at harvest, resulting in a high percentage remaining on the tree.

Harvest is generally from late August to mid-September. Where it is done mechanically by shaking machines, similar to those used for almonds, which remove the nuts. In addition to the shaker, a companion machine, the receiver, is located on the opposite side of the tree and is used to collect the nuts, which are not allowed to drop to the ground. Drying is accomplished at the processing plant rather than on the ground as for almonds. One primary reason for this is that pistachio nuts need to be dried quickly, otherwise the shell can become stained, making them less attractive to buyers.

Postharvest

From harvest to the onset of defoliation, there is very little outward appearance of tree activity. Following the removal of fruit, reproductive bud differentiation resumes and continues through October. Trees generally defoliate in mid to late November because of leaf senescence, which is accelerated by low temperatures.

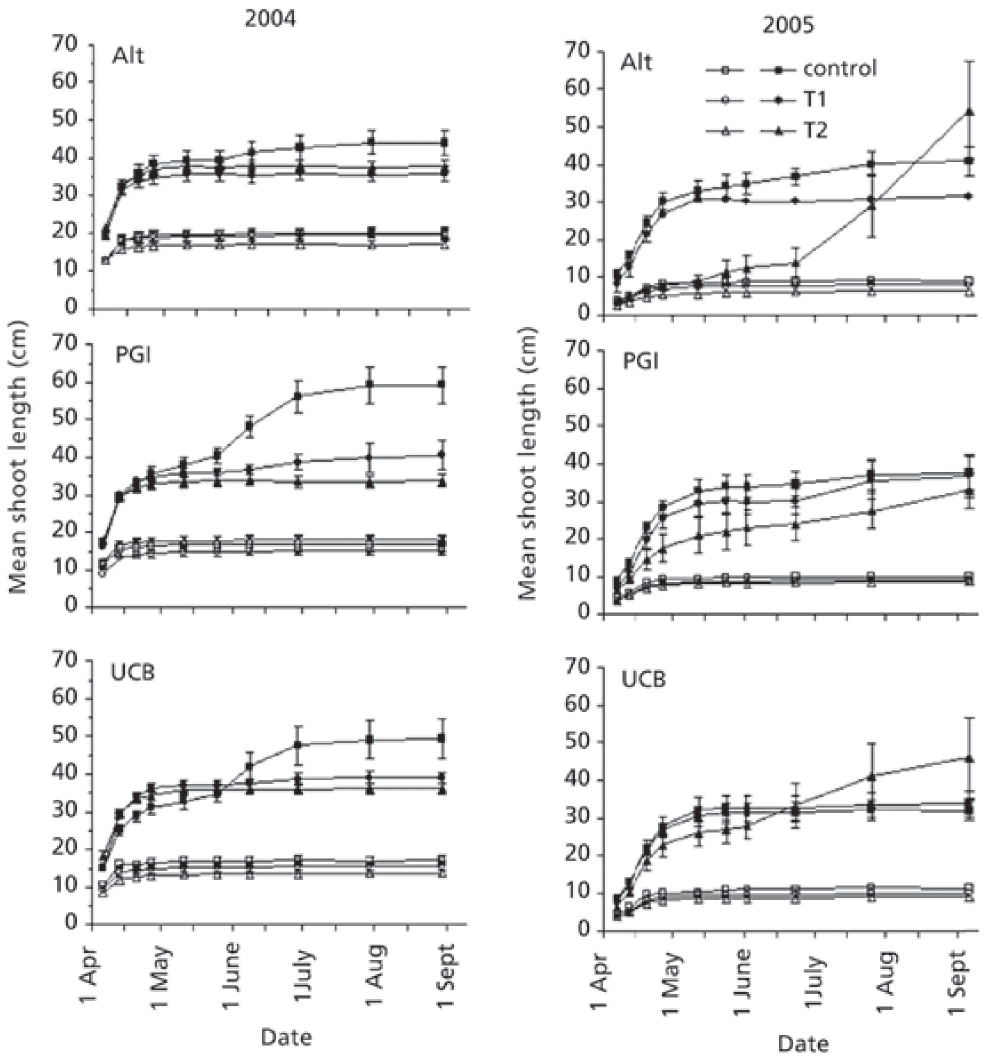
RESPONSES TO WATER DEFICITS

Pistachio has a well-deserved reputation as being drought tolerant. Measurable photosynthetic activity in the leaf has been measured even when leaf water potential (LWP) was in excess of -5 MPa (Behboudian *et al.,* 1986). This was attributed to the fact that pistachio trees had a turgor pressure of about 3 MPa even when the LWP was -6 MPa; a higher value that for even other xerophytes. Pistachio can maintain high turgor even with high soil salinity levels (Walter *et al.,* 1988), and high photosynthesis and stomatal conductance were found in different pistachio species under severe stress (Steduto *et al.,* 2002). Researchers ascribed this primarily to an extensive rooting system rather than xerophytic morphologic characteristics. Unirrigated trees of *P. atlantica* had transpiration rates about three times higher than *P. terebinthus* (Germana, 1997).' This suggests that pistachio trees can transpire at rates far higher than those normally found in mesophytes and that carbon assimilation with limited water supplies can be much higher than in other fruit crops, such as apple, peach, plum, cherry, citrus and almond. Pistachio exhibited a strong photosynthetic response to high N and water supply, although the rates of unirrigated trees were also quite high (Steduto *et al.*, 2002 and Aydın, 2004). With respect to water, pistachio is somewhat of a paradox; it transpires at an extremely rapid rate, in partly because the fact that its leaves are isolaterals meaning the upper and lower sides are similarly structured with almost identical stomatal density and conductance but, at the same time, it is also extremely drought tolerant.

Effects during Stage I

Spann and others tested RDI regimes that imposed water deficits of about -1.6 MPa midday shaded LWP on mature trees of Kerman on PG1, Atlantica, and UCB rootstocks during Stage I and both Stage I and Stage II. They found that especially for the 'short' shoots, those that are characterized as preformed growth, full elongation occurred by about the third week of April; well before the onset of Stage II. There were generally no reductions in this short shoot length because of these early season water deficits (Figure 3). However, stress during both Stages I and II significantly reduced the growth of the 'long' shoots; the neoformed growth (Figure 3). This did not decrease the number of fruiting positions since they are located mostly on the short shoots. Indeed, they found no differences in fruit load, fruit size and yield between these RDI regimes and the fully irrigated control. This was attributed to the fact that most fruit was borne on the preformed growth and that reducing neoformed growth was actually beneficial in commercial production since it must be pruned. Water and pruning costs are about 30 percent

FIGURE 3 Time course development of shoot length for both short (open symbols) and long (solid symbols) shoots of different cultivars for fully irrigated (Control) and two RDI regimes that imposed stress in Stage I (T1) and both Stage I and Stage II (T2). Vertical bars are plus and minus one standard error of the mean.



of the total for California pistachio growers and thus, the reductions in consumptive use and pruning attributed to the early season stress would likely increase grower profit (Beede *et al.,* 2004). Recent research with the UCB rootstock found some reduction in the total number of growing shoots per tree with both Stage I and Stage II stress that could reduce future yield if it continued for a number of years. This confirmed earlier work (Goldhamer *et al.,* 1987) that stress-related reductions in fruit load were primarily because of the reduction in the initiation of short shoots rather than potential or actual number of nuts per rachis.

Goldhamer and Beede imposed dryland conditions during Stage I with Kerman on Atlantica rootstock. They found that nut size was reduced by 6.1 percent relative to fully irrigated trees but that shell splitting was increased by 14.0 percent. They theorized that the stress impacted shell growth more than kernel growth, resulting in a greater splitting percentage. Since no other yield components were significantly affected, they reported slightly better total kernel yield of marketable product (split nuts) with Stage I stress (Goldhamer and Beede, 2004). More recent research has confirmed that shell splitting can be increased with Stage I stress but at the expense of nut size (Goldhamer *et al.,* 2005). Thus, the decision to use this strategy would depend on whether the grower had a severe problem with the production of closed shell nuts. Closed shell nuts can be as low as 5 percent of the harvested nut load and as high as 60 percent. Further, Stage I stress not only increased shell splitting but it increased the shell opening; the distance between shell halves at the distal end of the nut. This can result in the shell detaching from the kernel during commercial nut processing and the loose kernels can decrease the harvest value.

Effects during Stage II

Goldhamer and Beede evaluated an array of RDI treatments that imposed either dryland, applied water at 25 percent ET_c, or applied water at 50 percent ET_c during Stage II on mature Kerman on Atlantica rootstock under the high evaporative demand conditions of the western San Joaquin Valley in California (Goldhamer and Beede, 2004). These Stage II deficit irrigation treatments were coupled with different postharverst water regimes. They found that none of the Stage II stresses significantly reduced individual nut weight although there was a trend toward lighter nuts when Stage II irrigation was totally eliminated. One of these Stage II dryland treatments, when coupled with irrigation at 25 percent ET_c postharvest, significantly reduced the yield of split nuts. They concluded that Stage II was, indeed, a stress tolerant period, as has been found for other double sigmoid development fruit crops, such as peach, plum, and nectarine, and recommended an RDI regime that irrigated at 50 percent ET_c during Stage II (Goldhamer and Beede, 2004).

A June deficit irrigation schedule of 20 percent less than full irrigation doubled early splits, while a July deficit of 35 percent increased early splits by 30 percent (Sedaghati and Alipour, 2006). Early splits are nuts that split well before the onset of normal shell splitting. These nuts are not commercially viable. Moreover, they are susceptible to fungal diseases that can eventually result in Aflatoxin contamination. Doster and Michailides (1995) recommended that water stress in mid-May be avoided to decrease the incidence of early splits.

Effects during Stage III

Stress imposed during Stage III can have a dramatically negative impact on virtually all the yield components of pistachio. When a dryland treatment was imposed during Stage III, it was found that this reduced individual kernel weight by 10.6 percent, increased the sum of blanking and kernel abortion in the total tree nut load by 22.7 percent, and increased the production of closed shell nuts by 175 percent. Somewhat remarkably, the Stage III dryland treatment had no affect on total tree nut load. However, the yield of split nuts was reduced by 62.6 percent (Goldhamer and Beede, 2004).

Earlier work indicated that withholding irrigation during the first half of Stage III, which reduced consumptive use by 320 mm, had no significant impact on shell splitting but increased the number of filled nuts left in the trees after mechanical shaking by 119 percent. On the other hand, dryland conditions during the last half of Stage III (a 200 mm reduction in consumptive use) both increased the production of closed shell nuts at harvest by 31.6 percent and the number of filled nuts retained on the tree after mechanical shaking by 50 percent. It was concluded that

Stage III was the most stress sensitive period of the season for pistachio (Goldhamer *et al.,* 1991).

Of the numerous pistachio yield components, it is remarkable that tree nut load was unaffected by any of the nine deficit irrigation treatments imposed, including dryland conditions during Stage I, Stage II, Stage III, and postharvest and the various Stage II and postharvest stress combinations (Goldhamer and Beede, 2004). When averaged over the last two years of their four-year study, tree nut load ranged from 10 900 to 12 300 with the fully irrigated trees averaging 11 500 nuts per tree (Goldhamer and Beede, 2004). This suggests that there was enough preformed shoot growth very early in the season, even with Stage I dryland conditions, to produce the number of nodes (fruiting positions) necessary to support a full crop and that stored winter rainfall (200 mm per year) was sufficient to support this growth. This ability of the pistachio tree to produce equal fruit loads under a variety of stress regimes highlights the importance of the preformed shoot growth from mid-April to mid-May; a period when trees would normally rely on stored winter rainfall rather than irrigation. Indeed, the early work of Spiegel-Roy *et al*. (1977) found that 54 to 163 mm of annual precipitation was sufficient for dryland trees to differentiate enough flower buds to obtain appreciable yields.

Effects on alternate bearing

Kanber and others observed that a long duration of water stress aggravated alternate bearing and suggested that irrigation could alter periodicity, presumably by making more carbohydrates available during peak carbon demand periods (Kermani and Salehi, 2006). Goldhamer found that Stage I stress during an 'on' year (shown as 2004 in Figure 4) resulted in more than a three-fold increase in fruit load the following season (the subsequent 'off' year) relative to fully irrigated trees. The mechanisms of why this happened are unknown and it should be emphasized that the early season stress was possible only because winter rainfall was abnormally low. The following season, the winter rainfall eliminated any Stage I stress but the fruit loads of this RDI regime were 25 percent lower than the fully irrigated trees (Figure 4). This pattern continued in the succeeding season when this RDI regime had a fruit load 25 percent higher than those under full irrigation. It appears that regardless of why there are higher yields in a normally 'off' year, the one time higher yields can alter the alternate bearing pattern for the following years.

Crop load also influences the impact of deficit irrigation on the various yield components of pistachio. This was observed when dryland conditions with Kerman on Atlantica rootstock were imposed in both 'off' and 'on' alternate bearing years (Figure 5). All the yield components, with the exception of harvestability, were more negatively impacted in the 'on' year. Harvestability was higher in the 'on' year only because entire rachises, rather than individual nuts, were removed from the tree with the mechanical shaking. Thus, growers can anticipate greater negative impacts of serious droughts during 'on' versus 'off' alternate bearing years. In fact, a possible management strategy, with very limited water supplies under microirrigation, would be to cutoff irrigation to the trees with low fruit loads (those in the 'off' year), making that water available for the trees in the orchard with the high fruit loads.

Indicators of tree water status

The established method to quantify water stress for pistachio is to measure water potential with a pressure chamber. Although the standard method is to measure stem-water potential

FIGURE 4 Total tree nut load for trees subjected to RDI regime that imposed stress in Stage I compared with a fully irrigated control. Note the impact of RDI on the alternate bearing pattern. Vertical bars are plus and minus one standard error.

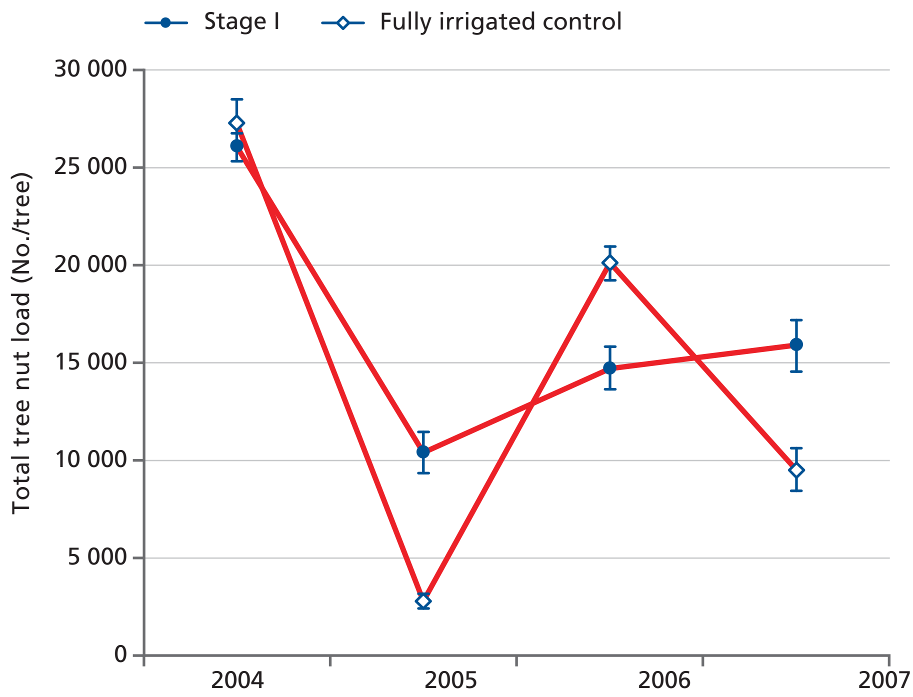
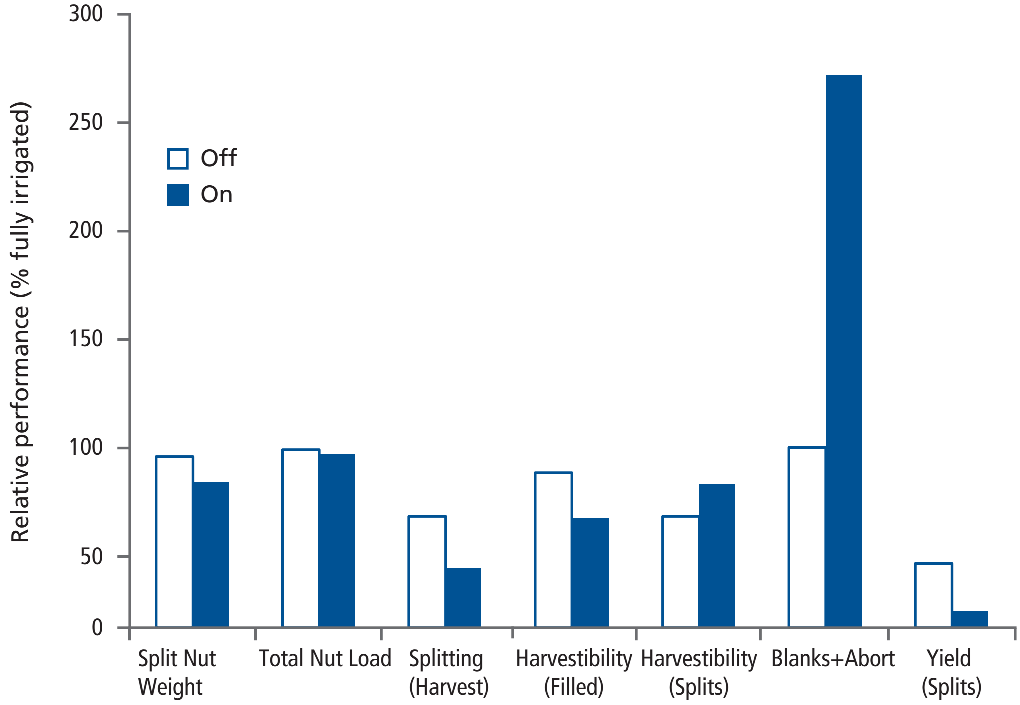


FIGURE 5 The impact of the first year of dryland conditions during both 'on' and 'off' alternate bearing years on the yield and yield components of previously fully irrigated pistachio trees.



(see Chapter 4), as in other species, there is a good correlation between midday shaded LWP (faster to measure) and stem-water potential (Goldhamer *et al.,* 2005).

One factor that complicates taking LWP measurement on pistachio leaves is that at the onset of gas injection into the chamber, exudates, presumably from the phloem, appear at the cut end of the petiole. These can interfere with identifying the instant xylem fluids appear. One approach to eliminating this problem is to use a cotton swab to soak up these exudates prior to the appearance of the xylem fluid. Another approach to eliminating this problem uses blotting paper positioned at the cut end of the petiole that absorbs only xylem fluid but excludes the other interfering fluids. A third approach is not to use individual leaves but small, interior shaded spurs that may have one to four leaves. The procedure involves covering the spur with a damp cloth just prior to excision. A few millimiters of bark is removed at the cut end with either a small knife or a thumbnail. The entire spur is placed in the chamber after the cloth is removed and the reading is taken. It is quite easy to identify the appearance of the xylem since there is no interference of phloem exudates and the cross-sectional area of view is larger than the leaf petiole. Goldhamer also found a good correlation between spur water potential and midday shaded LWP. The slope of the relationship was about unity but the intercept indicated that the spur water potential differs from the shaded LWP reading by about -0.7 MPa.

WATER REQUIREMENTS

Relatively few studies have quantified pistachio ET_c. Research in Iran with Ohadi on Badami Zarand rootstock (Kermani and Salehi, 2006), concluded that 600 and 1 200 mm per season should be applied with drip and flood irrigation, respectively, although 910 mm was reported as a 'previously determined' irrigation amount for mature pistachio trees (Kermani and Salehi, 2006). Early studies found that trees irrigated with a K_p (pan evaporation) value of 0.50 produced equally as well as those irrigated with a K_p of 0.75 for Larnaka on P. integerrima rootstock (Monstra *et al.,* 1995). In Southeast Turkey, the K_c values for Antep and Uzun varieties rose from 0.49 in May to 0.80 in August and continued at this magnitude through the first week of September when they declined to 0.32 during October because of leaf senescence (Kanber *et al.*, 1993). However, it was noted that while all irrigation regimes began the season with a nearly full soil water profile, they all ended with it nearly depleted. The researchers suspected that there was insufficient irrigation to meet ET_c for their most heavily irrigated trees (Kanber *et al.*, 1993).

A soil water balance approach with arrays of neutron probe access tubes to a depth of 3 m and ET_o estimates from a nearby weather station was used to calculate bimonthly K_c values for mature Kerman on Atlantica rootstock (Table 1) (Goldhamer *et al.*, 1985). A unique aspect of this approach was to make use of soil hydraulic conductivity data obtained in a separate experiment to eliminate one of the shortcomings of the water balance approach to determine ET_c: deep percolation below the deepest depth monitored.

TABLE 1 Crop coefficients relative to grass reference crop (ET_o) for mature pistachio trees ('Kerman' on *P. atlantica*) measured using on soil water balance approach in western Kings Co., CA (Goldhamer *et al.,* 1985).

Date	Crop Coefficient (K_c)
Apr. 1-15	0.07
Apr. 16-30	0.43
May 1-15	0.68
May 16-31	0.93
June 1-15	1.09
June 16-30	1.17
July 1-15	1.19
July 16-31	1.19
Aug. 1-15	1.19
Aug. 16-31	1.12
Sept. 1-15	0.99
Sept. 16-30	0.87
Oct. 1-15	0.67
Oct. 16-31	0.50
Nov. 1-15	0.35
Nov. 16 -30	0.28

WATER PRODUCTION FUNCTION

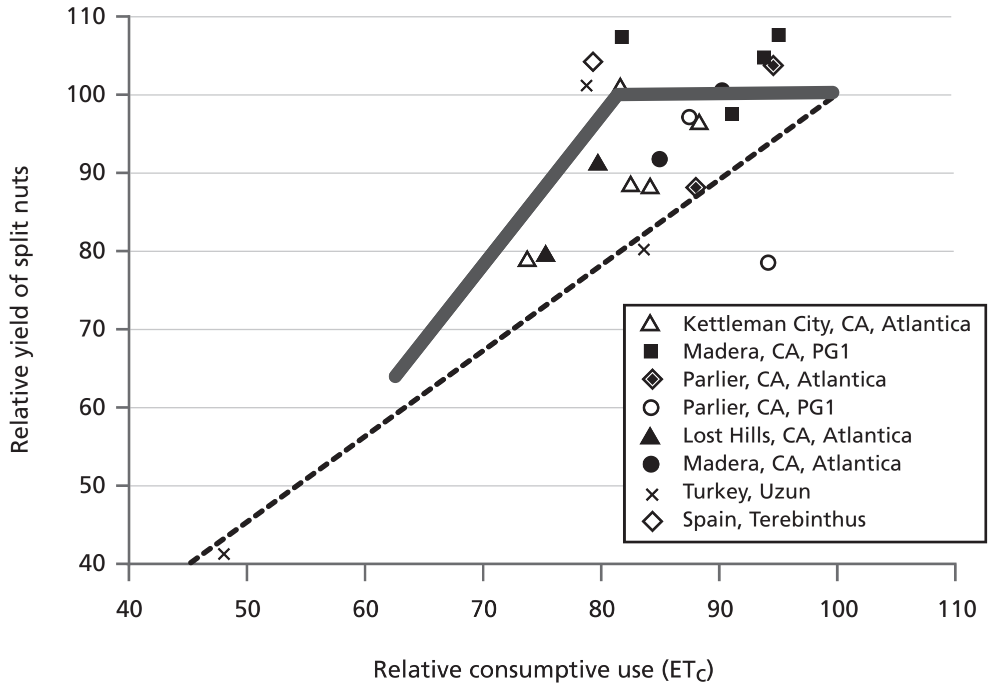
The current recommended optimal RDI regime applies stress during Stage II and postharvest to achieve the same production as fully irrigated trees while reducing the consumptive use of water (Goldhamer and Beede, 2004). These authors tested this approach in numerous field trials (Goldhamer *et al.*, 1984) in the San Joaquin Valley of California. The results of these experiments are summarized in the production function shown in Figure 6. While there is appreciable scatter in the data, it suggests that a plateau in the yield of marketable product is achieved with 10 to 20 percent less consumptive use than potential ET_c. Thus, reducing consumptive use by up to 20 percent can generally be achieved without a negative impact on the yield of marketable product. This occurred with both Altantica and PG1 rootstocks.

It should be emphasized that that a 10 to 20 percent reduction in ET_c would translate into a higher percentage reduction in applied water. For example, if ET_c was 1 100 mm of which 300 mm was effective rainfall, then applied irrigation water would have been 800 mm. A 15 percent reduction in ET_c would reduce consumptive use by 165 mm; that is equivalent to about a 21 percent reduction in applied water. Percentage reductions of applied water would increase as effective rainfall increased.

SUGGESTED RDI REGIMES

Based on the assumption that Stage II and postharvest are the most stress-tolerant periods, Stage I has intermediate tolerance, and Stage III is least tolerant, one can develop an array of drought irrigation strategies based on meeting certain percentages of ET_c during these periods (Table 2). The percentage amounts for each period vary depending on the available water supply. It should be pointed out that these recommendations are based on experimental results of applied water amounts generally above about 750 mm (about 65-70 percent ET_c); tests of RDI regimes below this amount have not been published. Thus, the suggested regimes here for water supplies below 750 mm are our best estimate of what would result in optimal tree performance, again based on the stress sensitivities of each growth stage.

FIGURE 6 Production function developed using RDI strategies that imposed stress during Stages I, II, and postharvest only for at least a four-year duration. Eight studies from USA and Europe met this criterion and are presented. The dashed line shows linear regression from full yield, through zero yield with a 7% ET_c; the level assumed necessary for tree survival.



Since the contribution of soil moisture to ET_c is difficult to determine, especially early in the season, the RDI management strategy of only irrigating at certain percentages of ET_c is problematic. An alternative is to use a plant-based indicator of tree water stress, such as leaf/spur water potential with the pressure chamber. In the studies cited above, midday shaded LWP during Stage I, Stage II, and postharvest did not exceed -1.8 to -2.0 MPa. Recommended values for fully irrigated, mature pistachio trees grown under high evaporative demand conditions should have midday shaded LWP values for Stage I, Stage II, Stage III, and postharvest of -0.7 to -0.8 MPa, -0.8 to -1.0 MPa, -1.0 to -1.1 MPa, and -1.0 to -1.2 MPa, respectively.

One pistachio grower in California has observed that there is little need to irrigate male trees at full ET_c since their only role is to supply pollen very early in the season. He suggests that male tree irrigation can be eliminated or substantially reduced after Stage I with no negative impact on the subsequent season's pollen formation. This can be accomplished relatively easily with microirrigation systems. However, given that male trees usually make up only about 4 percent of all trees, the reduction in irrigation would be small.

Typical microsprinkler application:

Tree spacing	289 ft^2	
Application rate	1.47 ft^3/hr	
Depth application rate per plant	0.01 ft/hr	(0.06 in/hr)
Amount per irrigation	1.47 in/24 hr	(37.2 mm/24 hr)

The grower would keep track of cumulative amounts to be applied with RDI scenarios. When the total is 37 mm, he irrigates. Thus, there would be one irrigation in April 16-30 with full water supply but with 300 mm available case, first irrigation would not be until third week of June.

TABLE 2 Suggested RDI strategies for different available water supply senarios from 900 to 300 mm when ET_c is 1 100 mm.

			Potential	900 mm available case		750 mm available case		600 mm available case		450 mm available case		300 mm available case	
Date	Growth Stage		ET_c in Period (mm)	Irrigation Rate (% ET_c)	Applied Amount (mm)	Irrigation Rate (% ET_c)	Applied Amount (mm)	Irrigation Rate (% ET_c)	Applied Amount (mm)	Irrigation Rate (% ET_c)	Applied Amount (mm)	Irrigation Rate (% ET_c)	Applied Amount (mm)
Apr. 16-30	1	Leafout, flowering; shoot elongation	33	100	33	50	16	50	16	25	8	10	3
May 1-15	1	Fruit set; hull, shell expansion	59	100	59	50	30	50	30	25	15	10	6
May 16-31	2	Shell hardening	91	50	45	25	23	25	23	25	23	10	9
June 1-15	2	Shell hardening	122	50	61	25	31	25	31	10	12	10	12
June 16-30	2	Shell hardening	137	50	68	25	34	25	34	10	14	10	14
July 1-15	3	Rapid kernel growth	128	100	128	100	128	75	96	10	13	10	13
July 16-31	3	Rapid kernel growth	123	100	123	100	123	75	93	75	93	50	62
Aug. 1-15	3	Shell splitting	124	100	124	100	124	75	93	75	93	50	62
Aug. 16-31	3	Hull breakdown	100	100	100	100	100	75	75	75	75	50	50
Sept. 1-15	Harvest		83	100	83	100	83	75	62	75	62	50	42
Sept. 16-30	Posthavest	Bud differentiation	56	100	56	25	14	25	14	25	14	10	6
Oct. 1-15	Posthavest	Bud differentiation	35	100	35	25	9	25	9	25	9	10	4
Oct. 16-31	Postharvest	Bud differentiation	19	100	19	25	5	25	5	25	5	10	2
Nov. 1-15	Postharvest	Defoliation	10	100	10	25	2	25	2	25	2	10	1
Total			**1 121**		**946**		**722**		**583**		**438**		**284**
Irrigations per season			30		25		19		16		12		8

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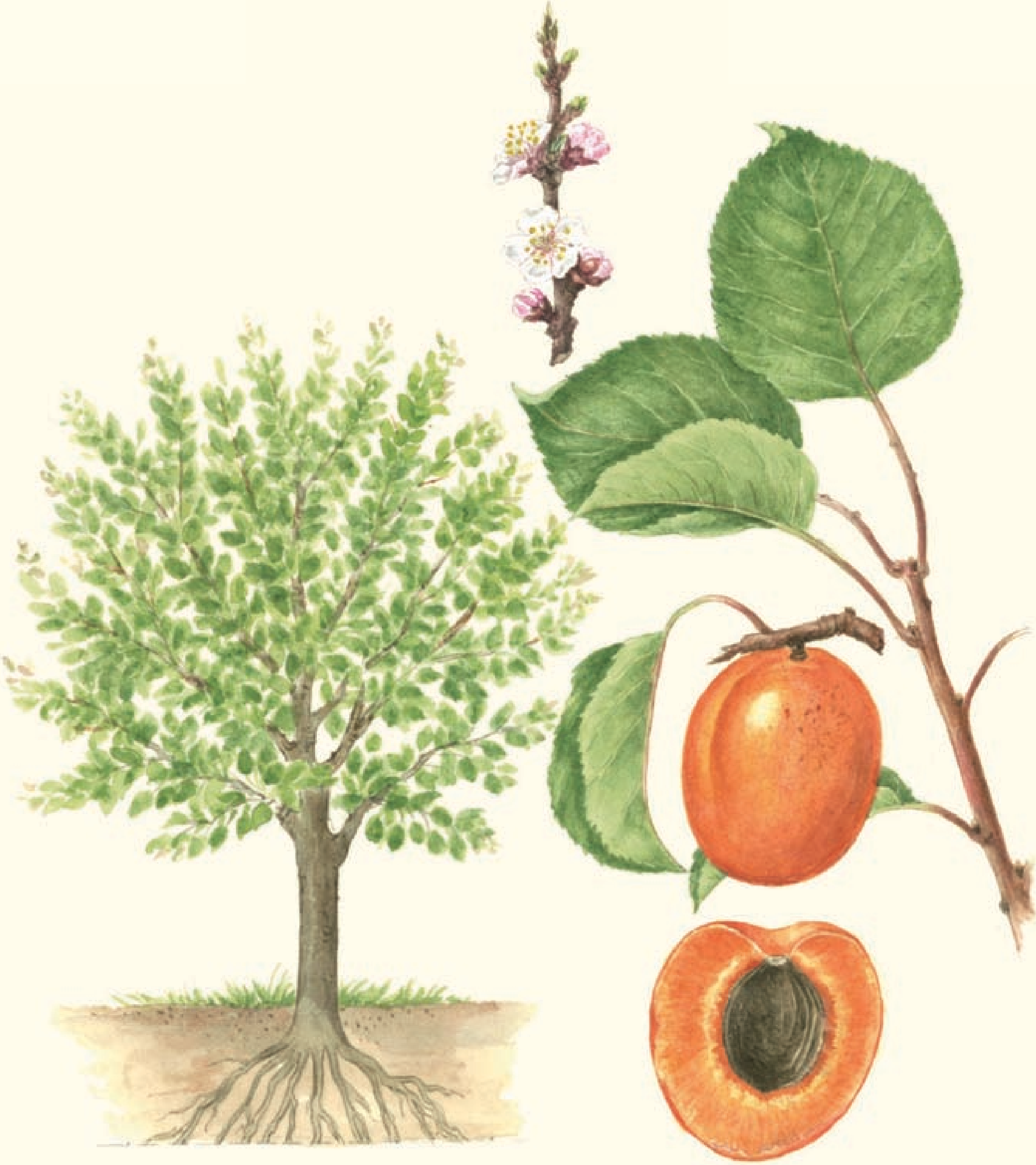

Apricot

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Apricot

INTRODUCTION AND BACKGROUND

Throughout the world, 90 percent of commercially grown apricots are derived from the *Prunus armeniaca* (L.) specie, a few cultivars are from *P. mume* or *P. sibirica*, or more recently, originate from apricot × plum (and *vice versa*) hybrids. Apricots are small-to-medium sized trees with spreading canopies (usually kept under 3.5 m), cultivated for fresh or processed fruit (dried, jam, juice), and for their oil extracted from the kernel. Apricot grows well in temperate regions; however, it is also able to tolerate very low temperatures during winter. Particularly, *P. sibirica* can tolerate air temperatures of about -35 °C, and soil temperatures down to -13 °C at the 40 cm depth did not damage its roots (Kramarenko, 2010). Total global production in 2009 was 3.73 million tonne on 504 000 ha (FAO, 2011). Figure 1 presents the evolution of production since 1985. Turkey is the main producer, followed by Iran; Italy is the first producer in the European Union. Most cultivars mature between the end of April and end of June (Northern Hemisphere). Over the last five years, new cultivars with a much later maturity date (August-September) have been bred and introduced in some areas.

Normal plantation density is about 400-500 tree/ha, using some training systems (e.g. transverse Y) density could reach 1 200–1 500 tree/ha. In this case careful canopy management (e.g. summer pruning) is required to minimize excessive shading that reduces water-use efficiency at the leaf level (Figure 2), the size, sugar content and colour of the fruit, bud induction and flower quality for next year yield and the level of carbohydrate stored in the buds, flowers and shoots (Nuzzo *et al.*, 1999 and Xiloyannis *et al.*, 2000).

STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Floral bud induction begins in late spring or summer. The chilling requirements for flowering (No.of hours < 7 °C), range from 300 to 1 200, depending on the cultivar. The minimum bloom temperature (namely the GDH heat units required after rest (Ruiz *et al.*, 2007)) is relatively low, causing apricots to bloom (and leaf out) early in most locations, thus apricot flowers and new shoots tend to suffer frost injury in early spring. Apricot trees break dormancy and begin to bloom in the Northern Hemisphere by mid-February, depending on the environmental conditions and cultivar. Usually, flowering

FIGURE 1 Production trends for apricots in the principal countries (FAO, 2011).

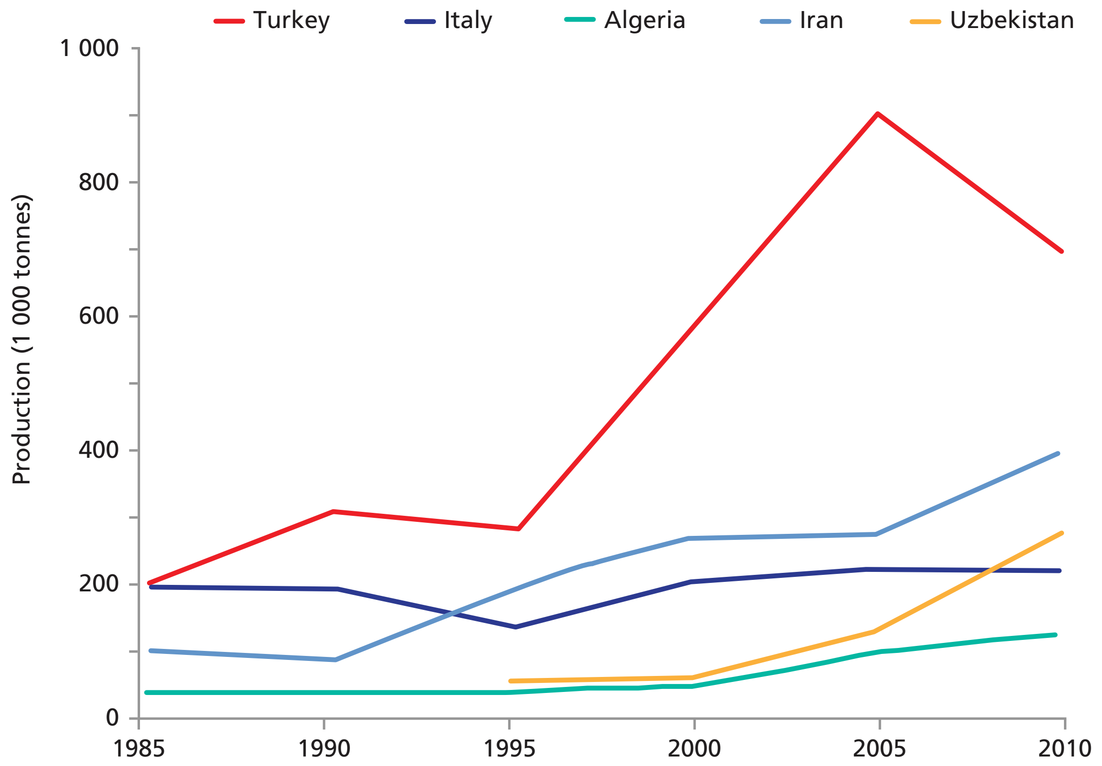
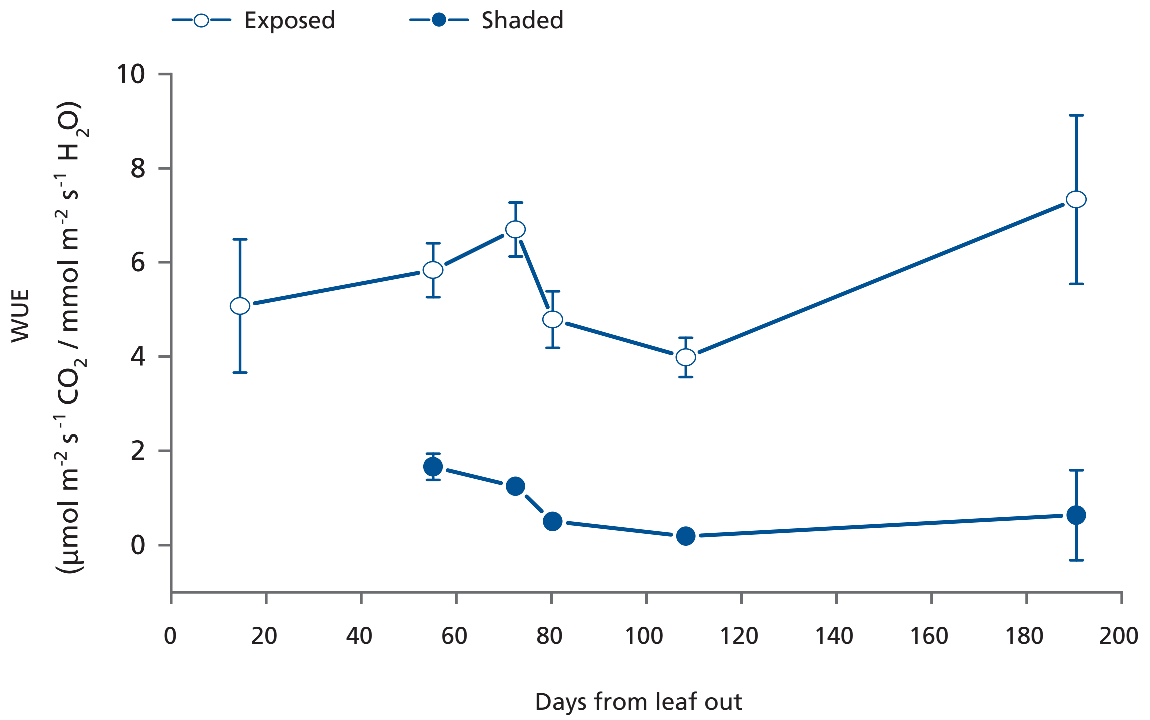


FIGURE 2 Seasonal variation of the daily mean water-use efficiency (WUE) (±SE) measured in exposed and shaded (< 350 µmol m^{-2} s^{-1} PAR) leaves in apricot trees trained to transverse-Y (cv. Tyrinthos, 1 111 plant/ha) (source: Xiloyannis *et al.*, 2000).

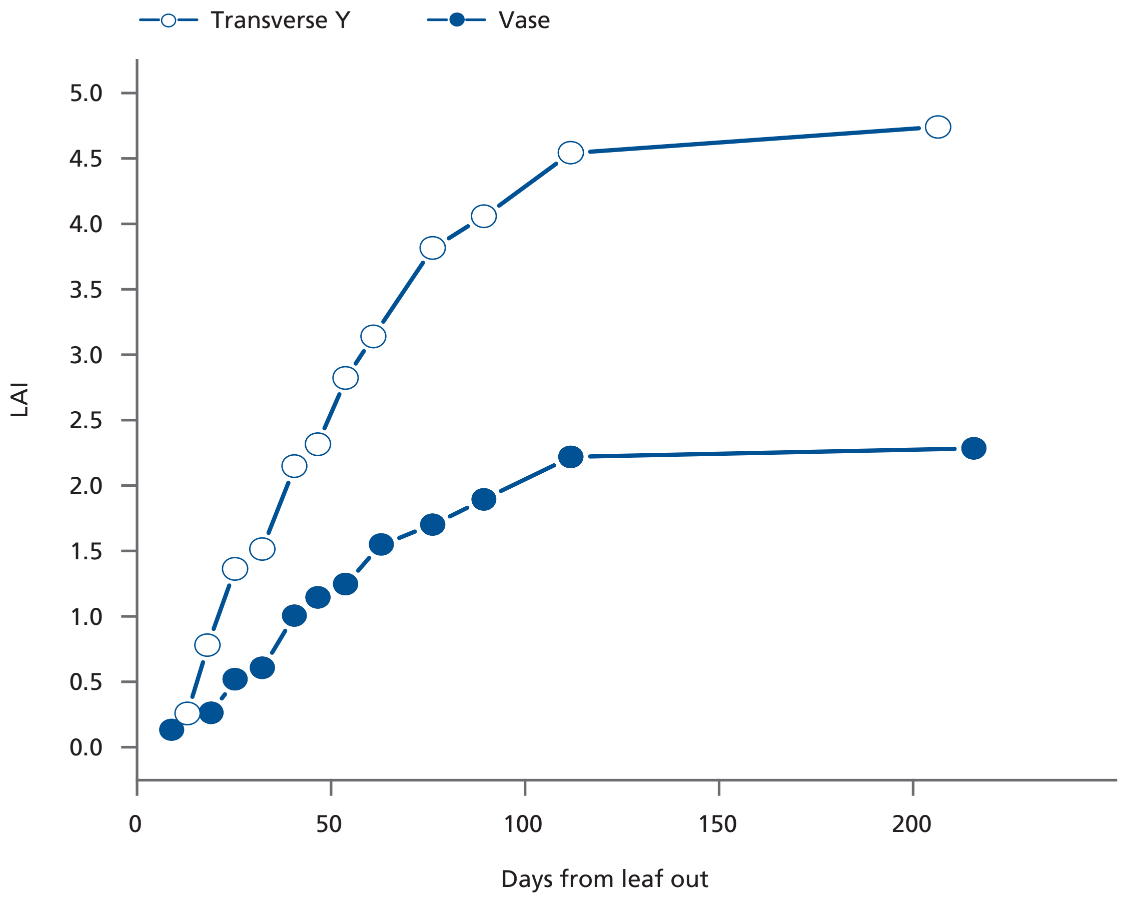


is completed within 20 days; thereafter fruit grows rapidly and attains its maximum size by mid-May (Northern Hemisphere). At this time, about 90 percent of total fruit dry matter has been gained (in early cultivars). In temperate regions, harvest starts by the end of May and lasts until the end of July; Northern Hemisphere).

Leaf emergence takes place at the end of February followed by fast shoot growth rates. About 80 percent of full leaf area is completed by the end of May. Thereafter, about 95 percent of final leaf area is achieved by the end of June (Figure 3). Values of leaf area index (LAI) range from about 2 in orchards with normal plantation density (~400 plant/ha) up to 4.5 in orchards planted in high density systems (~1 100 plant/ha) (Figure 3).

In Mediterranean climates, vegetative shoot growth of apricot trees continues (especially in young orchards) for several months after fruit have been picked, until October. During this postharvest period, carbohydrates and mineral elements stored in the different plant organs are of primary importance. Thus, it is important to provide sufficient mineral nutrition and water supply from irrigation to protect the trees from abiotic stress, during the postharvest period. In this way leaf photosynthetic activity is maintained and extended until natural leaf senescence, and in turn, storage of reserves in shoots, buds, branches and main roots is maximized.

FIGURE 3 Seasonal LAI evolution in apricot orchards (cv. Tyrinthos) trained to Vase (400 plant/ha) and Transverse Y (1 111 plant/ha) (redrawn from Dichio *et al.*, 1999).



RESPONSES TO WATER DEFICITS

In areas of winter and spring rainfall, water stress conditions rarely occur before harvest in early cultivars, particularly when soils are deep and with high water-holding capacity. The effects of reduced soil water availability, as well as the level of stress experienced by plants, depend on the intensity and duration of the water deficit, and on the plant phenological stage. Generally in June, July and August (months with high evaporative demand) the effects of water deficit are more evident.

Apricots, like most stone fruit trees, are sensitive to water shortages during the entire fruit development period. The early stages of fruit growth are of great significance not only for fruit size but also for the accumulation of some phloem-immobile nutrients (e.g. calcium, Ca). About 85 percent of fruit Ca content at harvest is gained within the early four weeks of development (Montanaro *et al.*, 2010). Hence optimal soil water supply during these weeks is essential to avoid reduction of water (and nutrients) uptake.

Water deficits during the later stages of fruit growth lead to smaller fruit at harvest. However, it has been reported that for the cv. Búlida, recovery from water stress (-1.0 MPa predawn leaf water potential (LWP)) during Stage II of fruit growth, induced a compensatory fruit growth rate during the final stages, which allowed the fruit to reach a similar diameter as fruit from fully irrigated plants (Torrecillas *et al.*, 2000). In the same experiment, water deficits applied during Stages I and II that imposed mild to moderate stress from mid-March to mid-May (predawn LWP of -1.1 MPa) caused a yield decline of about 15 percent in the last three years of a four-year experiment. Surprisingly, this difference was not statistically significant from the yield of a fully irrigated control (predawn LWP of -0.4 MPa) (Torrecillas *et al.*, 2000).

For mature trees water deficits (-1.0 MPa predawn LWP) negatively affected trunk growth during the drought period (Perez-Pastor *et al.*, 2009). However, upon recovery of optimal soil water condition trunk circumference may easily recover (Torrecillas *et al.*, 2000).

Water stress (-1.5 to -2.2 MPa of predawn LWP) occurring during the early postharvest period (~30 days after harvest), could have detrimental effects on the potential yield of the following year, particularly for early cultivars. This is because water deficits at this time negatively affect bud induction and the floral differentiation process, which happen in the early postharvest period.

WATER REQUIREMENTS

The water requirements for irrigation depend primarily on the annual water deficit of the environment, than on cultivar and yield target. For example, the amount of irrigation water needed to produce 1 kg of fruit in southern Italy, where the seasonal water deficit (ET_o-rainfall) is around 850 mm/year, is about 160 litre (~30 tonne/ha yield). For the same cultivar, this value decreases to about 40 litre/kg in northern Italy (44°08′ N; 12°44′ E) where the seasonal water deficit is only around 160 mm/year.

There have been very few measurements of the consumptive use (ET_c) of apricot trees. Crop coefficients (K_c) for apricot orchards are similar to those of other stone fruit such as plum or peach. However, because fruit is harvested quite early, limited post harvest irrigation is common, which affects the reported K_c values, sometimes much lower than the values that may be observed in orchards where the water supply is not limiting transpiration after harvest. Table 1 provides adjusted K_c values for mature drip-irrigated apricot orchards based on an experiment in southeastern Spain (37°52′ N; 1°25′ W) (Abrisqueta *et al.*, 2001).

TABLE 1 Crop coefficients for mature apricot trees (soil was not tilled, trees were drip irrigated).

Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
0.4	0.7	0.8	1.0	1.0	0.85	0.7	0.5

WATER PRODUCTION FUNCTION

Based on results from published experiments relating yield to different irrigation regimes for apricots (Torrecillas *et al.*, 2000 and Perez-Pastor *et al.*, 2009) and from our own experience, an SDI programme has been outlined in Table 2 and an RDI strategy in Figure 5. This programme reduces the seasonal applied water by 20 percent relative to a fully irrigated orchard, will decrease irrigation water use without impacting negatively on yield.

TABLE 2 Recommended crop coefficients for a SDI strategy. Data obtained in Southern Italy (40 N; 16°38′ E; C. Xiloyannis, unpublished).

Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
0.4	0.5	0.6	0.7	0.85	0.5	0.5	0.5

SUGGESTED RDI REGIMES

As described above, apricot trees have some positive characteristics that help them face water restrictions and these can be used in RDI strategies. Moreover, shoot and fruit growth are separated (Figure 4) in late cultivars. As for peach, this is highly relevant when adopting deficit irrigation strategies devoted to the control of vegetation without affecting fruit growth. However, the opportunity to reduce water application in Stage II is limited for apricots, in particular in early cultivars where the duration of Stage II is quite limited.

A regulated deficit irrigation strategy should avoid water deficits during the critical period of high sensitivity to water stress (i.e. the whole fruit growth and the early postharvest period, around 30 days after harvest). After this period, based on the amount of water available in the soil volume explored by roots, irrigation could start being reduced just after harvest. In this way, the trees deplete water from the deep soil layers and gradually adjust their water status without affecting bud induction and differentiation processes. It is recommended that in the early 30-day period after harvest, the predawn Ψ_{leaf} should not be below -0.7 MPa. After this period, a reduction of about 50 percent of the ET_c is a practicable deficit irrigation strategy (Figure 5). To avoid excessive tree water stress it is desirable to monitor tree water status (minimum predawn Ψ_{leaf} should not be below a threshold of -1.30 MPa, which corresponds

FIGURE 4 Apricot (cv. Búlida) shoot length and fruit diameter as % of their final value (Torrecillas *et al.* 2000).

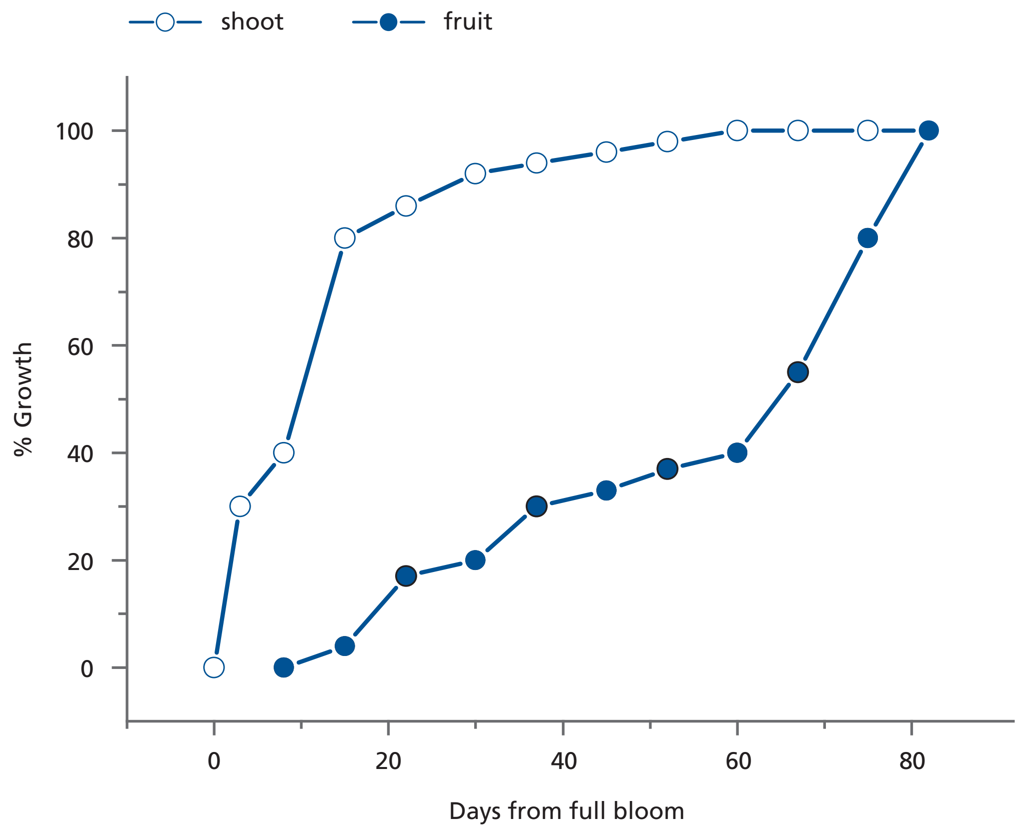
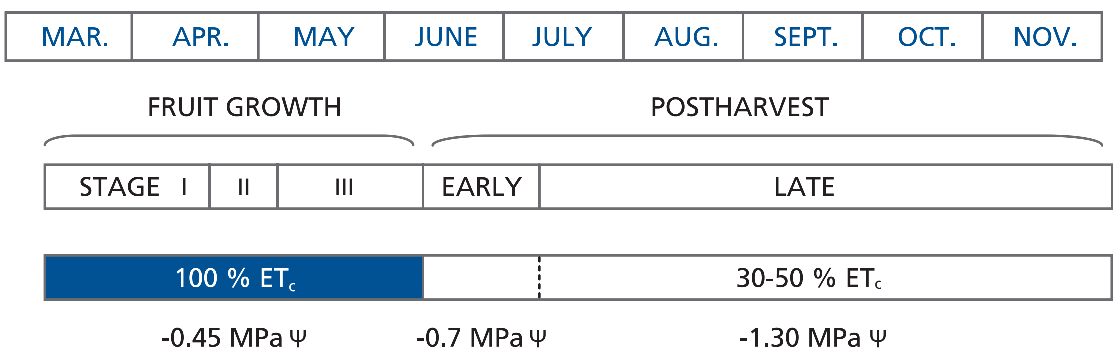


FIGURE 5 Schematic representation of the recommended RDI strategy during the season. A reduction down to 30-50 percent ET_c (depending on soil water holding capacity) should be evaluated according to the water availability in the soil explored by roots. Ψ indicates the minimum predawn leaf water potential below which there is risk of yield reduction. The developmental pattern is that of an early ripening cultivar.



to a midday value varying between -2.5 to 3.0 MPa). The percentage of ET_c reduction should be carefully evaluated according to the available water in the root zones, which is affected by soil hydraulic characteristics and rootstocks. Table 2 presents recommended K_c values for an SDI strategy tested in Southern Italy. This strategy was tested for three years in a drip irrigated apricot orchard (cv. S.Castrese, Palmette 740 plant/ha) grown in an area with 980 mm ET_o from April to September. About 5 600 m^3/ha were supplied during the whole season. Long-term application of the SDI strategy should be evaluated locally and season-by-season. The sustainability of the orchard under the RDI/SDI regime in the long run depends on how effectively winter rainfall refills the soil volume explored by roots.

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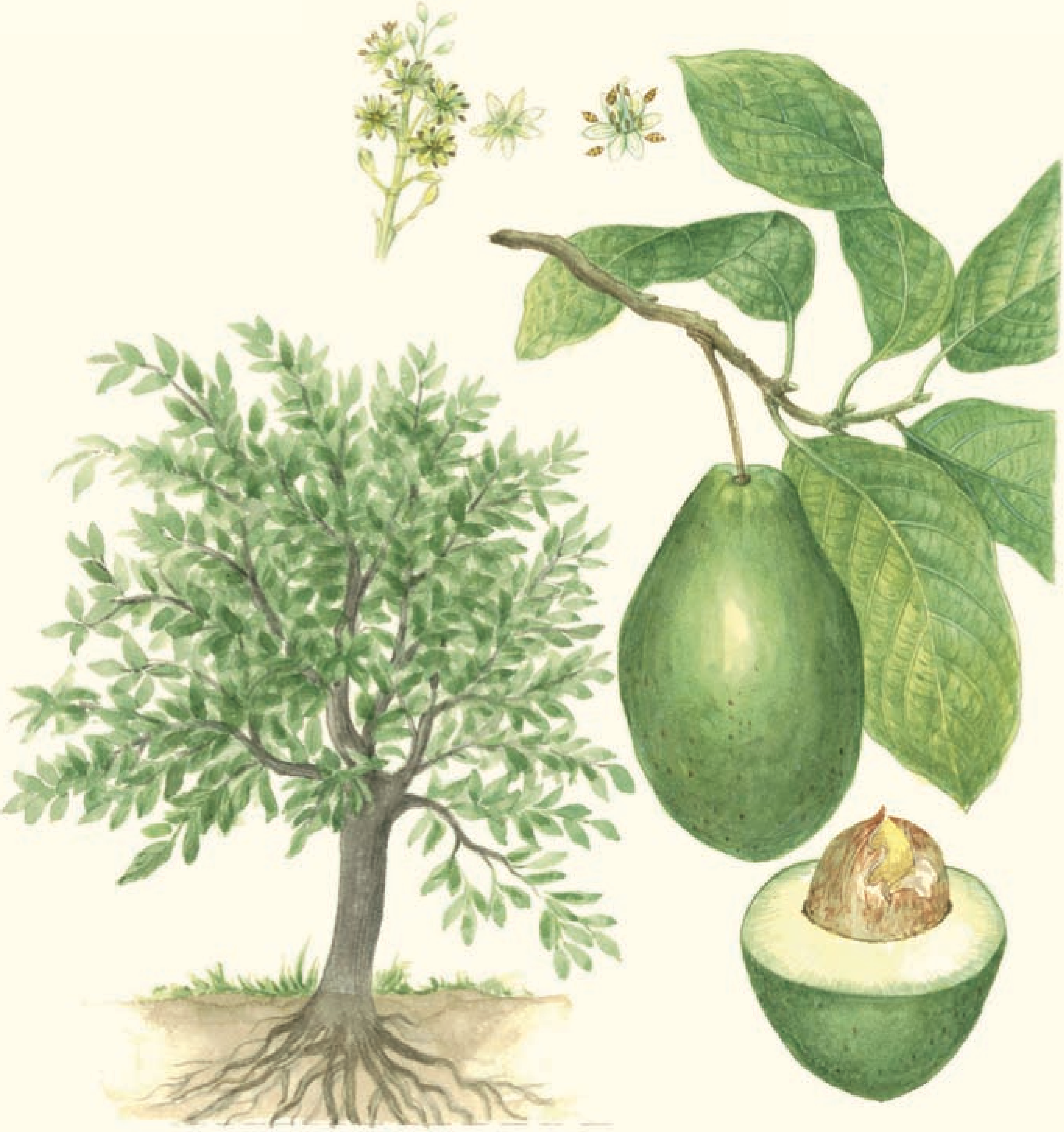

Avocado

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Avocado

INTRODUCTION AND BACKGROUND

A**vocado** *(Persea americana* Mill*)* is a tree that has been known for centuries in areas of Central and South America, but only recently has become a commercial crop. In 2009, there were over 430 000 ha of commercial plantings with a world average yield of 8.8 tonne/ha, with Mexico (100 000 ha), Chile and the United States as the main producing countries. Other countries with significant exports are South Africa, Spain, and Israel (FAO, 2011). Figure 1 presents the production trends of the main producing countries. Avocado fruit yields are comparatively low relative to those of other fruit trees because of the high energy requirements of producing fruit, because of both its large seed size and its composition, rich in oil (Wolstenholme, 1986). Average yields of the variety Hass, one of the most popular commercial cultivars, are around 12 tonne/ha, but may reach 25 tonne/ha in very good years, with the fruit containing up to 20 percent oil. There are three avocado races: Mexican, Guatemalan and West Indies, with different sensitivity in their responses to the environment. Avocadoes have evolved in volcanic soils that have very low bulk density, acid pH, and very high pore volume. It is therefore not surprising that this species is extremely sensitive to waterlogging and does not do well in heavy soils with aeration problems. Planting on berms or ridges is customary when feasible to improve drainage around the areas close to the trunk base. For this reason, sandy rather than heavy soils are preferred for planting avocados. Avocados are also very sensitive to low temperatures, and even light frosts (temperatures below -1 to -2 °C) may cause significant damage. Among the three races, the Mexican is most tolerant to cold temperatures, as it originated in the cool highlands of Mexico.

GROWTH AND DEVELOPMENT IN RELATION TO YIELD DETERMINATION.

Vegetative growth occurs in two flushes; a strong one in spring and a weaker one in the autumn. Flowering occurs in spring (between early October and mid-November in the Southern Hemisphere) and is followed by fruit set. Heavy fruit drop takes place during the first 3-4 weeks after fruit set, at the end of spring, leading to a first adjustment in fruit number, which is further adjusted with an additional fruit drop period, which takes place around the end of summer, when fruit size is between 10-40 percent of mature size. Figure 2 depicts the developmental stages of the cultivar Hass in Central Chile showing also two root growth periods occurring in early summer and at the beginning of fall.

FIGURE 1 Production trends for avocado in the principal countries (FAO, 2011).

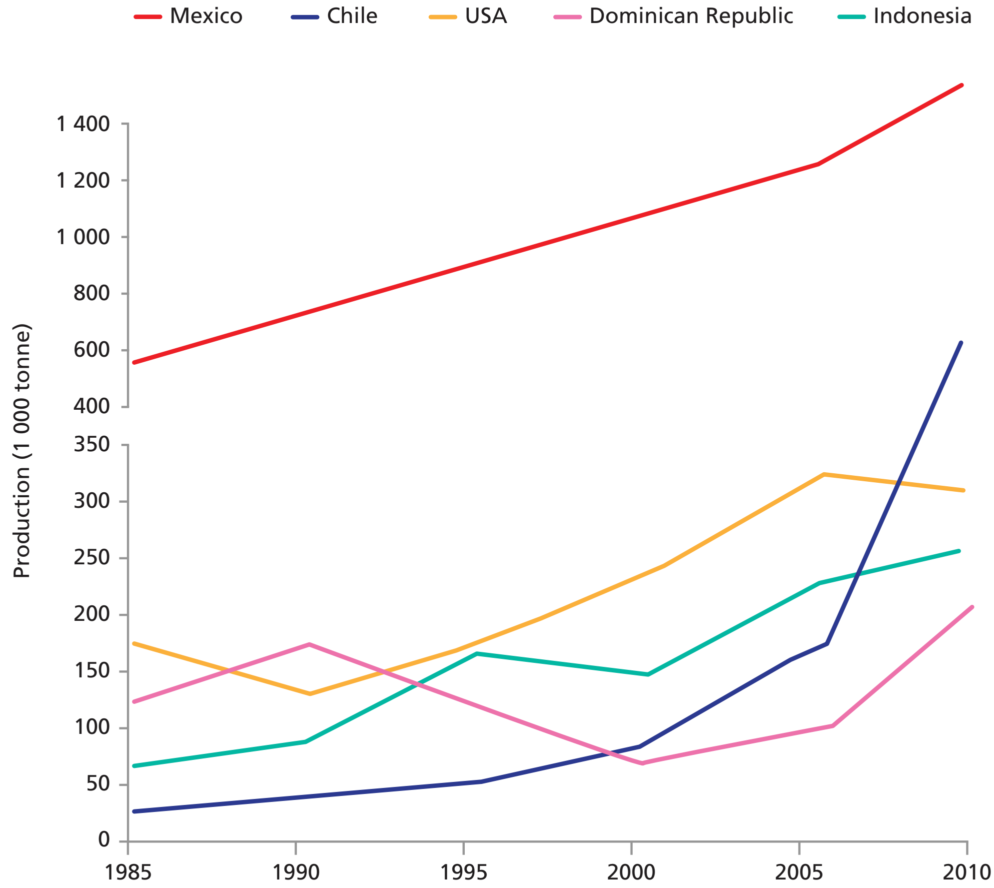
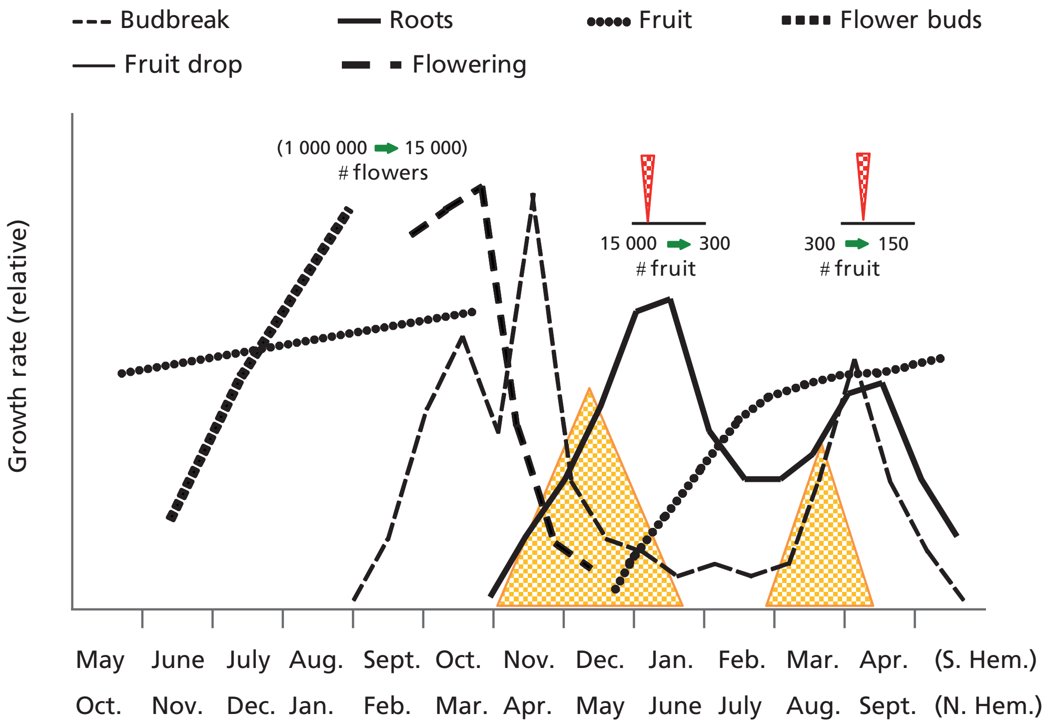


FIGURE 2 Developmental patterns of avocado (cv. Hass) as observed in the Central Valley of Chile.

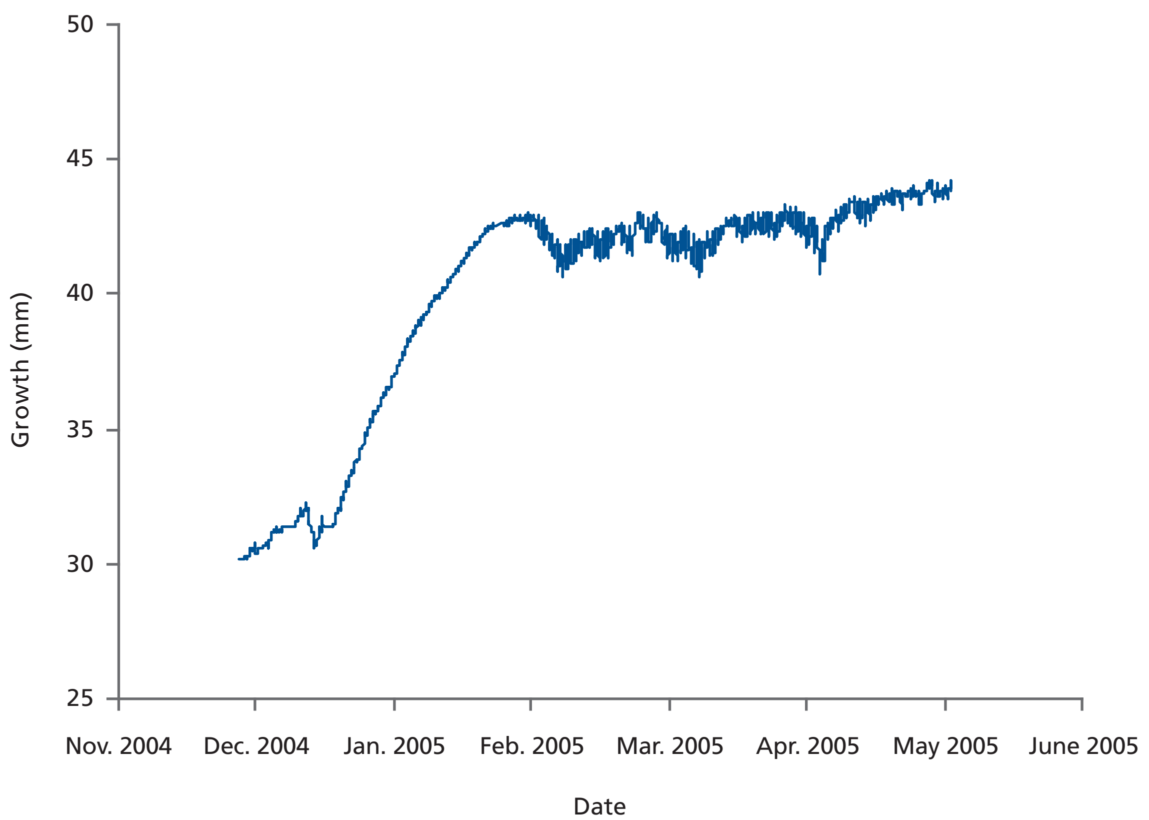


The most critical developmental period for avocado take place between late spring and early summer. At this time, there is vigorous shoot and root growth, the fruit are set and their final size is defined. Environmental stress could negatively affect fruit set, final fruit numbers and fruit size. It may induce some fruit internal defects as well. During that period, evaporative demand is relatively low and variable, and thus it is possible this inadequate irrigation practices cause water deficit or excess. Even though fruit expansion rates are quite high during a short time period, as shown in Figure 3, fruit growth and development takes a long time, from spring to fall. Fruit shape is also affected by temperature; it becomes more elongated with lower average temperatures.

RESPONSES TO WATER DEFICITS

Avocado trees are quite sensitive to water deficits; it has been determined that their inflorescences are more sensitive to water deficits than the surrounding leaves. The sensitivity of fruit set to water deficits is also quite high, and fruit drop may occur at any time between fruit set and about 50 percent of final size, if water stress is induced by lack of irrigation. Fruit size is affected by water deficits during its growth period that lasts about four months after fruit set. Water stress during fruit development in the later stages of fruit growth negatively affects the quality of mature fruit. When trees are frequently irrigated calcium concentration in the fruit increases and this seems to prevent several fruit physiological disorders.

FIGURE 3 Expansive growth of an avocado fruit of the cv. Hass, monitored continuously in central Chile.



Stem-water potential (SWP) values at midday of well-watered trees on a typical summer day oscillate between 0.5 MPa and -0.6 MPa. These values should be the reference threshold levels of SWP. Mild water deficits induce midday SWP values between -0.6 and -1.0 MPa. More severe water deficits are indicated by SWP levels below -1.0 MPa reaching down to -2.0 to -3.0 MPa. Stomatal conductance values are somewhat above those of citrus leaves but below the values observed in deciduous orchards. Average leaf conductance values around 0.3 cm/s have been measured for well-watered trees (Ferreyra *et al.*, 2007). Excess water in poorly drained soils does affect avocado tree water relations and, therefore, its overall performance. Low oxygen levels in the soil reduce leaf expansion rates as well as root growth and, if prolonged, may cause root necrosis and leaf abscission. Several studies measuring the oxygen diffusion rate have shown that avocado roots are extremely sensitive to anaerobic conditions. While most species vegetate well in soils, where just 10 percent of the pore volume is air filled, avocado roots seem to require a minimum of about 30 percent pore volume air filled for optimum performance (Ferreyra and Selles, 2007). In addition to the aeration problem, there is a pathogen, *Phytophthora cinamomi*, which thrives in waterlogged soils and can kill avocado trees upon infection (Stolzy *et al.*, 1967).

Avocado trees are also quite sensitive to salinity, the Mexican race being the most sensitive and the West Indian, the least. While sodium is excluded by the roots up to some level, chloride moves freely along with the transpirational stream and causes tip burn and leaf abscission.

WATER REQUIREMENTS

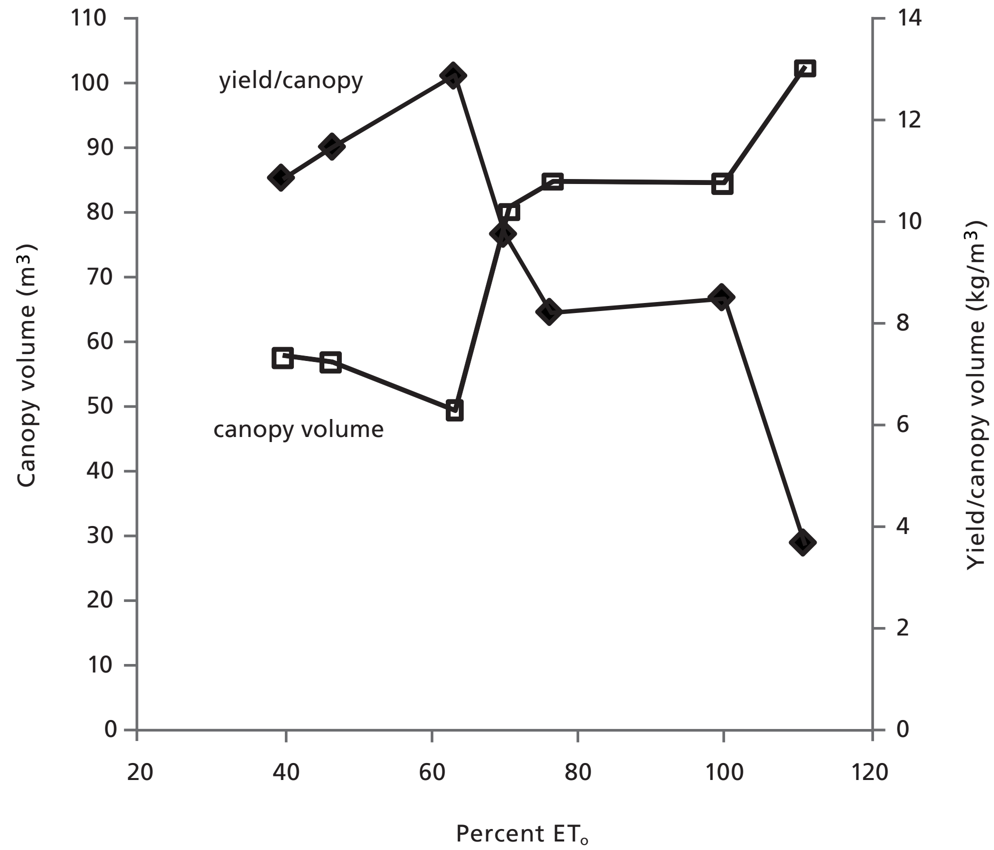
Avocado is an evergreen tree that follows the evaporative demand of the environment. Studies in Chile and in California indicate that an average crop coefficient (K_c) between 0.7 and 0.72 throughout the year adequately represents the ET_c of avocado. One additional study in California has suggested a somewhat lower K_c of 0.64. However, there are trade-offs between irrigation amounts, canopy size and production efficiency (Faber *et al.*, 1995) Figure 4 shows that the canopy size increases and yield per unit canopy volume drops as the fraction of ET_c increases from 60 to 115 percent of the requirements. Canopy size is therefore the determining factor of actual ET_c , but yields were maximized in the study when a K_c of 0.64 was used throughout the year (Faber *et al.*, 1995).

Part of the avocado water requirements are met by rainfall; in central Chile, annual gross irrigation needs vary between 800-900 mm, while in the drier areas of Southern California it may reach values of over 1 000 mm. To determine the actual irrigation needs in an area, there would be a need to carry out a water budget that takes into account the effective rainfall and the actual ET_c.

IRRIGATION SCHEDULING AND DEFICIT IRRIGATION

The extreme sensitivity to water deficits and water excess indicate that irrigation scheduling in avocado must focus on maintaining adequate aeration at the same time that tree water deficits are avoided (Lahav and Kalmar, 1983). In this situation, irrigation frequency is an important issue; in coarse-textured, well-drained soils, daily applications using drip or micro-sprinklers are appropriate. However, in heavier-textured soils that could suffer anaerobic

FIGURE 4 Effects of the level of applied water expressed as a fraction of reference ET (ET_o) on canopy volume and on the yield canopy volume ratio.



conditions, irrigating every 2-3 days is more desirable. Experiments in Chile have shown that allowing 50 to 60 percent soil water depletion between irrigation applications (every 5-6 days) did not affect yield and fruit size as compared to more frequent applications (Ferreyra, *et al.*, 2006). Irrigation frequencies that deplete about 25-30 percent of the tree-water reservoir are adequate for most soils as a compromise to maintain both adequate water and oxygen supply to the avocado root system. Under drip irrigation, it is important to be able to leach the excess salts out of the potential root zone, and to wet enough soil volume particularly in shallow, coarse-textured soils. Fruit oil content is an important quality feature that is negatively affected by inadequate irrigation.

All experimental evidence so far indicates that RDI is not a recommendable practice for irrigation of avocadoes, because of the high sensitivity of commercial yields to water deficits during most of the irrigation season. On the other hand, excess irrigation is highly detrimental, given the sensitivity to water logging and the high risks of fungal disease infection. Best irrigation practices for avocado should be based on supplying ET_c at optimal intervals that both prevent tree water deficits and supply adequate oxygen to the root system.

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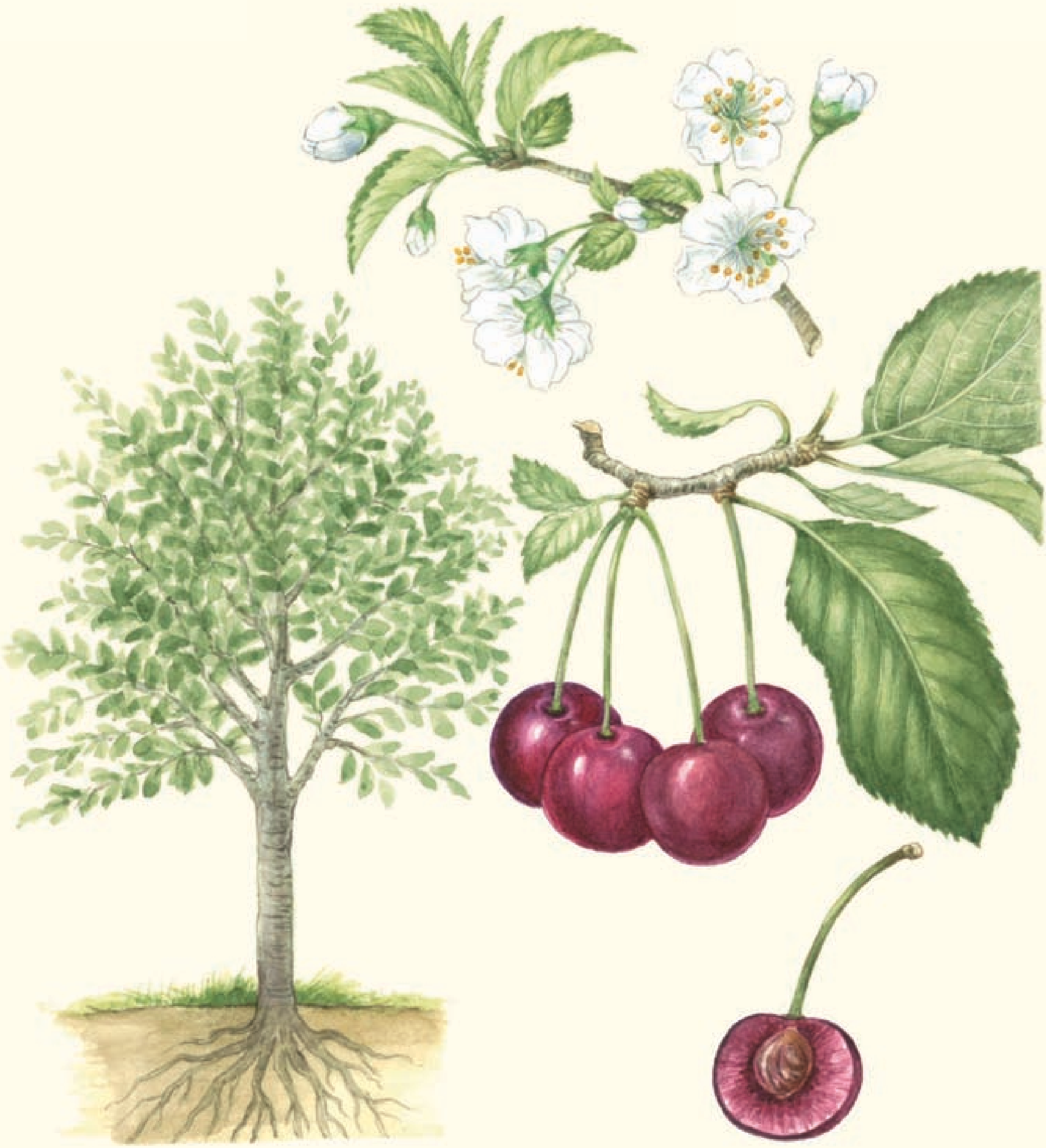

Sweet Cherry

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Sweet cherry

INTRODUCTION AND BACKGROUND

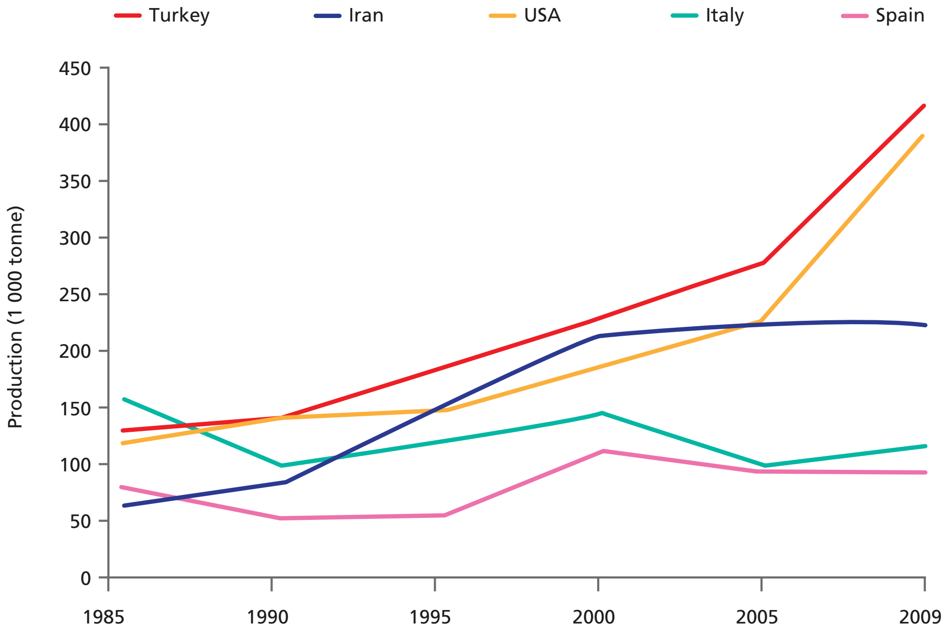
Sweet cherry *(Prunus avium* L.*)*, contribute modestly to the global economy of deciduous fruit tree species. However cherry production can be crucial at local level in regions specialized for cherry growing, while for other areas it can become a good alternative whenever the market for the main fruit trees, such as apple, peach, and pears slows down. In 2009, there were 381 000 ha with an average world yield of 5.8 tonne/ha (FAO, 2011). Figure 1 presents the production trends for the principal countries.

Foliage development of cherries follows a pattern similar to that described in the peach chapter. Cherry flowers develop in clusters from individual buds. Each bud bears two-to-five flowers. These buds can be borne laterally in individual buds or can be grouped in short spurs on two-year old twigs. Although cherry flowers are monopistil, in very hot summers many form two pistils that result in double fruit. It has been argued that water stress could have a role in helping the formation of undesired double fruit, as it occurs in peaches, but there is little evidence for this in sweet cherries (Beppu and Kataoka, 1999). In addition, air temperatures also affect fruit shape, becoming more irregular at high air temperatures. Canopies can be cooled by using overhead sprinkler irrigation. The majority of commercial sweet cherry cultivars are self-sterile and thus they require the use of pollinizers. Cherry trees are very vigorous and annual shoot extension rates can surpass 1 m when they are young. Cherry trees have an upright growth habit and may need the use of adequate rootstocks to help controlling vigour and induce early appearance of reproductive buds. Vigour control is commonly managed with growth regulators.

STAGES OF DEVELOPMENT

Cherry flower buds, initiate just before the end of the shoot enlargement phase, and will continue to form and develop throughout postharvest (Flore, 1994). Next spring cherry flowers will open before leaf appearance. The reproductive growth can be divided into approximately three growth stages; similar to the case of early maturing peach fruit. Stage I comprises the first month after full bloom and it is characterized by a rapid increase of fruit volume which is mainly produced by cell division (Figure 2). The extent of the activity in cell division will have a major contribution to fruit final size. Stage II corresponds to the pit hardening phase and it can coincide with a slowing of the fruit growth rate (Figure 2). Finally, Stage III takes place around 20 days

FIGURE 1 Production trends for sweet cherries in the principal countries (FAO, 2011).

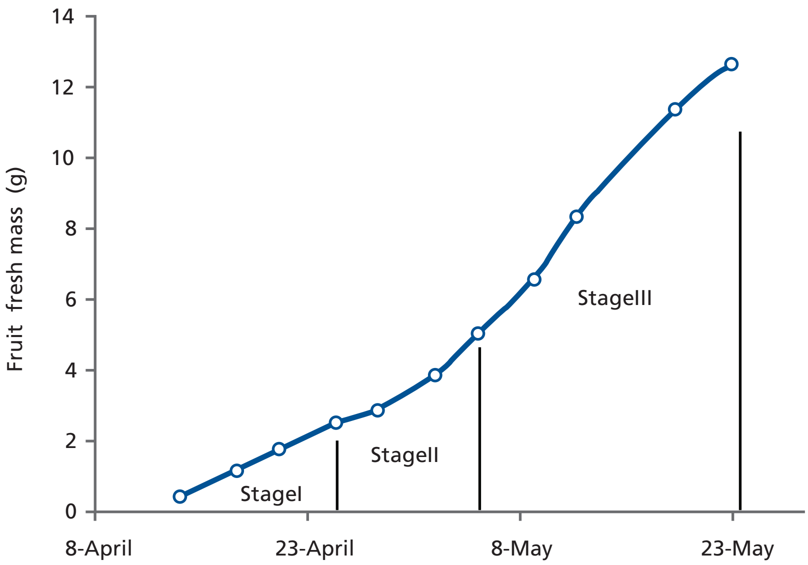


before maturation and leads to a rapid increase in fruit size (Figure 2). This is a phase of rapid expansive growth. All three stages may take place in less than three months depending on the cultivar used and the temperature regime (growing degree days) of the site.

RESPONSES TO WATER DEFICITS

The timing of water stress is important for cherry. Stages I and III are short and very sensitive to water stress. Stage II can be even shorter and usually overlaps with Stages I and III; for this reason

FIGURE 2 Daily patterns of mean individual Summit cherry fresh mass grown in fully irrigated trees. Fruit growth stages are signalled in-between vertical lines.



water stress should not be imposed on any of the fruit growth stages. However, irrigation can be reduced under certain conditions i.e. deep soils and low evaporimetric demand, without inducing plant water stress. The postharvest phase is the period for accumulation of reserves. Fruit set in the following spring will be affected by the level of carbohydrate reserves, which have been accumulated during the previous growing season, and more so if flower buds developed earlier than vegetative buds as for cherries. Sweet cherry trees do not grow well without irrigation in areas having dry and warm seasons (Proebsting *et al.*, 1981). Providing accurate information on how to irrigate cherry trees requires a good assessment of plant water status. The standard method of assessing plant water status in cherry orchards is to measure midday stem-water potential (SWP). Air vapour pressure deficit (VPD) has a definite impact on the measures of SWP in cherry trees and VPD reference lines need to be developed to account for this effect. In cherry, Ψstem values below -1.0 MPa during midseason are likely to be indicative of water stress conditions (Marsal, 2009 and Marsal, 2010). Therefore, the level of water stress in a tree having a SWP lower than -1.0 MPa would depend on the prevailing VPD conditions. For instance, early season (from late April until the end of May, Northern Hemisphere), with typically low VPD (< 1.5 kPa) and a canopy still under development, a non-water stressed cherry tree would have a Ψstem less than -0.7 MPa (Marsal, 2009 and Marsal, 2010). The level of SWP is related to tree transpiration because, as water stress increases leaf conductance to water vapour decreases. The response of leaf conductance to SWP for cherry trees follows a standard exponential function (Figure 3); however the response of tree transpiration to midday SWP has not yet been described. Incipient leaf wilting in cherry trees can be observed in the field at a SWP of -1.8 MPa. At this value, stomata are mostly closed and vegetative growth hastened (Figure 3 – midseason conditions). However, leaf wilting can be more clearly observed at SWP values below -2.2 MPa.

FIGURE 3 Relationship between midday stem-water potential and midday leaf conductance in two different times of its seasonal development (at harvest and at postharvest early September) in 'Summit' sweet cherry, obtained in different irrigation treatments.

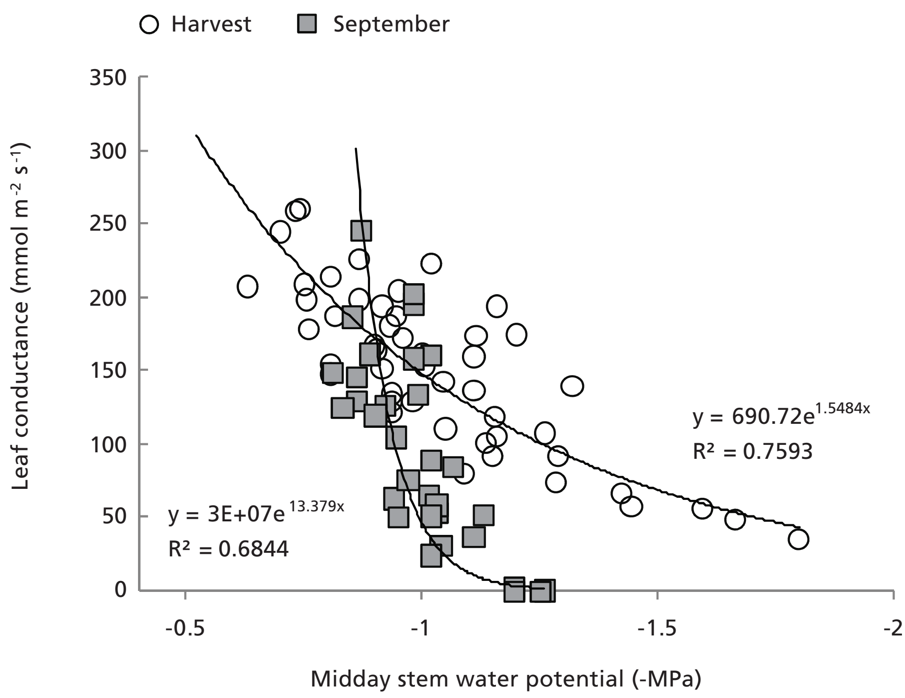


FIGURE 4 Daily patterns of sunlit leaf net assimilation rate measured after harvest with IRGA in Summit sweet cherry trees. Trees were fully irrigated throughout the season.

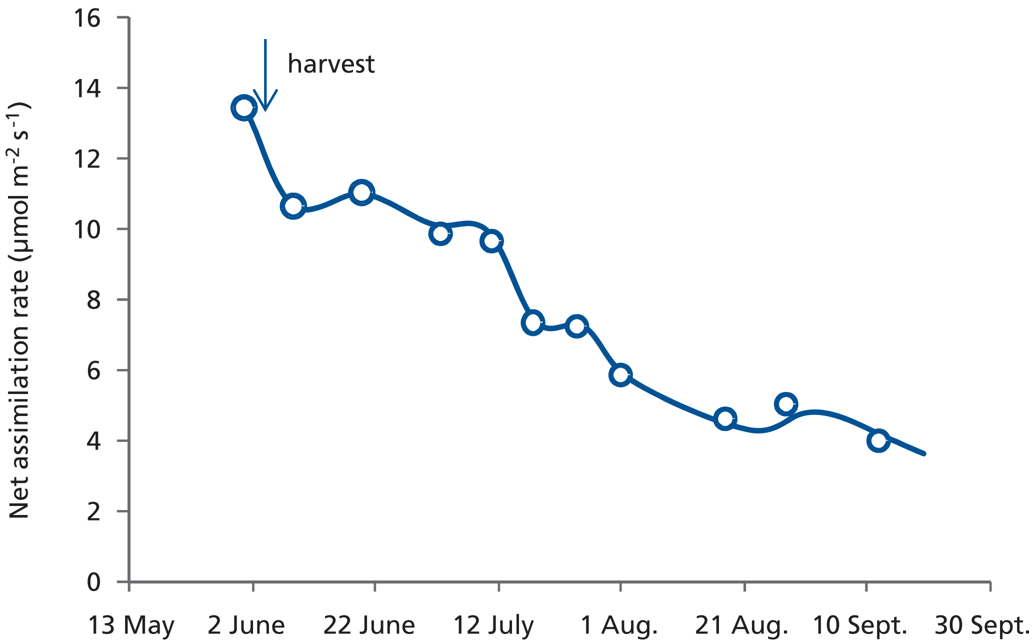
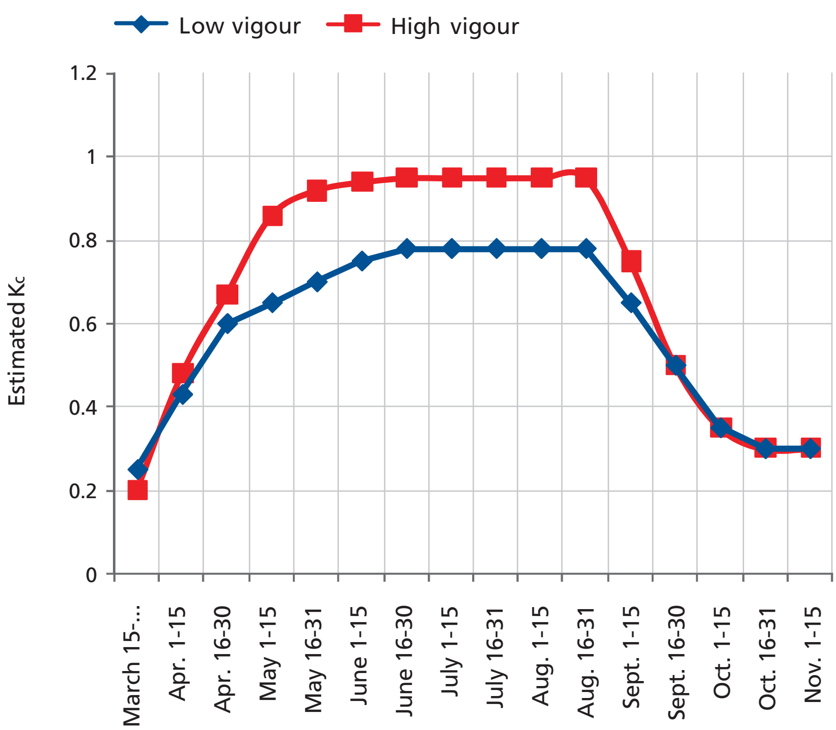


FIGURE 5 Estimated crop coefficients for mature sweet cherry trees grown in a vase training system under two different growing conditions (high vigour in squares and low vigour in rhomboids). The midday intercepted radiation for the high vigour and low vigour orchards during midseason was 0.54 and 0.45, respectively.



Under certain growing conditions, stomata remain slightly closed at the end of the postharvest season, even when the trees are not water stressed (Figure 3 – September conditions). This has been found in cherry orchards growing under warm Mediterranean conditions. Since the cherry market in these regions sets pressure for the use of early ripening cultivars, the postharvest period may last more than four months. During this period, little growth is being accomplished because tree growth is checked by the application of growth regulators. After harvest, leaf net photosynthetic rates tend to decrease with time (Figure 4). Reductions in photosynthesis usually come with reductions in stomata aperture and consequently, the transpiration also declines with time. This is referred in the physiology literature as photosynthetic down-regulation.

WATER USE

Although some preliminary work on modelling cherry tree transpiration has been done recently (Antunez, 2006), specific reports on measurements of cherry ET_c or K_c values are lacking in the literature. Cherry irrigation requirements could be approximated by using the information developed for peach trees (see Peach Section) where the K_c is related to tree intercepted radiation at midday. An example of the seasonal evolution of K_c is provided in Figure 5 where cherry tree intercepted radiation was measured every two weeks until mid-August. A steady decrease in K_c is assumed after mid-August. This K_c decline is due to a leaf die-back process, but also to the previously referred effect of the down-regulation of photosynthesis, which may already apparent by late July (Figure 5). Two different tree vigour conditions are considered in Figure 5, and the effects on crop intercepted radiation and estimated K_c is evident. Low vigour conditions had noticeable lower K_c, resulting in a 18 percent reduction in annual water requirements for the conditions in the Ebro basin, Spain (Marsal, 2010). This emphasizes the need to adjust the K_c values to the specific orchard conditions.

SUGGESTED RDI REGIMES

The application of RDI is currently widespread in some regions along with the use of growth regulators. However RDI before harvest is rarely used because besides reducing fruit growth and fruit final size (Werenfels, 1967), it can also increase cracking if stress is relieved during ripening (Sekse, 1995). RDI is more commonly applied after harvest. The reason for the grower acceptance of using postharvest RDI is because it decreases tree internal shading and controls excessive vigour. However, deficit irrigation is often applied after harvest in the absence of research-based recommendations. For instance, in certain areas irrigation is commonly reduced until visual leaf wilting without being aware of possible carryover effects during the following season. From the few research reports published it can be inferred that, under certain conditions, postharvest water deficits can negatively affect cherry quality the following season, with excessive water stress exacerbating this problem. A study on postharvest RDI in New Star sweet cherry grown in the semi-arid climate of Catalonia, Spain found a significant linear relationship between reduction in cherry firmness and soluble solids with the average midday stem-water potential experienced the previous postharvest season (Marsal, 2009). Another issue related to the use of postharvest RDI is the possibility of applying excessive water stress and negatively influencing fruit set and crop load in the next season, as it has been reported for peach and almond. In a recent study on Summit cherry, a postharvest RDI treatment, receiving 50 percent of the water given to a Control treatment, reduced fruit set and crop load in the following season (Marsal, 2010). However, the realization of possible yield reductions in the next season after a RDI postharvest treatment will depend on whether cherry thinning is being used to maintain fruit size (Marsal, 2010). Nevertheless, if water stress during postharvest is maintained above -1.5 MPa in midday stem-water potential, large savings of up to 40 percent of the water used in a fully irrigated control during postharvest can be achieved without noticeable negative impact on fruit yield and quality. The avoidance of water stress, more severe than a certain level (i.e. -1.5 MPa), implies that irrigation reduction must be adjusted with time and a fixed irrigation rate should only be maintained for a certain period to avoid surpassing such tree water status threshold. For this reason significant irrigation reductions during postharvest have to be applied cautiously. Irrigation could also be reduced during postharvest at lower rates (i.e. 80 percent full irrigation). The use of 80 percent full irrigation during postharvest produced water savings up to 15 percent of annual applied water with no detrimental effects on fruit yield and quality (Table 1) (Marsal, 2009 and Marsal, 2010) although the research indicated that cherry quality and yield responses to RDI are cultivar dependent. Therefore more research is needed before reliable assessments can be made for each specific growing condition.

TABLE 1 Suggested Postharvest RDI strategies for different available water supply scenarios from 690 to 430 mm. Weather data corresponds to the Ebro valley (Northeast Spain) and K_c corresponds to those presented in Figure 2 for high vigour growing conditions.

	Potential ET_c	Water req.	RDI-Postharvest (580 mm)		RDI-Postharvest (430 mm)	
	(mm)	(mm)	Irrigation rate (%)	(mm)	Irrigation rate (%)	(mm)
March 15-30	9	10	100	10	100	10
Apr. 1-15	24	26	100	26	100	26
Apr. 16-30	34	31	100	31	100	31
May 1-15	50	42	100	42	100	42
May 16-31	49	40	100	40	100	40
June 1-15	66	72	80	58	50	36
June 16-30	80	88	80	70	50	44
July 1-15	76	78	80	62	50	39
July 16-31	81	89	80	71	50	44
Aug. 1-15	70	77	80	62	50	39
Aug. 16-31	68	75	80	60	65	49
Sept. 1-15	38	42	80	34	50	21
Sept. 16-30	23	25	80	20	50	12
Oct. 1-15	11	0	80	0	50	0
Oct. 16-31	7	0	80	0	50	0
Nov. 1-15	5	0	80	0	50	0
Total	**690**	**696**		**587**		**434**

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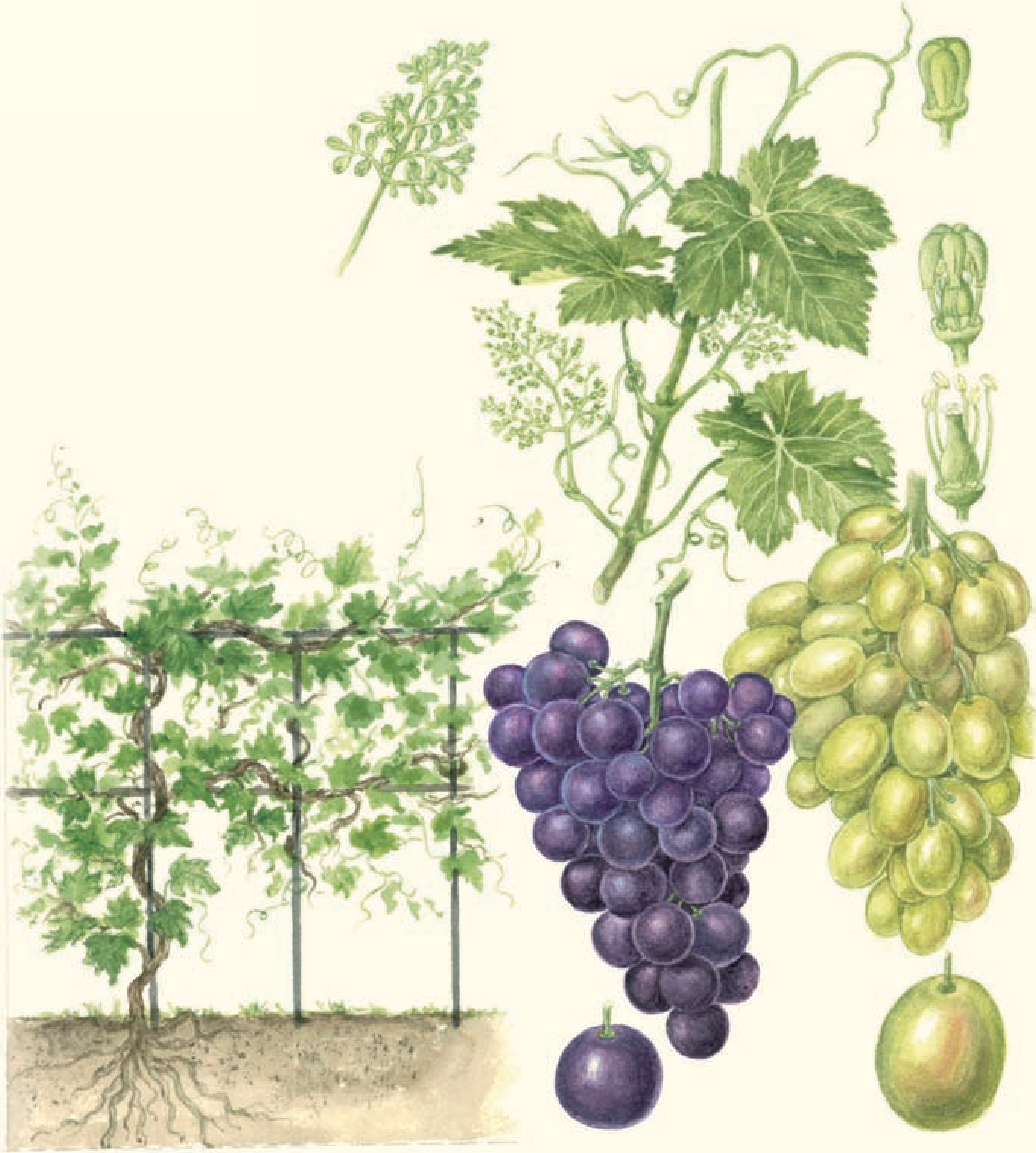

Grapevine

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Grapevine

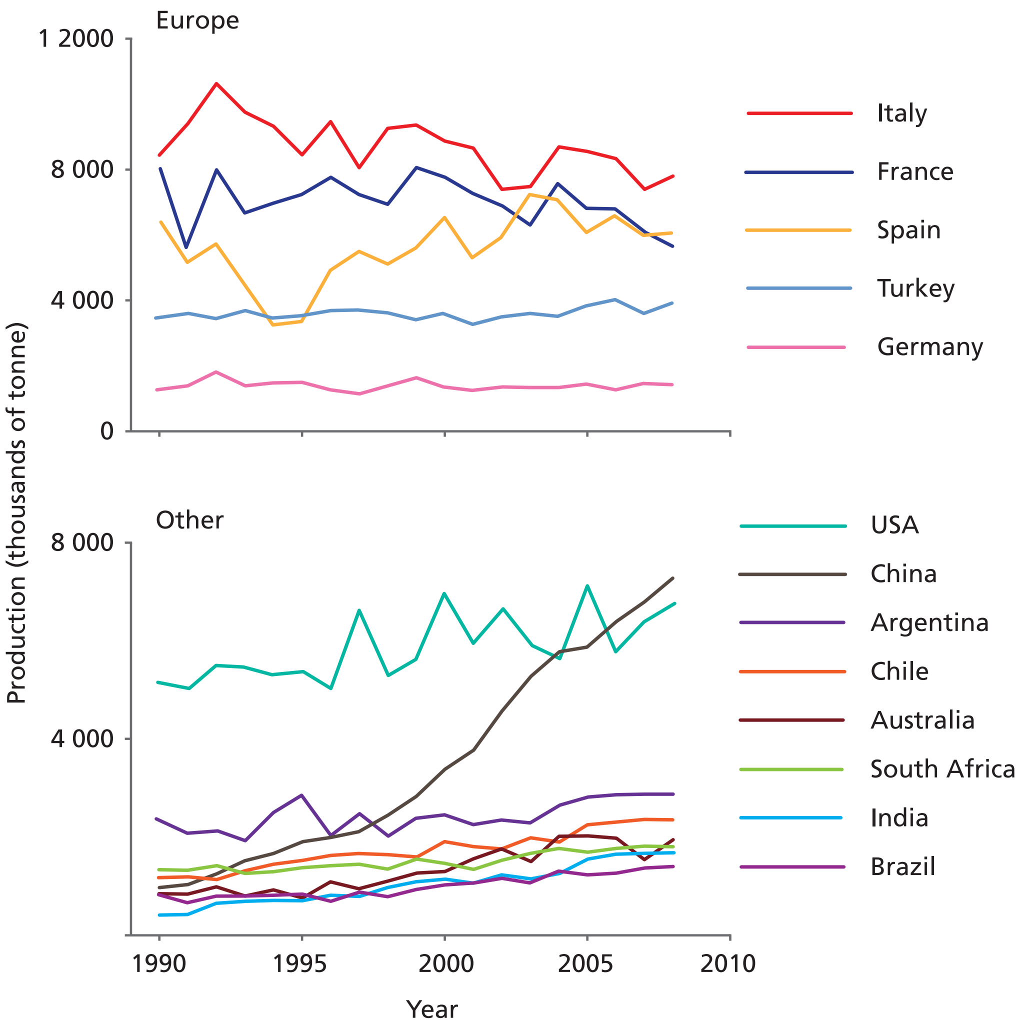
INTRODUCTION AND BACKGROUND

Grapevine is a long-lived deciduous crop traditionally grown in a latitudinal range between 30° and 50°. The geographical range of wine grapes includes the traditional European countries Italy, France and Spain that account for most of world production, and other countries where the industry has achieved different degrees of maturity (Figure 1). The crop is expanding into new areas in countries with an incipient industry; in 2000, Denmark was accepted as a commercial wine producing nation within the European Union and the Association of Danish Winegrowers had 1 400 members in 2009 (Bentzen and Smith, 2009). Tonietto and Carbonneau (2004) characterized worldwide macroclimates for viticulture using three indices: soil water balance over the growing cycle, solar radiation and temperature conditions, and night temperature during maturation relative to variety requirements, vintage and wine quality.

Profitability of the wine industry is related to both production volume and value per unit volume. The relative contribution of these two factors ranges from enterprises specializing in a high-volume approach to those targeting low-volume, high-value product. Trade-offs between high yield and berry traits related to wine quality are not universal but are common and may constrain the dual maximization of volume and value per unit volume of production. The trade-off between yield and quality underlies regulations in some European countries where no irrigation is allowed for quality wine production. Accepting that wines attracting higher prices are often from vines producing low to moderate yields, the critical question from an irrigation viewpoint is how to manage irrigation to capture the benefit of high yield while achieving a level of quality that maximizes economic returns.

Thus, whereas the core of the grapevine crop remains in the temperate latitudinal band, there is an increasing diversity of environments that, together with diverse production objectives and potential trade-offs dictate contrasting water-management practices in the vineyard. Additionally, the grape and wine industries operate in a global context of competing agricultural and non-agricultural uses of scarce resources – chiefly land, water, and energy – increasing environmental concerns, and shifts in climates and markets.

FIGURE 1 Grape production between 1990 and 2008 (FAO, 2011).



STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

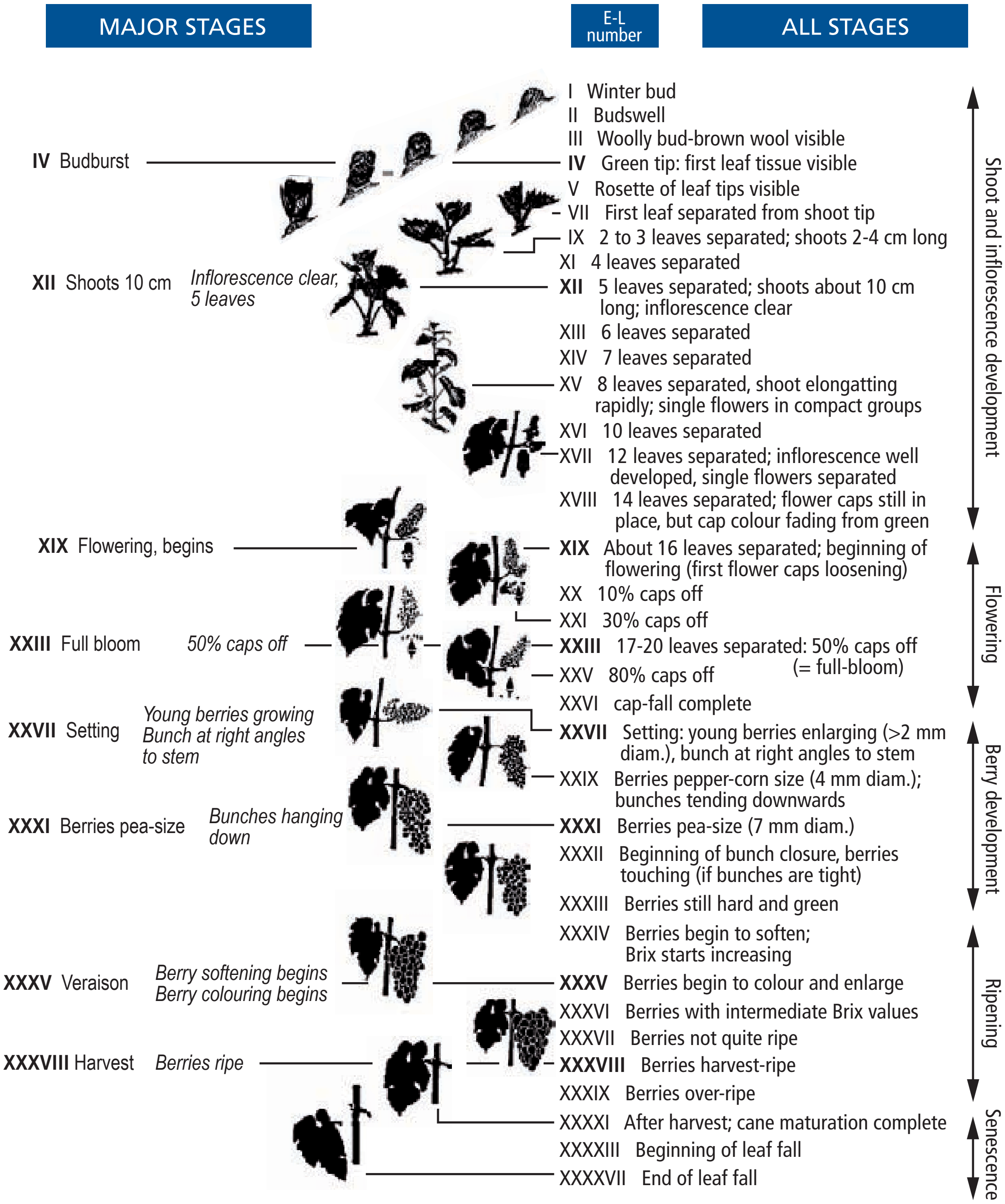
Overview

The annual cycle of grapevine in temperate and cool environments includes a dormancy phase and a phase of active vegetative and reproductive development and growth. In tropical environments, vine physiological activity is continuous during the year. Figure 2 shows a scale accounting for phenological stages in temperate environments and Table 1 illustrates the range of key vegetative and reproductive components of grapevines in vineyards with contrasting yield targets.

After an overwintering period, when vegetative and reproductive buds remain dormant, visible leaf tissue marks the beginning of budburst (Stage IV in Figure 2). Early shoot growth depends on plant reserves and is initially slow; it then accelerates in late spring. Parallel to root and vegetative shoot growth, two important reproductive processes take place: (a) inflorescence primordia initiated in the previous season resume growth, branching, branch elongation and flower formation, and (b) a new set of reproductive buds is induced and starts differentiation that will be completed in the following season (Dunn, 2005). Bunch number is generally the largest source of seasonal and site-related variation in grapevine yield (Tables 1 and 3).

Current season inflorescences become visible several weeks after budburst. Flower cap fall and stamen release marks the full bloom stage (Stage 23 in Figure 2). Berries per bunch, the second yield component, depend on number of flowers and berry set, which may be particularly affected in some particular combinations of sites, seasons and cultivars, e.g. Chardonnay in cool conditions. As in most flowering plants, however, only a fraction of flowers set fruit, typically for grapevine this is 20-50 percent.

FIGURE 2 Major stages in the modified Eichhorn and Lorenz (E-L) phenological scale (from Coombe 1995).



Modified from Eich horn and Lorenz 1977 by B.G. Coombe

TABLE 1 Key vegetative and reproductive components in low and high-yielding vineyards (*Pearce and Coombe,* 2005).

Component	Low	High
Yield (kg m^{-2})	0.20	5.0
Equivalent volume of table wine (litre m^{-2})	0.12	3.0
Pruning weight (kg m^{-2})	0.03	1.0
Leaf area index (m^2 m^{-2})	0.50	5.0
Number of nodes (m^{-2})	3	30
Number of shoots (m^{-2})	2.5	25
Number of bunches (m^{-2})	5	50

Berry growth has a characteristic double-sigmoidal pattern; it is dominated by cell division in the first two weeks after flowering and by cell expansion afterwards. The first sigmoidal trajectory reaches a plateau in synchrony with full seed size in seeded varieties. After an intervening lag-phase, the onset of the second sigmoidal phase is characterized by berry softening, accumulation of sugars, decline in acid concentration and accumulation of pigments in the skin of coloured varieties. This stage is called veraison (Stage 35 in Figure 2) and is very responsive to environmental factors. For example in physically constrained berries, the threshold cell turgor pressure ≈ 0.1 MPa associated with veraison under the experimental conditions of Matthews *et al.* (2009) was delayed by two weeks in relation to controls, and a similar delay was recorded for the onset of sugar accumulation. The second sigmoidal stage ends in a plateau corresponding to variety- and environment-specific maximum berry size. Varieties like Shiraz, which often exhibit substantial berry dehydration late in the season are characterized by a decline in fresh weight rather than a plateau at the end of the second phase (Sadras and McCarthy, 2007). This decline is also observed when harvest is delayed to enhance berry traits associated with wine quality at the expense of fruit weight and yield. Harvest maturity (Stage 38 in Figure 2) is defined by winemaking criteria for fruit composition; it is often specified in terms of sugar concentration or sugar: acid ratio in cooler climates, but colour and flavour criteria complement these simple definitions. Environmental variables including temperature, radiation and water availability during berry growth and ripening can have substantial impact on berry composition and hence on wine attributes. This viticulturally important aspect of berry biology is beyond the scope of this section, but readers are referred to reviews by Coombe and Iland (2005), Conde *et al*. (2007), and Dai *et al.* (2010). We focus on the effects of water deficits on berry and wine attributes in a further on in this section.

Varietal differences in development

The developmental plan outlined in the previous section applies to all grape varieties. However, the actual timing of each critical stage and the resultant season length are genetically controlled and modulated by the environment, chiefly temperature. Some phenological stages may also be responsive to management practices, e.g. timing of pruning may shift the timing of budburst, and manipulation of canopy-to-fruit ratio by defoliation or bunch removal may delay or advance ripening in some conditions.

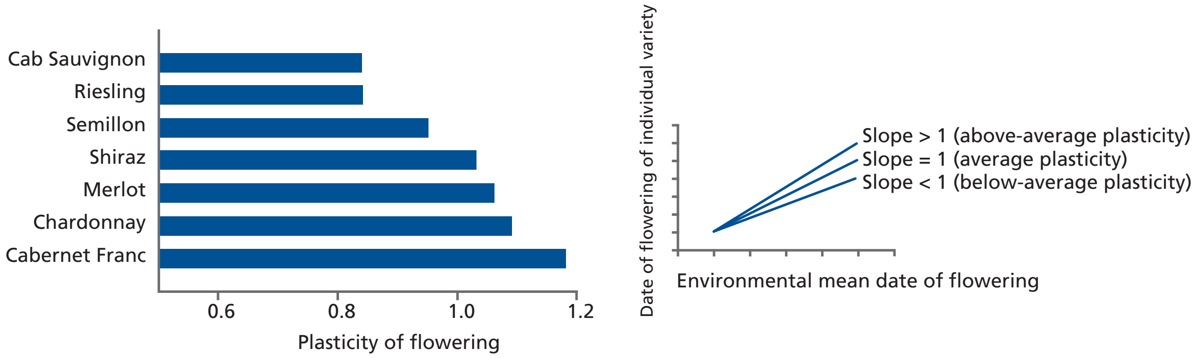
There are two distinct aspects related to the variety-dependent phenological pattern. One is the average time to reach a certain stage; for example Gladstones (1992) classified varieties in eight maturity groups (Table 2). The other aspect is the plasticity of phenological development, defined as the degree of response in phenology to environmental conditions. Cabernet franc and Riesling, for example, have comparable maturity requirements ~ 1 200-1 250 °Cd (Table 2), but under South Australian conditions Cabernet franc is phenologically more plastic than Riesling (Figure 3), as its flowering date varies more in different environments than that of

TABLE 2 Maturity groups and biologically effective thermal time* from October 1st (Southern hemisphere) or April 1st (Northern Hemisphere) to ripeness of grapevines according to Gladstones (1992).

Maturity group (°Cd to maturity)	Red wine	White or rosé wine
1 (1 050)		Madeleine, Madeleine-Sylvaner
2 (1 100)	Blue Portuguese	Chasselas, Müller-Thurgau, Siegerrebe, Bacchus, Pinot Gris, Muscat Ottonel, Red Veltliner, Pinot Noir, Meunier
3 (1 150)	Pinot Noir, Meunier, Gamay, Dolcetto, Bastardo, Tinta Carvalla, Tinta Amarella	Traminer, Sylvaner, Scheurebe, Elbling, Morio-Muskat, Kerner, Green Veltliner, Cardonnay, Aligoté, Melon, Sauvignon Blanc, Frontignac, Pedro Ximenes, Verdelho, Sultana
4 (1 200)	Malbec, Durif, Zinfandel, Schiava, Tempranillo, Tinta Madeira, Pinotage	Sémillon, Muscadelle, Riesling, Welschriesling, Furmint, Leanyka, Harslevelu, Sercial, Malvasia Bianca, Cabernet Franc
5 (1 250)	Merlot, Cabernet Franc, Shiraz, Cinsaut, Barbera, Sangiovese, Touriga,	Chenin Blanc, Folle Blanche, Crouchen, Roussanne, Marsanne, Viognier, Taminga, Cabernet Sauvignon
6 (1 300)	Cabernet Sauvignon, Ruby Cabernet, Mondeuse, Tannat, Kadarka, Corvina, Nebbiolo, Ramisco, Alvarelhão, Mourisco Tinto, Valdiguié	Colombard, Palomino, Dona Branca, Rabigato, Grenache
7 (1 350)	Aramon, Petit Verdot, Mataro, Carignan, Grenache, Freisa, Negrara, Grignolino, Souzão, Graciano, Monastrell	Muscat Gordo Blanco, Trebbiano, Montils
8 (1 400)	Tarrango, Terret Noir	Clairette, Grenache Blanc, Doradillo, Biancone

** calculated using a base temperature of 10 °C, and a cutoff in the monthly average temperature at 19 °C.*

FIGURE 3 Plasticity of flowering of grapevine varieties in southeastern Australia. Plasticity is calculated as the slopes of the lines relating date of flowering of each variety and the environmental mean date of flowering (inset). Adapted from Sadras *et al.* (2009).



Riesling. The actual timing of occurrence of critical phenological stages, total season length and phenological plasticity are critical traits in the quest to match varieties and environments including the fine-tuning of irrigation management.

Grapevine development and warming trends

Phenology is temperature driven; therefore warming trends recorded since the middle of the twentieth century are reflected in grapevine phenological shifts of great significance for vine management and winemaking (Duchene *et al.*, 2010). Several studies have assessed the rates of change associated with phenological variables in both the northern and Southern Hemisphere (Wolfe *et al.*, 2005 and Duchene and Schneider, 2005). Not surprisingly, vines develop faster in warmer conditions but the actual rates need consideration. Two important aspects of these responses are the differential sensitivity of particular phenological phases, and the potential decoupling of berry attributes. For example faster sugar accumulation that is not fully compensated by early harvest means higher sugar content in berries and higher alcohol potential, as suggested for Riesling in Alsace and for Cabernet Sauvignon and Shiraz in Australia (Petrie and Sadras, 2008 and Duchene and Schneider, 2005).

RESPONSE TO WATER DEFICITS

Overview: rainfall patterns and development of water deficit

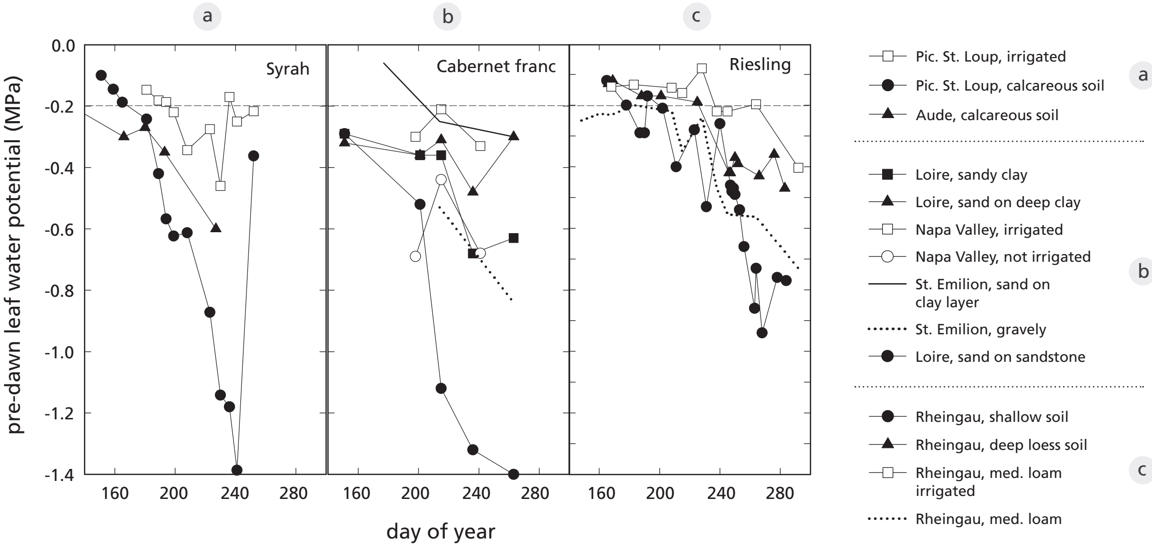
Rainfall pattern and soil-water storage capacity are major drivers of the temporal pattern of water supply and water deficit in rainfed systems, as illustrated by comparison of winter- and summer-rainfall viticultural regions. Aschmann (1973) highlighted the concentration of rainfall in the winter half-year as the most distinctive element of the Mediterranean climate, and proposed 65 percent of annual rainfall in this period as a boundary in his definition. Grapevines are grown in Mediterranean-type climates in southern Europe, California, and parts of South Africa, Chile and Australia. Winter rainfall often ensures soil water storage that allows for early growth, whereas a pattern of terminal drought is typical of rainfed vines in Mediterranean environments. Temporary water deficits are common in temperate, summer rainfall regions of western and central Europe where vineyards are established in shallow soils or soils with low water-holding capacity. In these environments, rainfall pulses and limited buffering capacity of soils drive marked wet-dry cycles. The frequency, duration and severity of the dry spells in these cycles are largely unpredictable. Owing to drying trends and reliability of quality wine supply required by globalized markets, supplemental irrigation is likely to increase even in these areas that have been traditionally rainfed.

Figure 4 compares the plant water status of rainfed vines from contrasting climates and soils within a given region; examples from irrigated vines are also included. It is clear that irrigation stabilizes predawn leaf water potential at a level rarely found naturally over the growing season in these areas, including the very cool climate regions of the Loire Valley in France and the Rheingau in Germany. Figure 4 also shows that the differences in water status between vineyards within each of the regions could be larger than the differences in general water status between different climate zones. It is also clear that variation in water status during a particular season increases from warm and dry climates to summer rainfall because of the irregularity of the frequency and intensity of summer precipitation in the latter.

Growth and yield

Crop responses to water deficit depend on the intensity, duration and timing of stress. Intra-specific variation has been reported for major traits related to the development, water and carbon economy of grapevine including phenology, susceptibility to embolism, stomatal density and stomatal conductance in response to both soil water content and vapour pressure deficit, biomass per unit transpiration, dry mater partitioning, and rootstock response to water deficit, salinity and soil-borne diseases.

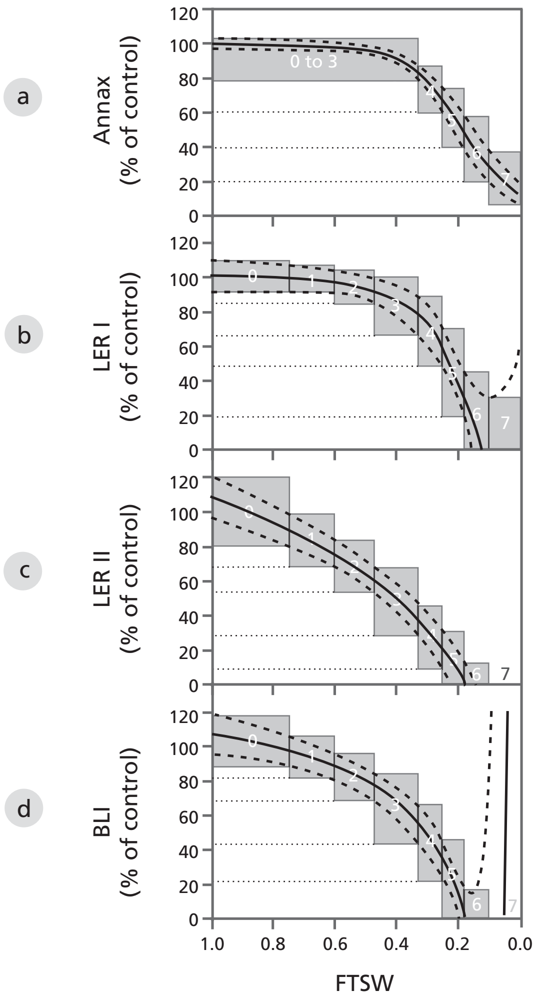
FIGURE 4 Seasonal courses of predawn leaf water potential from different vineyard sites in contrasting environments. Left panel is Syrah from two warm, dry areas in southern France: Pic St. Loup area north of Montpellier (Schultz, 2003) and Aude region (Winkel and Rambal, 1993). Central panel is Cabernet franc from vineyards with three contrasting soils in the cool, summery rainfall Loire Valley of France (Morlat *et al.*,1992), the warm, summer rainfall St. Emilion region of France (van Leeuwen and Seguin, 1994), and the warm, dry Napa Valley of California for an irrigated treatment and a water deficit treatment after veraison (Schultz and Matthews unpublished). Right panel is White Riesling from the cool, summer rainfall Rheingau region in Germany collected in 1999 (open symbol and dotted line) and 2002 (closed symbols); adapted from Gruber and Schultz (Gruber and Schultz, 2005). All treatments were rainfed, unless otherwise indicated.



In common with most crops, tissue expansion in grapevine is more sensitive to water deficit than stomatal regulation and gas exchange (Figure 5a-d). The effects of intensity and duration of water stress have been integrated in stress indices based, for example, on soil water status (Figure 5a-d), plant-water status or canopy temperature (Figure 6). Box 2 summarizes techniques used to monitor water status of vines, and below analyses yield response to water deficit from the perspective of production functions.

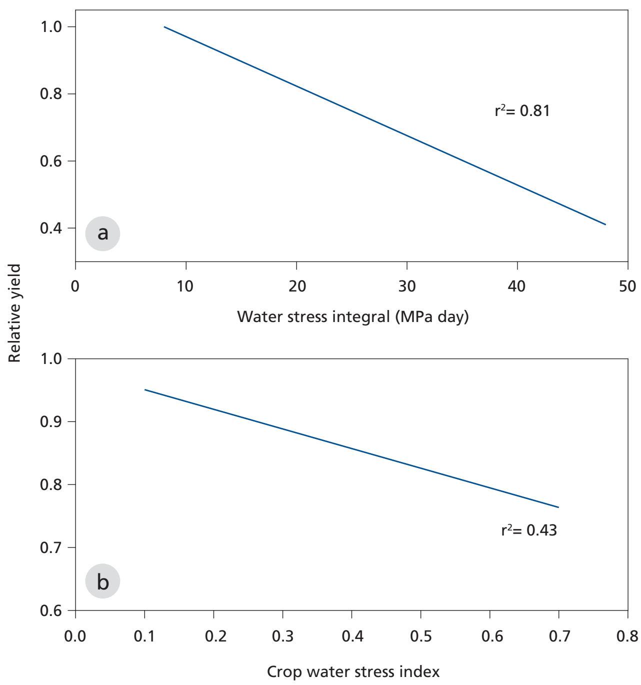
Owing to the developmental programme of the plant and the definition of yield over two consecutive seasons, we need to consider the effects of water deficits in the previous season on the growth and yield in the current season. All possible responses have been reported, namely effects

FIGURE 5 Scheme for water management derived for Shiraz, Grenache and Mourvèdre in southern France. Relationships between fraction of transpirable soil water (FTSW) and the rate of (a) light-saturated net photosynthesis; leaf emergence rate in (b) first-, or (c) second-order lateral branches, and (d) final length of first-order lateral branches. Rates measured in water-deficit treatments are normalized with respect to well-watered controls. The boxes (0 to 7) represent eight classes with characteristic impairment of plant function by drying soil; for instance in (a) light saturated photosynthesis is above 80 percent of controls in classes 0 to 3, and is reduced to 60, 40, 20 and 7 percent of controls as soil dries from classes 4 to 7. The table shows recommended level of water stress (FTSW class) for quality red wine production at different phenological stages. Adapted from Pellegrino *et al.* (2006).



Phenophase (E-L stage)	FTSW class for quality red wine production
Budburst to flowering (4 to 23)	0 to 1
Flowering to bunch closure (23 to 32)	2
Bunch closure to veraison (32 to 35)	3
Veraison to harvest (35 to 38)	5 to 6

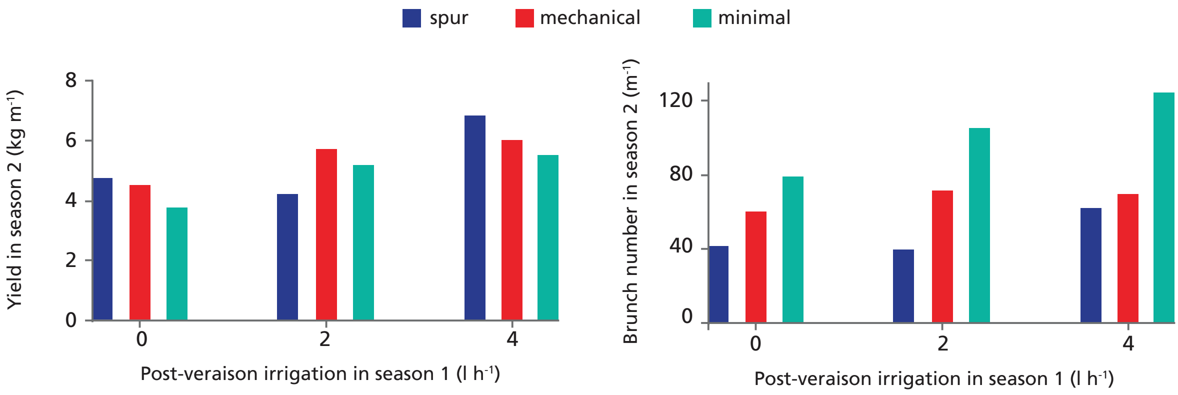
FIGURE 6 Yield reduction with increasing water deficit quantified using (a) the integral of stem-water potential and (b) the difference between canopy and air temperature corrected by vapour pressure deficit. Sources: (a) Salón *et al.* (2005), (b) Grimes and Williams (1990).



of water deficit in season 1 had negative, neutral or positive effect on reproductive outcome in season 2 (Williams and Matthews, 1990). This diversity of responses is partially the result of differences in varietal sensitivity, timing, intensity and duration of water deficit, interactions with other factors, and in same cases to poorly designed experiments. In a well-designed factorial experiment looking at the combined effects of pruning and post-veraison irrigation on Shiraz, Petrie *et al.* (2004) measured statistically significant reductions in shoot number, bunch number and yield in season 2 in response to reduction in irrigation rate in season 1 (Figure 7). In an equally well designed experiment with Tempranillo, Intrigliolo and Castel (2010) found no carry over effect of irrigation regime on bud fertility. Nevertheless, grape growers do have some capacity to regulate yield components by pruning and bunch thinning (Table 1, Figure 8).

Many studies measured the effect of in-season water supply on yield and its components, as illustrated in Table 3 for three contrasting production systems. The combination of cultivar, environment and management resulted in yield of fully irrigated vines from 10 kg/vine for Bobal in Requena and Chardonnay in Niagara to 20 kg per vine for Shiraz in Riverland. Comparison of rainfed and fully irrigated crops shows a large (up to twofold) benefit of irrigation in the drier environments (Riverland, Requena) in comparison to yield gains of only 10-25 percent in the cooler, humid environment (Niagara). Bunch number shows large variation among production systems, but is relatively stable in response to in-season water supply, as expected from the reproductive cycle of vines. In-season water deficit therefore reduces yield by reducing bunch weight, and the relative importance of its components, namely berry number and size, depends on the timing of water deficits. Water deficit around anthesis and berry set has the potential to reduce berry number and size, whereas water deficit at later stages only reduces berry size. The post-veraison period is particularly critical because of the trade-off between maintenance

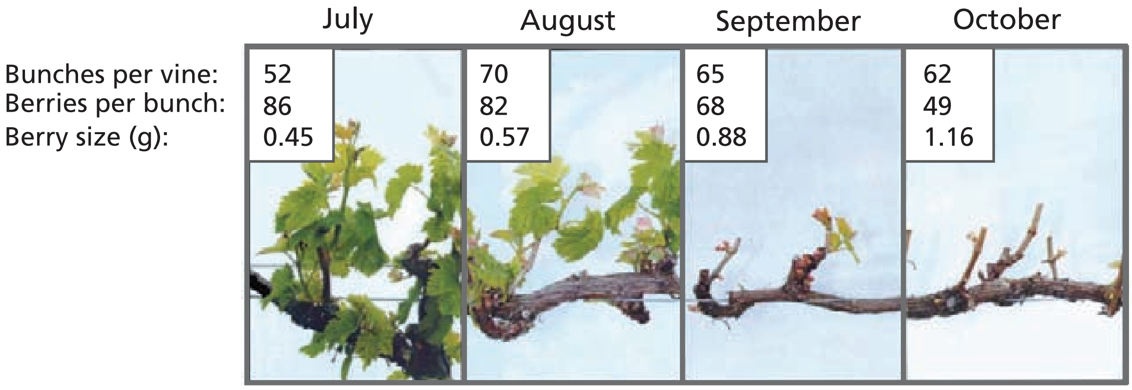
FIGURE 7 Reduction in irrigation rate post-veraison in season 1 reduced yield and bunch number of Shiraz in season 2 irrespective of pruning system. Yield and bunch number are expressed as per metre of canopy. Source: Petrie *et al.* (2004).



irrigation: $P < 0.05$
pruning: n.s.
interaction: n.s.

irrigation: $P < 0.05$
pruning: $P < 0.01$
interaction: n.s.

FIGURE 8 Shoot development recorded on mid-October (photographs) and yield components at harvest (numbers) in Merlot vines pruned at monthly intervals between mid-July to mid-October. Source: Friend and Trought (2007) for experiments in Marlborough (41 °S, 174 °E), New Zealand.



of water supply to ensure berry growth and the requirements of berry composition, which may benefit from controlled water deficit.

Fewer studies characterized the long-term effect of water deficit on grapevine yield. For Riesling on a steep slope vineyard in Germany, the combination of in-season and across-season temporary water deficits reduced long-term production from an average 7.6 tonne/ha in vines with small amounts of supplementary irrigation (29 litre/m^2 per season) to 5.0 tonne/ha for rainfed vines (Table 4).

Availability of water after harvest has at least two effects. First, it may influence canopy activity, build up of reserves and hence the performance of the crop in the following growing cycle. Second, irrigation between harvest and leaf fall may alter phenology under some conditions; for instance reduced irrigation after harvest may advance budburst in the following season (Williams *et al., 1991*), potentially increasing frost risk in some environments.

TABLE 3 Yield and yield components of Shiraz in Riverland (Australia), Bobal in Utiel Requena (Spain) and Chardonnay in Niagara-on-the-Lake (Canada) in response to irrigation regime. Values are ranges over three seasons. Sources: Riverland, McCarthy (1997); Utiel Requena, Salón *et al.* (2005); Niagara, Reynolds *et al.* (2005).

Irrigation regime		Yield (kg/vine)	Bunches per vine	Bunch weight (g)	Berries per bunch	Berry weight (g)
Riverland						
Fully irrigated	(between budburst and harvest)	13.4-19.5	166-182	81-108	67-81	1.2-1.5
Post-anthesis deficit	(irrigation withheld for 1 month after anthesis)	9.8-18.3	156-190	63-104	57-81	1.1-1.5
Pre-veraison deficit	(irrigation withheld for 1 month before veraison)	11.4-20.1	168-210	68-97	62-75	1.1-1.3
Post-veraison deficit	(irrigation withheld for 1 month after veraison)	11.2-18.2	160-193	71-98	63-77	1.1-1.3
Pre-harvest deficit	(irrigation withheld for 1 month before harvest)	12.4-20.1	154-197	81-106	67-78	1.2-1.5
Anthesis-veraison deficit	(irrigation withheld between anthesis and veraison)	9.6-19.9	164-204	58-99	59-77	1.0-1.4
Veraison-harvest deficit	(irrigation whithheld between veraison and harvest)	11.2-17.3	154-176	73-99	62-76	1.2-1.4
Rainfed	(no irrigation)	4.7-13.8	153-200	29-80	42-73	0.7-1.3
Utiel Requena						
Fully irrigated	(between anthesis and harvest)	6.4-9.5	11-14	613-711	107-263	2.7-3.0
Post-veraison mild deficit	(50% of control irrigation from veraison)	6.7-8.0	11-14	549-738	193-271	2.7-2.9
Post-veraison severe deficit	(irrigation withheld from veraison)	6.8-8.6	10-14	488-727	202-253	2.4-3.0
Rainfed	(no irrigation)	3.5-4.2	9-13	346-476	169-248	1.8-2.1
Niagara						
Fully irrigated		3.2-9.2	39-84	83-110	56-66	1.4-1.7
Post-set deficit	(irrigation withheld after fruit set)	3.2-8.4	39-88	81-106	58-67	1.4-1.6
Post-lag phase deficit	(irrigation withheld after lag phase)	2.7-8.7	35-84	76-103	54-65	1.4-1.6
Post-veraison deficit	(irrigation withheld after veraison)	2.6-10.0	33-78	79-128	60-83	1.3-1.7
Rainfed	(no irrigation)	2.9-7.8	36-84	81-102	60-66	1.4-1.6

TABLE 4 Yield, fruit sugar concentration and sugar yield of irrigated and rainfed Riesling on a steep slope vineyard close to Geisenheim (50 °N), Germany. Values are mean ± standard deviation for eight consecutive years since 2002. Combination of an irrigation threshold of -0.3 MPa predawn water potential and weekly irrigation decision interval resulted in 7.4 ± 3.4 irrigation events per season, and applied water 29.3 ± 12.2 litre/m^2 (Gruber and Schultz, unpublished).

Response variable	Irrigated	Rainfed
Yield (tonne/ha)	7.6 ± 3.22	5.0 ± 2.16
sugar conc. (g/litre)	212 ± 19.5	204 ± 29.7
sugar yield (kg/ha)	1 182 ± 460.1	728 ± 280.1

Berry and wine attributes

Wine quality is an elusive concept and attempts to quantify it are bound to be controversial (Box 1). Quantitative assessments of berry and wine attributes in response to water deficit are, however, essential for irrigation scheduling. Indeed, regulation of grapevine water relations is an important tool for quality management in irrigated viticulture. There is a significant body of literature dealing with the effects of water relations on the composition of red grapes, especially on phenolic compounds; information regarding the effects of plant water status on the composition of white varieties is scarce.

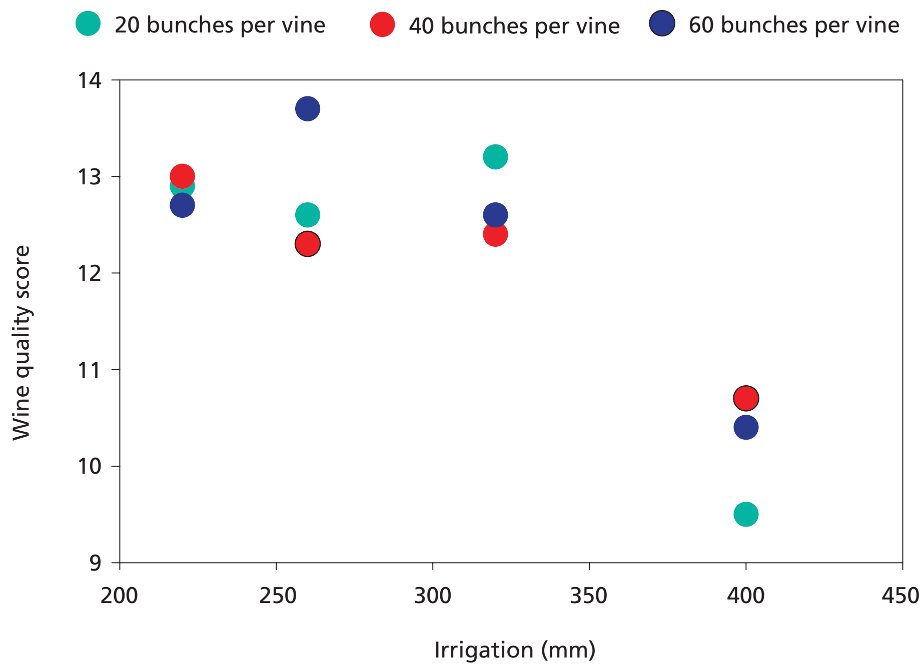
Red varieties

Figure 9 illustrates a typical, although not universal, relationship between wine quality and irrigation for red varieties. The negative association between water supply and wine quality is partially mediated by an apparent trade-off between yield and quality attributes of berries (Figure 10, Figure 11). The negative associations between rate of accumulation of sugar and anthocyanins and yield components in Figure 10b probably reflect a high fruit-to-canopy ratio, rather than high yield per se. If this hypothesis is correct, manipulation of this ratio by irrigation,

BOX 1 Wine quality

The elusiveness of 'wine quality' stems from the complexity of wine attributes compounded by the complexity and variability of human smell and taste sensitivity. Temporal and regional variation in wine quality has been assessed with price and vintage ratings (Cicchetti and Cicchetti, 2009 and Almenberg and Dreber, 2009). The drawbacks of each of these approaches are many, including marketing factors influencing price beyond specific quality parameters, and vintage scores derived from expert, albeit subjective evaluations (Sadras *et al.*, 2007). Views on vintage scores range from "…controversial, potentially misleading and essentially impossible to get consistently correct…" (Fuller and Walsh, 1999) to the proposal of ratings that "…express the likelihood of what might reasonably be expected from a wine of a given year…" (Stevenson, 2005). Individual attributes of berries and wine such as colour or content of many critical compounds, on the other hand, can be measured with accuracy. The challenge to this approach is however, the integration of individual measurements into a complete measure of quality. There is no doubt that wine quality is a controversial concept, and there is no doubt either that, however imperfect, quantification of key berry and wine attributes is essential to irrigation management.

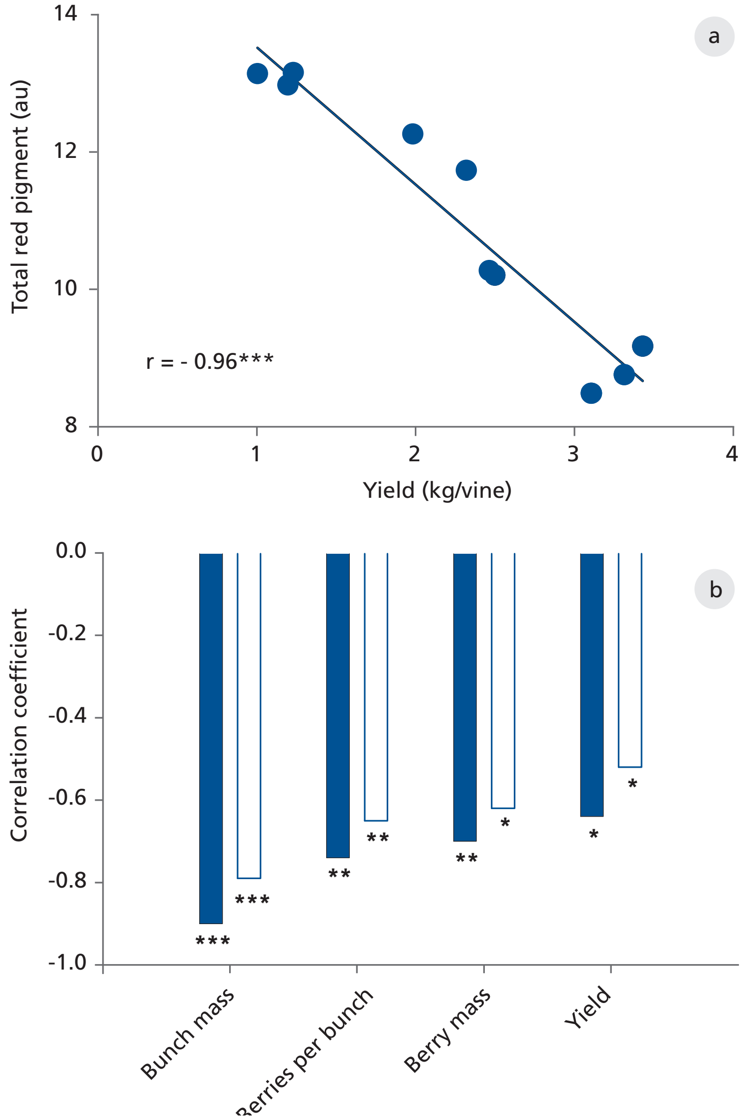
FIGURE 9 Wine quality score as a function of total irrigation for Cabernet Sauvignon in Adulam, Israel. Source: Bravdo *et al.* (1985).



pruning, thinning, and canopy management maybe important to achieve both high yield and high quality.

Water deficit generally increases the concentration of phenolic compounds, but has a differential effect on individual groups of phenols depending on timing and severity of the stress. Tannin biosynthesis can be negatively affected by severe stress after anthesis (Ojeda, 2002), but later deficits often increase tannin concentration (Roby *et al.,* 2004). In most cases, anthocyanin concentration responds positively to water shortage after veraison but less frequently to pre-veraison deficits (Matthews and Anderson, 1988); although the expression of genes involved in anthocyanin biosynthesis can be increased by water stress pre-veraison (Castellarin *et al.,* 2007). Aside from phenolic compounds, aroma attributes may also be affected (Chapman *et al.,* 2005). Differences in the response of varieties are likely but not well documented (see: Suggested RDI regimes below for examples). In addition to the effects on amount and proportion of key compounds, water deficit can cause more subtle but relevant effects. For example, water deficit after veraison has been shown to increase the structural complexity (degree of polymerisation) and to reduce the extractability of phenolic compounds in berries of several red varieties (Ojeda *et al.,* 2002; Sivilotti *et al., 2005*). The effects of water deficit on berry attributes are partially related to reductions in berry size, although size-independent effects have also been reported. Allometric analysis is required (i) to separate size-dependent effects of water deficit on a particular component, e.g. sugar, and (ii) to compare the relative responsiveness of different berry components to water deficit (Sadras *et al.,* 2007 and Sadras and McCarthy, 2007). For example, allometric analysis revealed that water deficit accelerated the rate of accumulation of anthocyanins with respect to sugar of Cabernet Sauvignon in a warm environment (Figure 12). Water management is therefore important to ensure a certain coupling of key berry components during ripening; this will eventually affect wine balance.

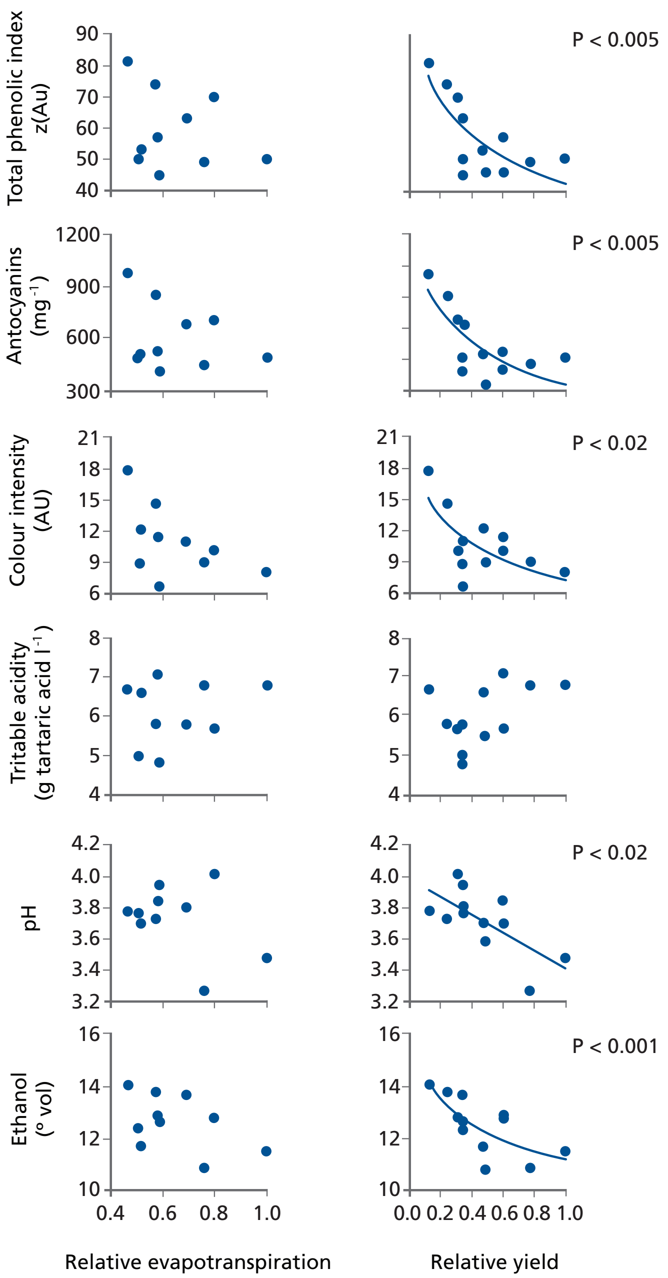
FIGURE 10 Negative associations between berry traits related to wine quality and yield. (a) Total red pigments in berry skins of Pinot Noir grown in a cool climate. (b) Correlation coefficients of the regressions between the rate of anthocyanins or soluble solid accumulation in berries and yield related variables in Cabernet Sauvignon grown in a warm environment. Sources of variation were (a) source: sink manipulation through bunch thinning and pruning, and (b) season, water supply and fruit load. Asterisks indicate P < 0.05 (*), P < 0.01 (**) and P < 0.0001 (***). Adapted from (a) Dunn *et al*. (2005) and (b) Sadras *et al*. (2007).



White varieties

Compared to red varieties, white varieties are generally more sensitive to stress periods and can show negative compositional changes (Christoph *et al.,* 1998 and Peyrot des Gachons *et al.,* 2005). Phenolic compounds are judged less desirable in white grapes, since sensory attributes such as astringency or bitterness, associated with both flavonoid, i.e. flavan-3-ols and proanthocyanidins (Singleton and Noble, 1976 and Brossaud *et al.,* 2001) and nonflavonoid phenols, i.e. hydroxycinnamic acids or their esters (Arnold *et al.*, 1980 and Hufnagel and Hofmann, 2008) are incompatible with the current type of white wine popular

FIGURE 11 Wine attributes of Tempranillo in Requena, Spain, as a function of relative evapotranspiration and relative yield. Fitted models are shown when significant (P < 0.05).
Source*:* Intrigliolo and Castel (2008).

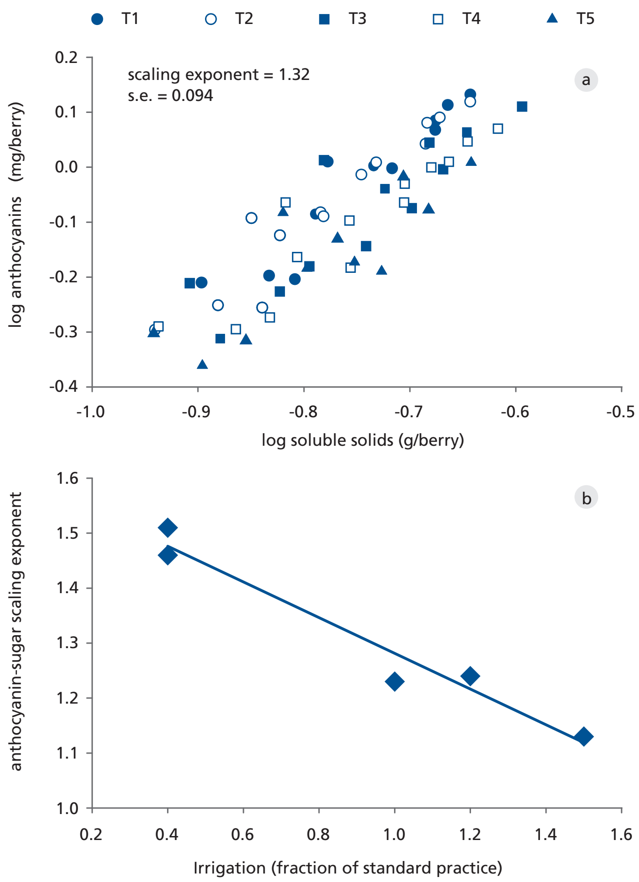


with the consumer. Flavonoids undergo oxidative polymerisation, thus lowering their flavour threshold during wine ageing (Schneider, 1995) and can negatively affect the volatility of flavour compounds (Aronson and Ebeler, 2004). Depending on the variety, water stress and associated reduction in nitrogen uptake, have been implicated in alterations of flavour-quality of various white varieties such as Chasselas, Silvaner, Sauvignon blanc and Riesling (Peyrot des Gachons *et al.*, 2005 and Linsenmeier, 2008). In one example, the development of negatively judged wine attributes after only a short period of bottle ageing was retarded by irrigation (Table 5). However, there has been at least one report showing an increase in glycosidically bound monoterpenes contributing to the flavour profile of White Riesling under water deficit

TABLE 5 Sensory evaluation of experimental wines from White Riesling either receiving supplemental irrigation or only natural precipitation from the 2003 vintage in the Rheingau region, Germany. Bottled wines (screw cap) of both treatments were in part 'artificially aged' by warm-storing these bottles at 25 °C for three months. Wine attributes were rated on a scale from 0-5 (higher values indicated more intense perception of the respective attribute) by 115 judges on 7 September, 2004. Source: Schultz and Gruber (2005).

Attribute	Irrigated		Non-irrigated	
	not aged	artificially aged	not aged	artificially aged
Positive aroma attributes	3.45	2.37	2.85	1.93
Negative aroma attributes	2.10	2.61	2.43	3.79
Acidity	2.35	2.95	2.43	2.95
Bitterness	2.40	2.63	2.70	2.87

FIGURE 12 (a) Allometric relationship between amount of sugars and amount of anthocyanins during the linear phase of accumulation in Cabernet Sauvignon berries under five treatments (irrigation and fruit load) during three seasons. The scaling exponent (i.e. slope of the regression in a log-log scale) is greater than 1, thus indicating that the relative rate of accumulation of anthocyanins was greater than the relative rate of accumulation of sugar across treatments. (b) Relationship between the sugar-anthocyanin scaling exponent and irrigation; the standard treatment received 160 mm in 2003-2004, 210 mm in 2004-2005, and 220 mm in 2005-2006. Source: Sadras *et al.* (2007).



(McCarthy and Coombe, 1999), but even in that particular trial, sensory attributes changed differentially over time.

WATER REQUIREMENTS

Crop evapotranspiration increases with vine age from establishment until the canopy and root system reach their full capacity to capture radiation and water (Figure 13). For established vines, seasonal ET_c in semi-arid to arid environments, e.g. central California (United States), and Riverina (Australia) ranges from approximately 500 to 800 mm (Williams and Matthews, 1990). Figure 14 shows the seasonal dynamics of K_c as affected by crop age and environment (temperate vs tropical). The seasonal dynamics of crop coefficients comprises two phases with increasing K_c from onset of active growth to peak canopy size, and decreasing K_c during leaf senescence. Assuming linearity, the average rate of increase of K_c was 0.005 d^{-1} for young vines, 0.007 d^{-1} for older vines in Washington, and 0.013 d^{-1} in the tropical São Francisco region. In the declining stage, the rate of change in K_c was 0.006, 0.011, and 0.042 d^{-1}, respectively. In addition to differences in rate of change in K_c, non-zero K_c at the onset of the irrigation season in tropical environments reflects the lack of dormancy and continuous physiological activity during the year in tropical environments.

More refined crop coefficients could be obtained on the grounds of a direct, often non-linear association with canopy light interception or related variables such as leaf area index. Owing to large variation in canopy structure with pruning and training systems, however, the relationship

FIGURE 13 Change in crop evapotranspiration (ET_c) with vine age in Washington, USA. ET_c was measured in large drainage lysimeters. Seasonal (1 April to 31 October) reference evapotranspiration (ET_o) derived from Penman (alfalfa reference) is also shown; the dotted line is the average. Adapted from Evans *et al.* (1993).

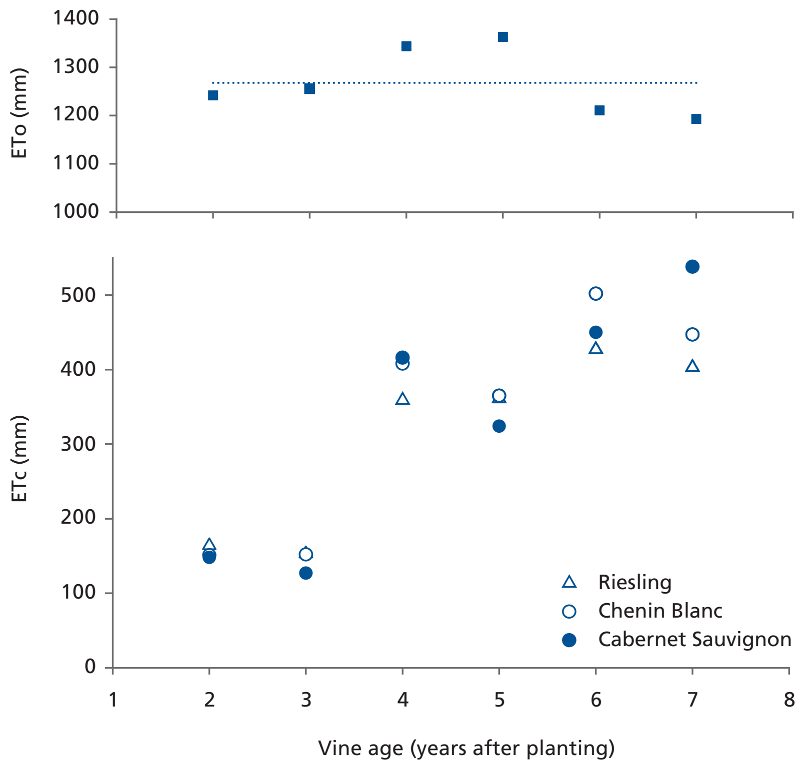
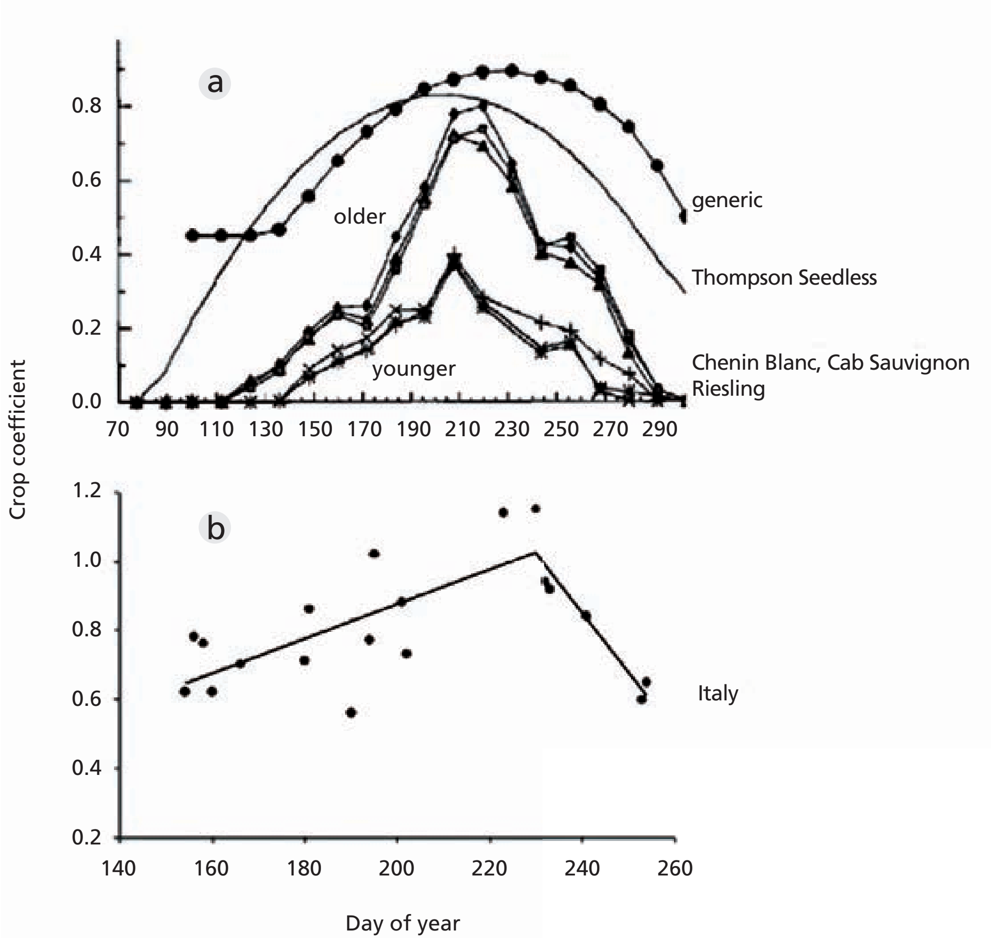


FIGURE 14 Seasonal dynamics of crop coefficients for vines in (a) central Washington (46 ºN, USA) and (b) São Francisco (9 ºS, Brazil). Sources: (a) Evans *et al.* (1993) and (b) Teixeira (1999).

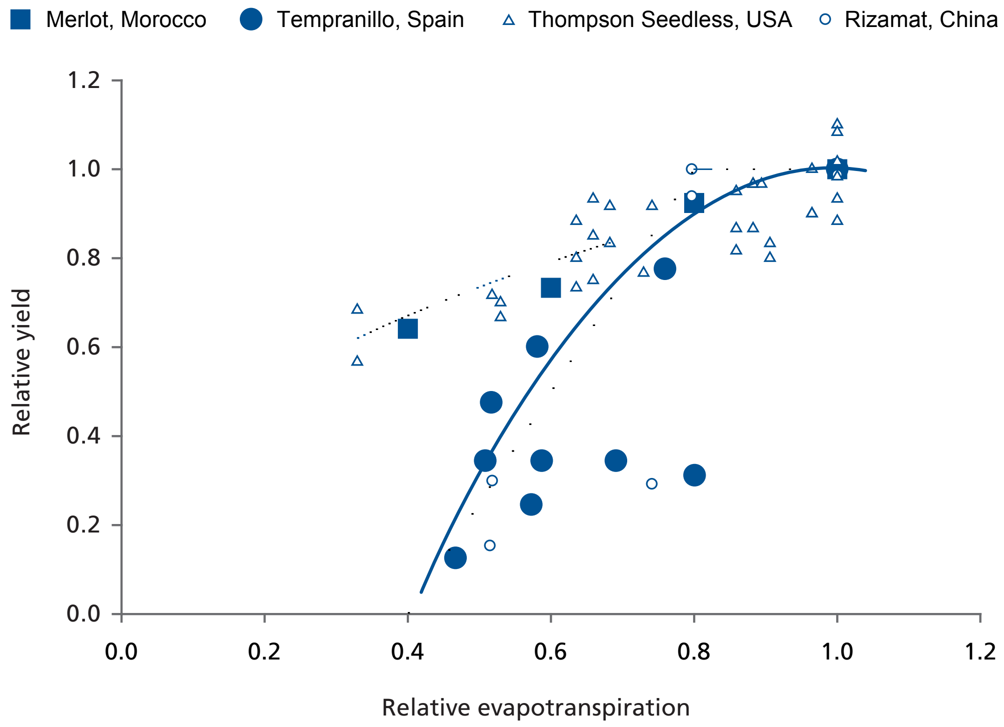


between crop coefficient and leaf area index is not unique. The relationship between crop coefficient and leaf area index may also show hysteresis, i.e. the relationship is different for increasing or decreasing K_c (Netzer *et al.*, 2009). To deal with these problems, Williams and Ayars (2005) proposed an approach to characterize crop coefficients on the basis of canopy light interception, and demonstrated the robustness of a practical grid-method to measure the amount of shade cast on the ground by table grapes.

WATER PRODUCTION FUNCTIONS

The diversity of production systems targeting different combinations of fruit volume and quality contribute to the large scatter in the relationship between yield and water use. Furthermore, scarcity of data means the actual shape of the function remains speculative in particular for relative ET_c below 0.4 (Figure 15). In common with other tree crops yield is maintained until relative ET_c approximates 0.8, and a consistent almost linear decline is observed in the range of relative ET_c from 0.8 to 0.4. The data for Tempranillo wine grapes suggest a more sensitive response to relative ET deficits in contrast with the response of table grapes (Figure 15). This is probably because of a limitation in the maximum ET_c imposed by pruning and other cultural techniques in the case of wine grapes, while such limitation is not normally imposed in table

FIGURE 15 Relative yield as a function of relative evapotranspiration in wine grapes (closed symbols). The solid and dashed lines attempt to capture the upper limit for wine grapes. Table grapes (open symbols) and the function fitted for Thompson Seedless (dotted line) are shown for comparison. Sources: Messaoudi and El-Fellah (2004), Intrigliolo and Castel (2008), Du *et al.* (2006) and Grimes and Williams (1990).



grapes. The variations in the scarce data in wine grapes of Figure 15 suggest that the production function is probably variety and cropping system dependent.

Qualitatively, the relationship between gross revenue and ET_c in wine grapes is expected to feature an optimum resulting from the mismatch between the ET_c required to maximize yield and the ET_c required to maximize quality and value per unit volume (Box 19 in Chapter 4). The actual parameters of this function, however, are likely to be specific for local production systems with their own water and grape prices.

SUGGESTED RDI REGIMES

For wine grapes, where the quality objective is critical to profit, the recommended irrigation regime must account for many more factors than in most other crops. To achieve the triple aim of high yield, quality and irrigation water productivity, irrigation of red grape varieties in temperate environments needs to ensure vegetative growth and early reproductive growth in spring, and allow for progressive water deficit to develop towards maturity. For white grapes, water management should seek to avoid both severe water deficit and excess water supply. Management of irrigation after harvest accounts for the need to build up carbohydrate reserves in vines. Owing to the many factors involved, we selected five case studies to illustrate this general pattern, and the variations particular to the target production system. These examples also highlight the application of different monitoring methods (Box 2).

Box 2 Crop and soil measurements to schedule grapevine irrigation

Plant, crop and soil indices of water status have been tested in vines grown in diverse environments. The table below presents some examples, and: Suggested RDI regimes outlines the application of some of these methods in irrigation scheduling. Measurement of leaf water potential is time consuming and requires considerable expertise, but seems more consistent than faster measurements including trunk diameter and stomatal conductance.

Under the conditions of the study of Girona *et al.* (2006), midday leaf water potential outperformed soil water balance as a trigger for irrigation, i.e. leaf water potential captured spatial variability better, and crops managed using this plant-based index had less variability in yield and berry composition, that could potentially improve the homogeneity of grape juice. Thermal, visible and hyperspectral imagery are attracting increasing attention (*Moller et al., 2007; Rodriguez-Perez et al., 2007*). These technologies, coupled with GIS, allow for effective account of spatial variation at relevant scales from region to fields. There is a large variation in cost and expertise required for the implementation of these approaches, form relatively cheap, easy-to-use hand-held infra-red thermometers to tractor-mounted, air-borne or satellite imagery across wide spectral ranges. Soil water status can be assessed indirectly through predawn leaf water potential, and directly through measurements with a range of instruments including neutron probes, time domain reflectometry and pressure transducer tensiometers (Chapter 4). A water balance model is often a practical alternative to direct measurements of soil water status (Pellegrino *et al.,* 2006).

Suitable indices for irrigation management need to combine flexibility, and a reasonable accuracy-to-acquisition cost ratio in terms of time, resources and skills. In addition to trade-offs between accuracy and cost, there are also trade-offs between the multiple effects of irrigation on yield, quality, reserves and diseases (Pellegrino *et al.*, 2006). Pellegrino *et al.* (2006) developed an elegant method that combines a soil water model and simple, empirical response function that allow for the changes in crop responsiveness to water deficit through the growing season (Section 5.1).

Box 2 (CONTINUED)

Principle	Crop and region	Features	Source
Hyperspectral remote sensing	Pinot Noir California (38 °N)	Reflection and transmission measures, 350-2 500 nm. Alternatives of top-of-canopy, i.e. mounted on vehicle (0.7 m), airborne or satellite imaging. Block scale; spatial resolution. Generally consistent with measures of leaf water status (leaf water potential and water content). Variable results with canopy shape, sun or sensor perspective.	72
Thermal and visible imagery	Merlot Israel (33 °N)	Thermal imager (7.5-13 µm); digital colour images. Mounted on truck-crane (15 m). Crop water index closely associated with stomatal conductance.	73
Thermal imagery	Castelão, Aragoněs SE Portugal	Thermal imager (8-12 µm) with 0.1 °C resolution. Wet and dry references. Crop water stress index related to stomatal conductance.	74
Trunk diameter	Tempranillo Spain (39 °N)	Trunk diameter measured with linear variable differential transformers; logged at 30 second intervals. Maximum daily trunk shrinkage and trunk growth rate were highly variable and had no resolution after veraison.	76
Water potential, stomatal conductance	Tempranillo Spain (39 °N)	Predawn and mid day leaf water potential; morning and midday stem-water potential measured with pressure chamber. Midday stomatal conductance measured with diffusion porometer. Predawn and morning water potentials best indicators. Large influence of canopy size.	77
Water potential	Cabernet Sauvignon Spain (40 °N)	Explored relationship between timing of measurement of leaf water potential (predawn, midmorning and noon) and net CO_2 assimilation rate, vegetative growth rate, yield components and must composition.	78
Water potential	Pinot Noir Spain (42 °N)	Midday leaf water potential measured with pressure chamber. Compared to water balance method, midday leaf water potential was better to capture spatial variation.	43
Sap flow	Malagouzia Greece (41 °N)	Sap flow measured with the Granier method, which allows for continuous measurement and logging compared to heath-pulse system. Requires fully irrigated reference. Reasonable correlations with vapour pressure deficit and midday leaf water potential.	79
Vegetative growth	Shiraz Controlled environment	Length and leaf number of lateral branches was sensitive to medium-mild water deficits. These indicators were more sensitive to soil water deficit than predawn leaf water potential stomatal conductance.	80
Modelled soil water balance linked to plant response functions	Several varieties Southern France (43 °N)	Modelled soil water budget is linked to photosynthesis and tissue-expansion related responses to the fraction of transpirable soil water (FTSW). Allowance is made for variable stress during the crop cycle.	41

Shiraz, Grenache and Mourvèdre in southern France

Figure 5 outlines a scheme for water management derived for Shiraz, Grenache and Mourvèdre in vineyards of southern France (43 °N) with contrasting soil types (Pellegrino *et al.*, 2006). This scheme is based on eight classes of water deficit and aims at quality wine production. It highlights the need for good water supply, i.e. fraction of transpirable soil water (FTSW) above 0.6, early in the season. This allows for the establishment of a balanced canopy and fruit load, and proper development of inflorescence buds that would largely determine next season's yield. A mild water deficit from flowering to veraison, (FTSW between 0.6 and 0.4) leads to a drier finish to account for disease and berry composition at harvest. High water supply, particularly during ripening, may lead to a combination of undesirable indirect (e.g. disease) and direct effects on berry composition and wine quality. The goal of this RDI regime is to achieve a dry finish that often leads to higher concentration of colour and flavour compounds in berries.

Cabernet Sauvignon in California, United States

Prichard (2009) derived an RDI regime based on extensive experimentation with mature Cabernet Sauvignon at Lodi (38 °N). The regime aims at the best yield/quality relationship and is conceptually similar to the general pattern outlined above, namely ensure good water supply at the beginning of the growing season, and progressively reduce water supply towards ripening. After harvest, full watering is recommended to encourage root growth and accumulation of plant reserves in an environment notably warmer and with greater evaporative demand than in the previous case study.

Pinot Noir and Tempranillo in Lleida, Spain

Girona *et al.* (2006) used mid-day leaf water potential to schedule irrigation of 12-year-old Pinot Noir vines at Raïmat (42 °N) during three consecutive seasons. They used the same general principle of ensuring water supply early in the season and allowing for a deficit at late reproductive stages using the thresholds summarized in Table 6. The RDI in this study reduced yield by 14-43 percent, increased irrigation water productivity by 28-46 percent and improved concentration of anthocyanins and polyphenols in berries by 10-19 percent (Table 6).

Working with Tempranillo in the same environment, Girona *et al.* (2009) measured the effect of timing of water deficit on must attributes including soluble solids content, polyphenol, and anthocyanin concentration. They found negative impact of water deficit between fruit set and veraison and positive effects of mild water deficit after veraison. They proposed that irrigation management should aim to avoid severe water deficits for Tempranillo before veraison and that RDI should target the window between veraison and harvest.

Sauvignon Blanc in Marlborough, New Zealand

Irrigation in this cool climate needs to account for the high evaporative demand in mid-summer (ET_o > 7 mm/d) and the risk of excess irrigation with negative effects in terms of both wine quality and environmental deterioration associated with leaching of nutrients and pesticides. Greven *et al.* (2005) established an RDI study on 5 ha of 9-year old Sauvignon Blanc. They combined measurements of vine water use, assessments of vegetative and berry growth, and modelling to calculate transpiration. Before veraison, vines were irrigated when predawn leaf water potential was below –0.2 MPa and the threshold was –0.4 MPa between veraison and harvest. Preliminary

TABLE 6 Comparison of three irrigation regimes based on thresholds for midday leaf water potential and their effects on yield, irrigation water productivity (IWP, yield per unit irrigation), and anthocyanins and polyphenols in berries of Pinot Noir. Source: Girona *et al.* (2006).

Treatment	Threshold SWP (MPa)			Irrigation[a]	Yield[b]	IWP [c]	Anthocyanins[d]	Polyphenols[e]
	Vegetative	Initial berry growth	Post-veraison					
Control	-0.73	-0.88	-0.93	1	1	1	1	1
Control-deficit	-0.73	-0.86	-1.12	0.67	0.85	1.28	1.12	1.10
Deficit-deficit	-0.86	-1.13	-1.20	0.39	0.57	1.46	1.19	1.17

a fraction of control; control ~ 378 mm
b fraction of control; control ~ 10.8 kg/vine
c fraction of control; control ~ 54 kg/ha per mm
d fraction of control; control ~ 556 mg/kg
e fraction of control; control ~ 13.0 mg/kg

conclusions for this particular production system are that yield and juice attributes were unaffected by reductions in seasonal irrigation up to 40 percent from fully irrigated vines receiving 360-690 mm.

Riesling in the Rheingau area, Germany

The region is characterized by vineyards on slopes, some of them very steep with shallow soils (depth < 0.8-1 m). Midsummer reference evapotranspiration is between 3 and 6 mm d^{-1} and annual precipitation is 534 mm. Due to the strong variability in cloud cover, temperature and vapour pressure deficit (also in the absence of precipitation), leaf or stem-water potential are not stable enough to schedule irrigation. The irrigation threshold used is a predawn water potential of -0.3 to -0.4 MPa throughout berry development, with the exception of the first berry growth phase, where no irrigation is applied. Very small amounts of water are given at each irrigation event (on average 4 litre/m^2) to minimize the risk of excess water when precipitation occurs shortly after an irrigation. Over a period of 8 years, vines were irrigated 7.4 times per year on average with a total of 29.3 mm per year (Table 4), which represents about 5.5 percent of annual precipitation. Despite these small amounts, yield of the irrigated vines was about 50 percent higher at similar sugar concentrations (Table 4).

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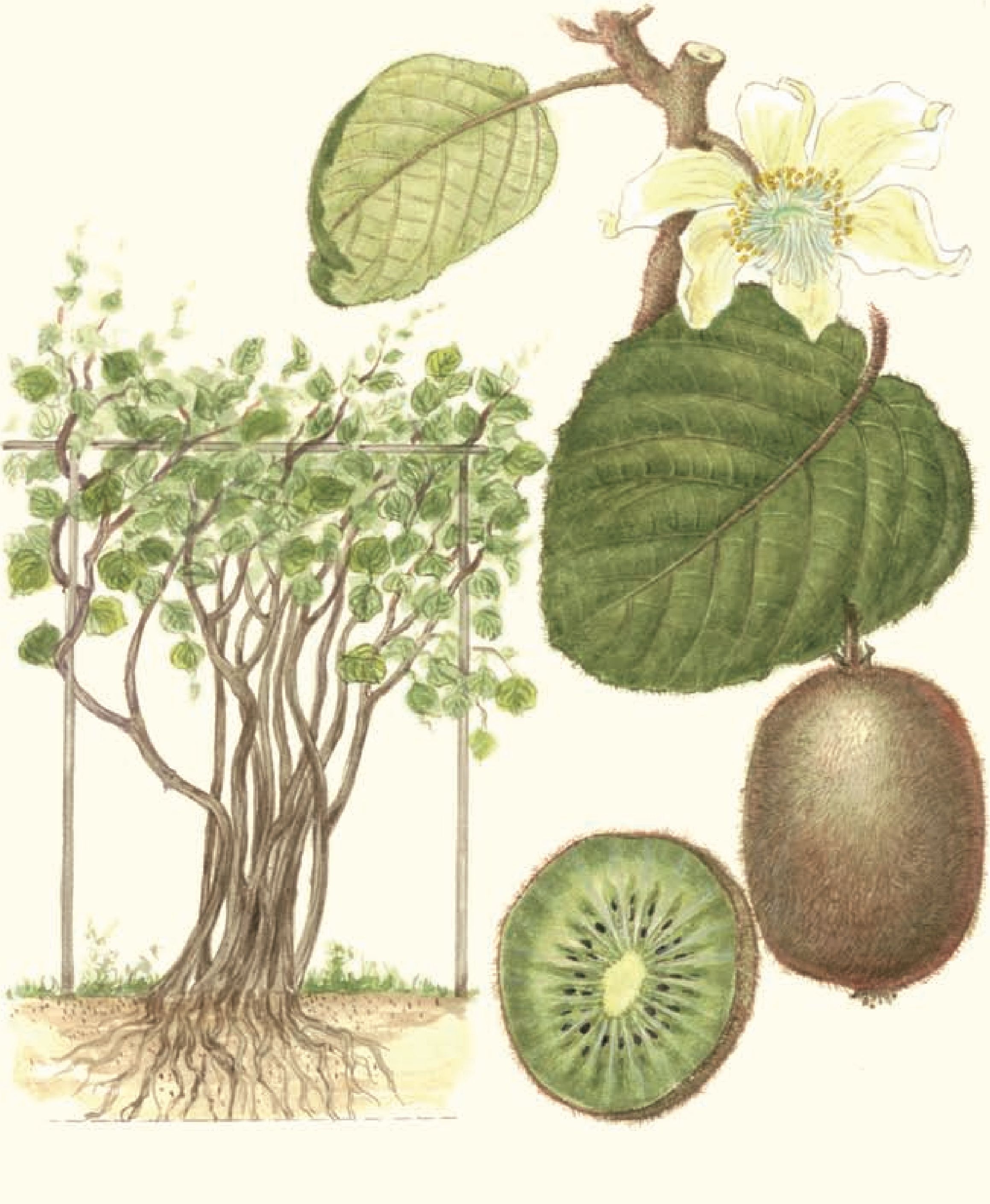

Kiwifruit

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Kiwifruit

INTRODUCTION AND BACKGROUND

G**lobally**, the green kiwifruit (*Actinidia deliciosa* [A.Chev.] C.F. Liang and A.R. Ferguson), represents about 95 percent of the commercial kiwifruit, all produced with just one variety, Hayward. Other species, such as *Actinidia arguta* (known as baby kiwi) is grown for a niche market and is also recognized for ornamental purposes. Only recently, some yellow fleshed varieties that originated in in New Zealand and Italy (*Actinidia chinensis* Planch.) have appeared on the international markets.

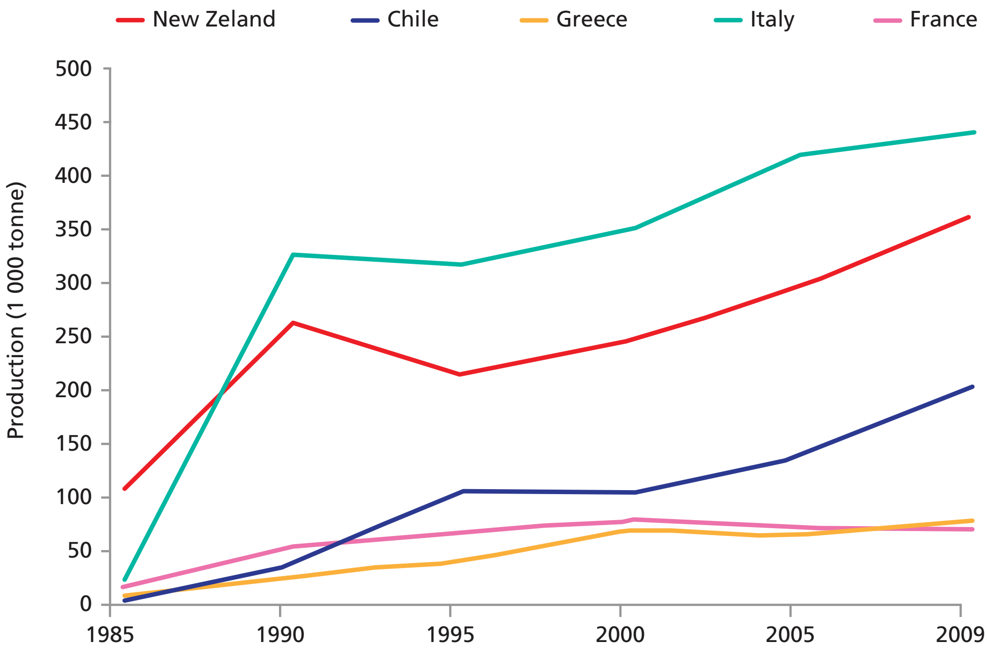
The main training systems adopted for the kiwifruit are the T-bar and the Pergola, with plantation densities ranging from 400-600 (Pergola) up to 720 plant/ha (T-bar). Canopy management should focus on determining the appropriate bud load (150 000 - 200 000 bud/ha) in winter and on maximizing the carbon budget during the growing season by reducing the amount of shaded leaves by summer pruning (Xiloyannis *et al.*, 1999). This in turn enhances light availability within the canopy improving fruit growth and some fruit quality traits (e.g. calcium content, Montanaro *et al.*, 2006).

As for pistachio, kiwifruit needs male plants to produce pollen for the female. The standard male to female plant ratio adopted is 1:6. Distribution of male plants is important to ensure pollination and adequate fruit size and yield. The use of bee hives or artificial pollen distribution during bloom is recommended.

Total global production in 2008 was 1.31 tonne, on 82 547 ha production area (FAO, 2011). Italy is the first producing country in the world (36 percent) followed by New Zealand (28 percent) and Chile (13 percent). However, these statistics do not include China, whose production has been estimated at 403 000 tonne of fruit in 2004 (about 65 000 ha producing area). Figure 1 presents the production trends of the main countries since 1985.

In addition to the green cultivar Hayward, a recent review describes the new cultivars of *A. deliciosa* and *A. chinensis* (yellow fleshed), which have been recently selected and released (Testolin and Ferguson, 2009).

FIGURE 1 Production trends for kiwifruit in the principal countries (FAO, 2011).



Quality considerations

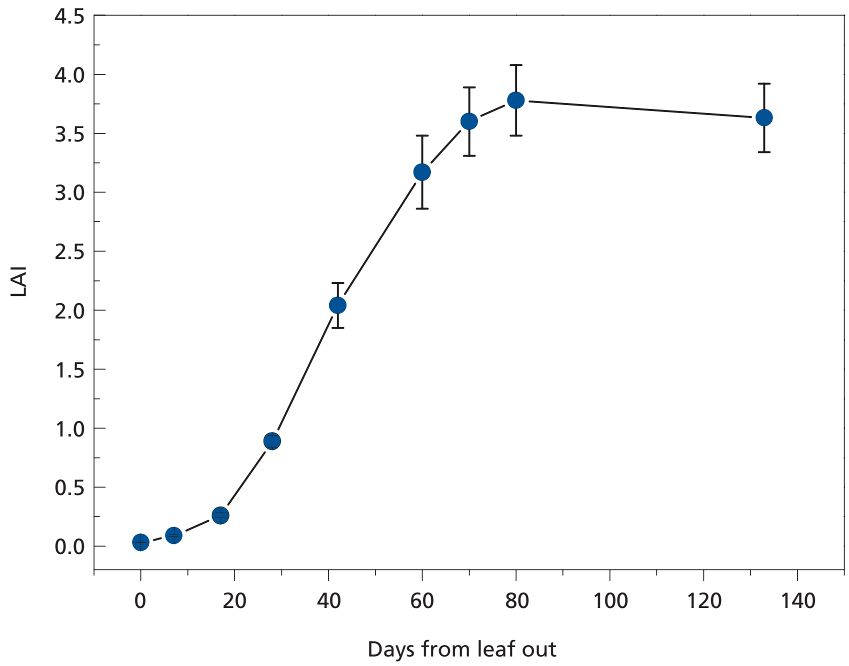
Particular attention should be paid to kiwifruit calcium (Ca) nutrition because of its involvement in determining tissue mechanical strength and tolerance to biotic and abiotic stresses. Cessation of Ca import into fruit has been linked to a number of morpho-anatomical changes of fruit properties related to reductions in fruit water loss, as transpiration from the fruit is the only mechanism responsible for Ca import. Therefore, it is desirable that canopy and irrigation management ensure adequate light distribution and windspeed within the canopy to enhance fruit transpiration and Ca accumulation. (Montanaro *et al.*, 2006; Xiloyannis *et al.*, 2008).

STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Bud development starts in spring and is largely completed by midsummer. Some buds are vegetative in that they give rise to vegetative shoots, while others are mixed, generating both leaves and flowers that develop from the same bud. The induction of the reproductive development of the bud occurs during late-summer to autumn followed by inflorescence differentiation, which will be completed by the next spring.

The chilling requirement to break dormancy is about 700-800 Richardson units for the Hayward cultivar (Linsley-Noakes, 1989), while for the yellow-fleshed cultivars chilling requirements are lower (500-600 units). The growing-degree-hours for bud break range from about 9 000 to 16 000 (Wall *et al.*, 2008). The buds break in spring which takes 10-15 days, thereafter shoots elongate quickly reaching 20-30 cm after 3 weeks. Leaves expand very rapidly during the early 30 days of growth, and the full leaf area is reached within three months (Figure 2). Values of LAI

FIGURE 2 Seasonal pattern of the leaf area index (LAI) in a *A. deliciosa* (Hayward) mature orchard in Italy (Pergola, 625 plants/ha). The day 0 is the April 10th (Xiloyannis *et al.*, 1999).



are around 2.5-3 in orchards trained to T-bar (~400 vine/ha), and up to 4-5 in orchards trained to the pergola system (~700 vine/ha). Different vigour rootstocks could greatly affect the LAI (Figure 3) particularly during the early years after planting. The evolution of LAI during the first years of planting is shown in Figure 4. Because the fraction of shaded leaves may represent up to 60 percent of LAI in pergola trained vines (Figure 5), it is important to control growth by summer pruning so that the proportion of leaves with high water use efficiency increases (Figure 6) and some fruit quality traits (e.g. calcium content) related to light availability are enhanced (Montanaro *et al.*, 2006).

After fruit set, the development of a fruit entails an initial rapid growth (predominant cell division stage) which spans about 50 days and is followed by the cell enlargement stage that slows down late in the season. The pattern of fruit growth, described as changes in fruit length or surface area, is shown in Figure 7.

RESPONSES TO WATER DEFICITS

Kiwifruit is quite sensitive to water deficit; vines do not survive stress levels associated with predawn leaf water potential values (LWP) below -1.5 MPa. Even mild water deficits determine rapid stomatal closure and increase in leaf temperature, which results initially in leaf tip burn and later leads to necrosis of the entire lamina. Restriction of water supply over the summer easily reduces fruit size at harvest. Mild water stress (about -0.5 MPa predawn LWP) occurring during the early growth of fruit (cell division stage) or later during fruit growth, causes a reduction in fruit size (Figure 8). However, in the case of deep soils with high water-holding capacity, an initial irrigation deficit may be tolerated without affecting fruit size (Reid *et al.*, 1996) as long as the soil

FIGURE 3 Evolution of the LAI in *A. chinensis* (cv. Hort16A) scion grafted on two Actinidia rootstocks in the Southern Hemisphere (Clearwater *et al.*, 2004).

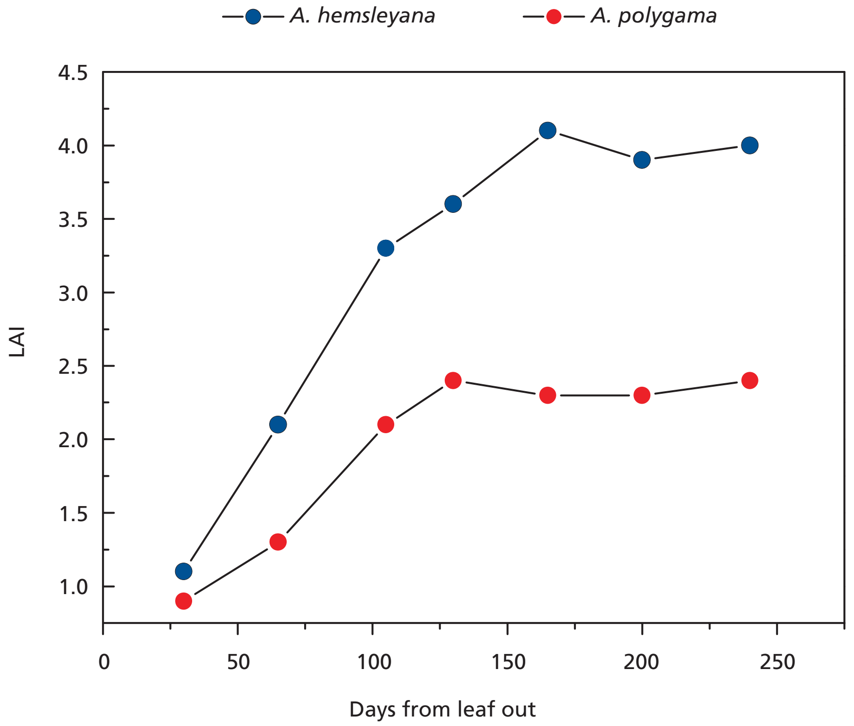


FIGURE 4 Variation of LAI in kiwifruit vines (cv. Hayward) trained to T-bar during the early 4 years after planting. Vines were planted at distances of 4.5 m between rows and 3 m along the row. The yield at the third year was 7 tonne/ha. (Xiloyannis *et al.*, 1999).

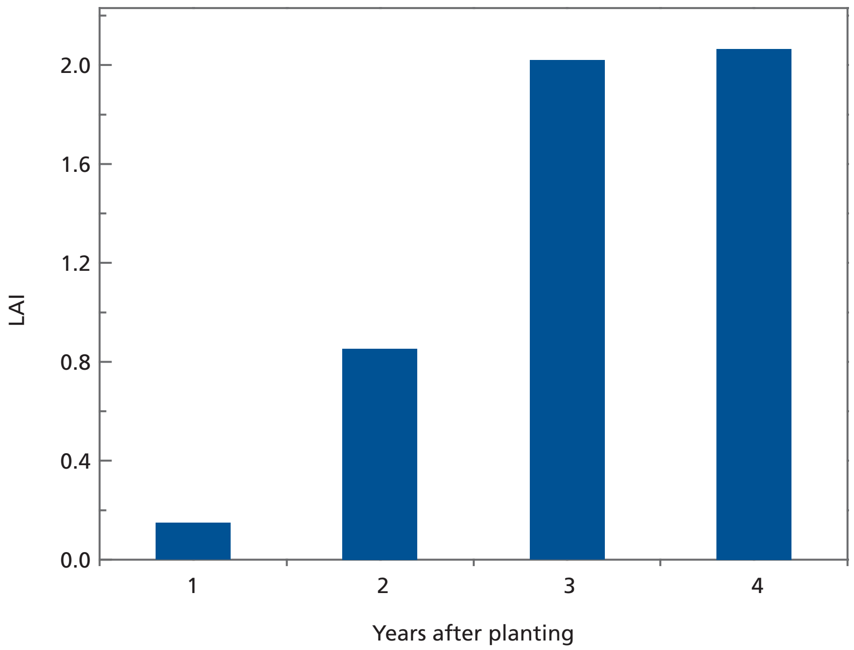


FIGURE 5 Fraction of the exposed and shaded (< 350 µmol m^{-2} s^{-1} PAR) LAI in a Pergola-trained Hayward kiwifruit.

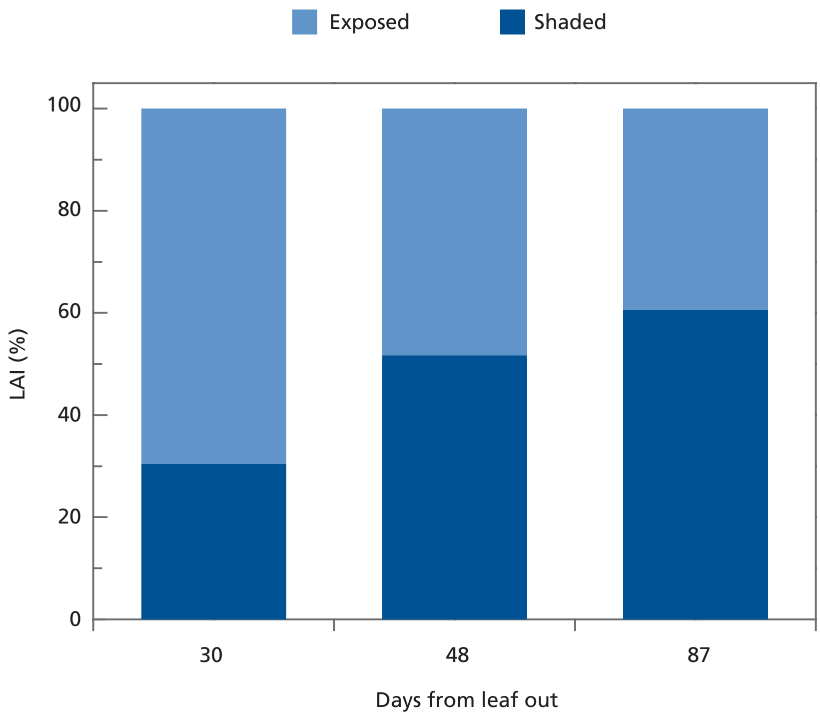


FIGURE 6 Daily mean water use efficiency (WUE) in exposed (•) and shaded (o) leaves during the season. DOY = Day of Year (Xiloyannis *et al.*, 1999).

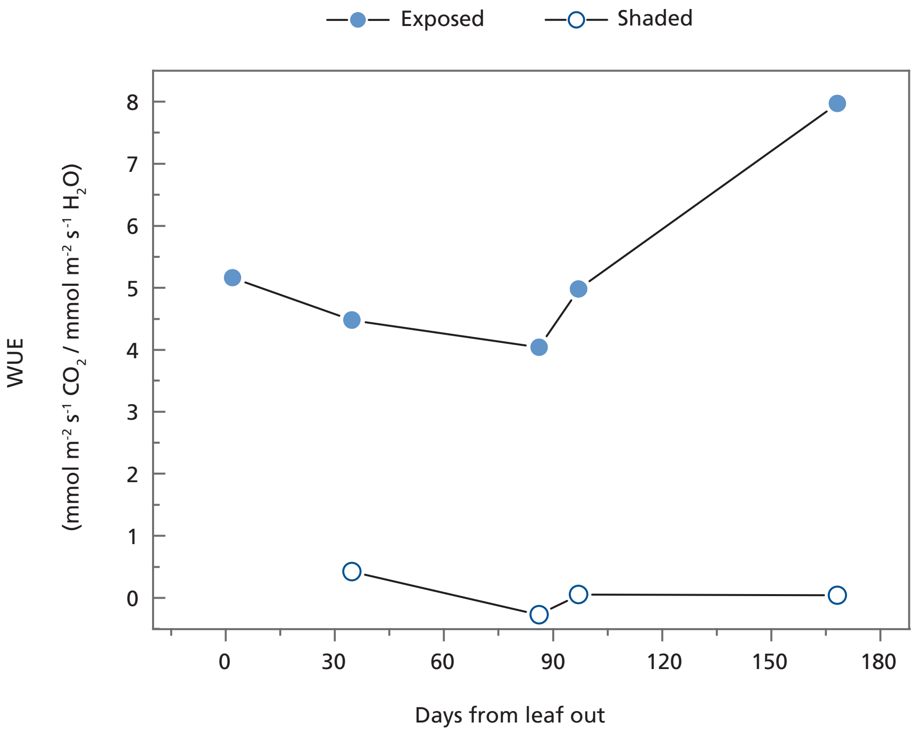


FIGURE 7 Schematic representation of the seasonal evolution of fruit length (continuous line) and of the fruit surface area (dotted line) in a mature kiwifruit orchard (cv. Hayward).

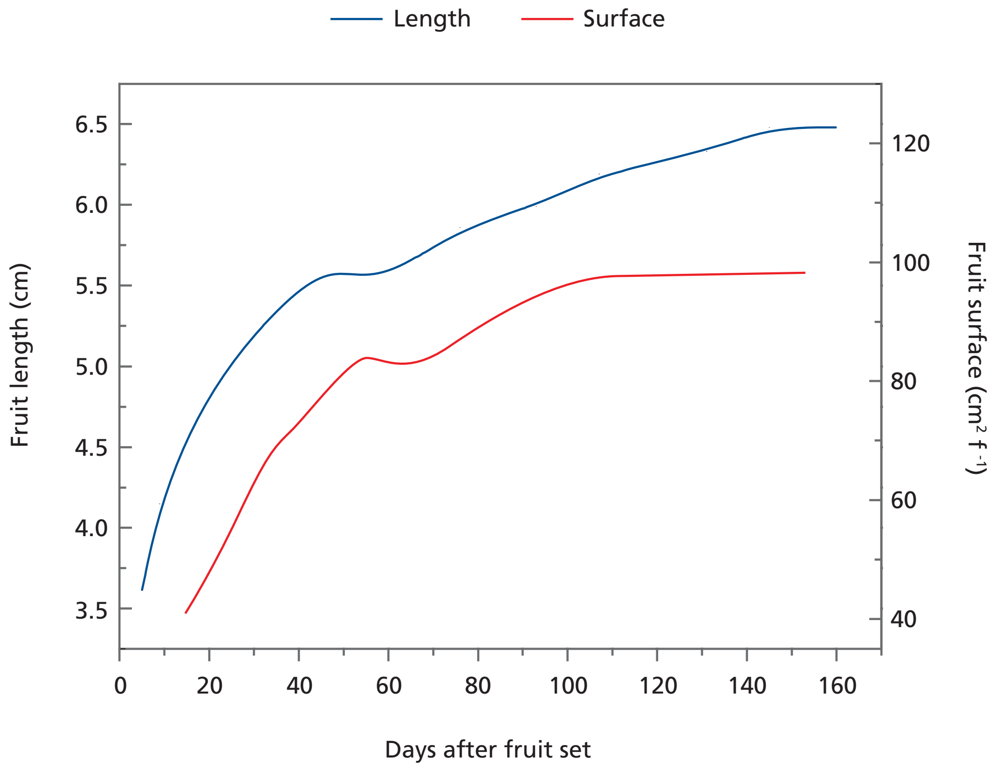


FIGURE 8 Effects on kiwifruit volume of water stress period (21 days) imposed in early (green line) or late summer (red line) compared to well-irrigated vines (blue line).
The grey strips represent the period of water deficit (Redrawn from Miller *et al.*, 1998).

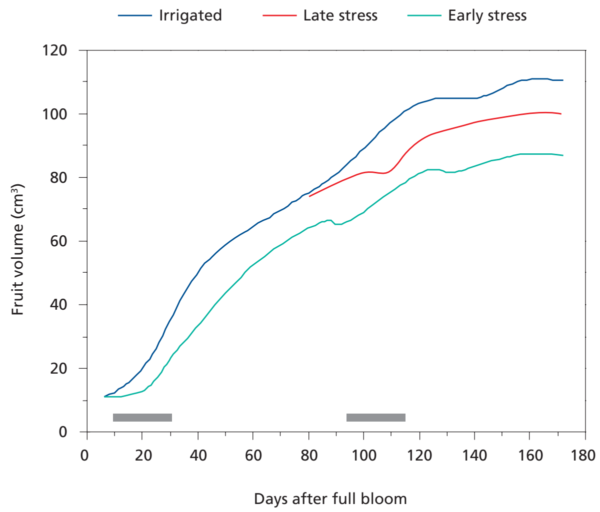


FIGURE 9 Soil volume explored by roots and the relative available water in an ownrooted kiwifruit orchard (740 plant/ha) during the early 4-years after planting. The yield at the third year was 7 tonne/ha. (Field capacity: 22.3 percent DW; wilting point: 11 percent DW) (Adapted from Xiloyannis *et al.*, 1993).

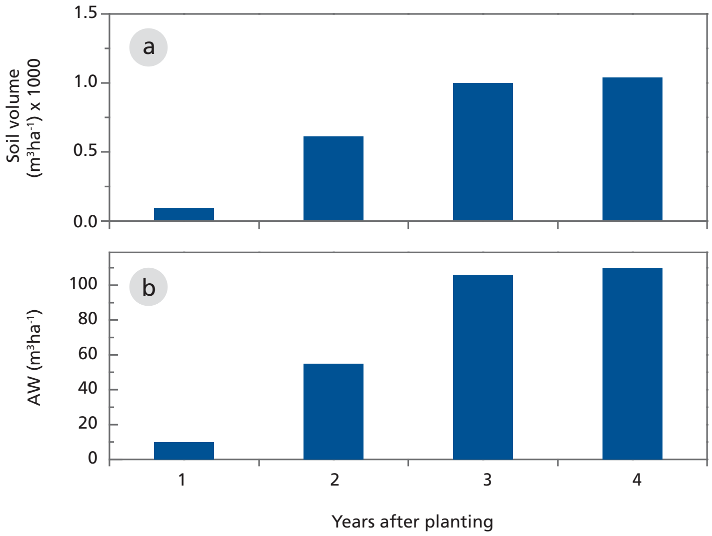
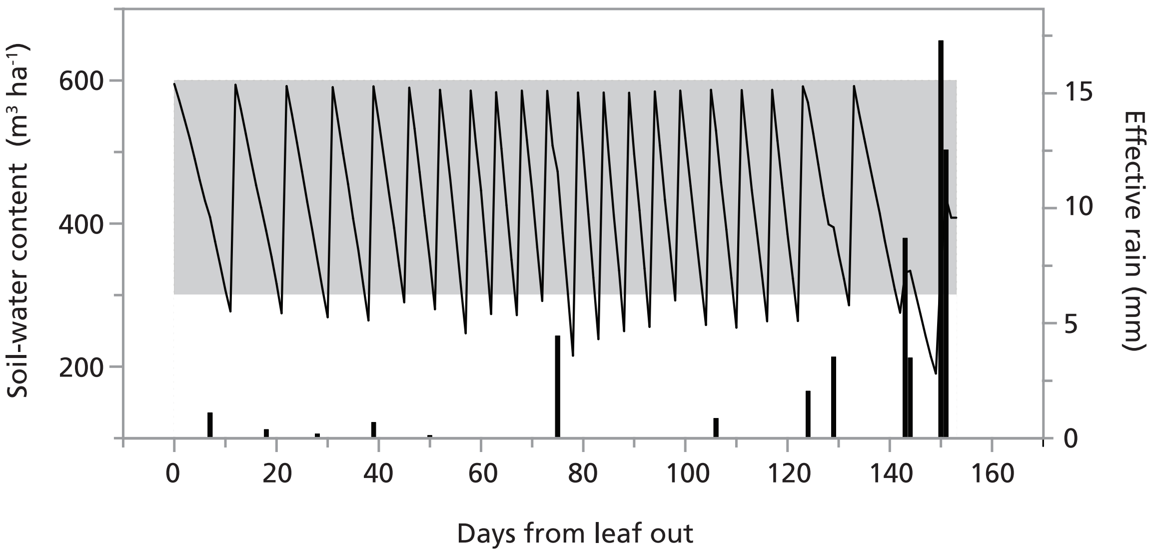


FIGURE 10 Variation of the volumetric soil-water content in a 0-70 cm soil layer. Irrigation has been scheduled when soil water content was below the lower threshold of the readily available water (RAW) (seasonal irrigation volume = 10 012 m^3/ha; ET_o from April to September = 993.7 mm). The grey strip represents the RAW. Bars are the effective rainfall. DOY = day of year. (Soil was not tilled, vines were irrigated by microjet wetting the whole soil surface) (from Montanaro *et al.*, in preparation).



water content is high enough to avoid mild water stress. Further, the evaporative demand and vine water consumption are low at this time.

Achieving a specific fruit dry matter (DM) target has been identified by the industry as a key component in the ongoing sustainability of kiwifruit production. Moreover, the minimum DM content for marketable fruit has been established in some countries (e.g. 15 percent DM is the minimum threshold for European markets (EC, 2004). The accumulation of DM in the fruit depends on maintaining high canopy photosynthesis, which is related to the training system, the light distribution inside the canopy and the level of orchard management (irrigation, fertilization, protection from biotic stress). Photosynthetic rates recover within about 10 days upon re-watering in severely (-1.0 MPa predawn LWP) stressed vines (Montanaro *et al.*, 2007) but apparently the loss in dry matter accumulation during a stressed period is never recovered.

Kiwifruit is quite sensitive to water stress throughout the whole growing season, hence soil water content should not decline below 70 percent of the water available in the root zone (Miller *et al.,* 1998). Knowledge of the effective soil volume explored by roots is of great significance when designing and managing irrigation of both mature and young orchards (Figure 8). Because of the peculiar kiwifruit root system, which has low dominance of root apex and a high number of lateral roots (Figure 9 and Photo 1), the kiwifruit has an overall high rooting density in the explored soil volume (~ 0.9 cm per cm^3) (Miller *et al.*, 1998) in comparison to other fruit tree species, but the lack of dominance of a tap root slows down and limits the exploration of the subsoil by kiwi roots. This pattern of root exploration may be partly responsible for the high sensitivity of kiwi to water deficits.

PHOTO 1 Root system of a self-rooted kiwifruit vine uprooted at the end of the fourth year after planting.

WATER REQUIREMENTS AND IRRIGATION MANAGEMENT RECOMMENDATION

On a midsummer day, a Mediterranean kiwifruit orchard consumes ~ 60-70 m^3 of water per ha, and seasonally, around 300-350 litre of water per kg of fruit are supplied (for a yield of 35 tonne/ha). Because of its high water demand and the sensitivity to dry environments, kiwifruit grown in areas of high evaporative demand must be irrigated by microsprinklers in order to maximize the soil surface area that is wetted. Volumetric soil water content should remain close to field capacity at all times (never reaching values below 30 percent of the root zone water storage capacity), hence the need for frequent irrigation applications. The recommended crop coefficients for kiwi are reported in Table 1, and Figure 10 shows an example of the seasonal variation of soil water content in a Hayward kiwifruit orchard (southern Italy 40°08′ N; 16°38′ E).

TABLE 1 Crop coefficients for a mature microjet irrigated kiwifruit (Hayward) orchard grown in the Northern Hemisphere (N 40° 23′ E 16° 45′). (seasonal irrigation volume = 10 012 m^3/ha). Note that the whole soil surface area was wetted and the soil was not tilled.

Apr.	May	June	July	Aug.	Sept.	Oct.
0.5	0.7	0.9	1.1	1.1	0.80	0.80

In conclusion, because of the sensitivity of kiwifruit to water deficits, RDI is not feasible in this species, and full water supply to meet the crop water requirements must be ensured for sustainable kiwifruit production.

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5. Epilogue

This publication, *Irrigation and Drainage Paper No. 66*, follows the tradition of FAO in producing papers addressing pressing land and water issues and providing guidelines to improve agricultural resources management.

With this new I&D paper, FAO is providing an enhanced set of tools, methods and knowledge, for the analysis and assessment of crop production in relation to climate, to water supply and shortage, to advance management strategies for improving crop productivity and water saving. The targeted potential users are agricultural practitioners, including farmer associations, irrigation districts, extension services, consulting engineers, governmental and non-governmental agencies, research scientists, agricultural and natural resource economists.

In the face of the increased threats of water scarcity worldwide, this publication comes at a time of great demand for maximizing the efficiency and productive water use. There is a need to sustainably intensify agricultural production in the face of incessant acceleration of competition for finite water resources, along with the uncertainties arising from climate change.

The tools and methods presented are effective as long as the user is fully aware of the strengths and limitations of their applications. The user is urged to carefully read the various Chapters, so not to fall into simplistic and inappropriate assessments.

Chapter 2 discusses the original FAO water production function method (*I&D* No. 33) of assessing yield response to water. This empirical approach is mostly suitable when a quick and first approximation of yield reduction related to water limitation is needed. This method has found many applications, particularly in various interdisciplinary studies at regional or even national scales, where generalized crop conditions prevaile and rapid assessments of yield reductions under limited water supply are required. Caution is necessary as the simplification introduced limits its applicability for accurate estimates of yield responses to water.

The use of *AquaCrop* (Chapter 3) is confined to herbaceous crops only, but with a wide spectrum of applications from the plot to field level and can be scaled up to watershed or regional level through aggregation. It can be used for yield gap assessment, to benchmark irrigation performance, and can assist in making informed water-related operational management decisions ranging from tactical to strategic. It can be used to optimize the cropping system in terms of crop and cultivar choice, planting time, and irrigation schedule for a given soil-climate combination where water is limiting. *AquaCrop* is also particularly suitable for the analysis of the impact of climate change scenarios on crop productivity, water requirements and consumption. Caution is required in the use of *AquaCrop* as its performance mostly depends on the accuracy of the input information and how well the crop has been calibrated. A well-calibrated crop and accurate local parameters, particularly the weather data, soil water characteristics, and phenology of the cultivar, are prerequisite for high-quality simulation results. Therefore the users are recommended to not rely solely on the crop file for the parameters of a particular crop, but check the *AquaCrop* web-page (www.fao.org/nr/water/aquacrop.html) for update of the crop parameters, and pay special attention to rough estimations or approximations involved in determining the local parameters. Questions and request for assistance regarding the model should be directed to the *AquaCrop* help-desk at its dedicated e-mail address (AquaCrop@fao.org).

The yield response to water of tree crops and vines is tackled through *Guidelines* for *Trees and Vines* (Chapter 4), as the current level of knowledge and the complexity of perennial crops prevented the development of a simulation model such as *AquaCrop*. Irrigation management of fruit and vine production must be based on accurate estimates of crop water requirements and on the crop-specific responses to water deficits, with emphasis on fruit quality. General concepts and applications are discussed first, followed by sections on specific crops where yield responses to water supply are generalized in the form of production functions. For many of these perennial crop plants, there are trade-offs between fruit quality and yield, as the maximum net economic return is achieved at irrigation levels below those needed for maximum yield. One outstanding example of this response is described in the section on grapes for wine production. Given such trade-offs and the increased water scarcity of many world areas, guidelines on the use of regulated deficit irrigation are included in every chapter, under certain assumptions on the restriction levels of water supply. The focus is on providing guidelines to optimize the use of a limited water supply, taking into account the sensitivity of certain growth stages to water deficits.

The perennial crops tackled in Chapter 4 are mostly grown in the temperate zones because insufficient information prevented inclusion of some important tropical tree crops. Given the growing demand for fruit, this subject matter is now receiving increased attention in research programmes. Guidelines for additional perennial crops will be introduced in future versions of this publication. The synthesis responses of fruit trees and vines to water presented here offers guidelines not only for improving the efficiency of water use in plantations but, also, for dealing with situations of water scarcity, which are a major threat to the viability and sustainability of fruit production in many areas of the world.

Included in this new publication is a CD containing a copy of each of the following: (i) this whole publication (*I&D Pape*r No. 66), (ii) the original FAO water production function (*I&D Paper* No. 33), (iii) the FAO guideline on crop evapotranspiration (*I&D Paper* No. 56), and (iv) a document listing potentially useful free-ware software and the internet link.

As next steps, the maintenance and development of the model *AquaCrop* has three aspects. (1) One is the continuous improvement of the model and refinement of the parameters for the crops already calibrated. It is anticipated that a new version of the model, prompted by feedbacks from users and testing with more extensive experimental data sets, may be released on the *AquaCrop* web-page as and when warranted. Regarding the crop parameters, as indicated on the *AquaCrop* website, the thoroughness of the parameterization varies from crop-to-crop. As more experimental data becomes available for calibration and testing, refinement in the parameter values are expected, and they will be posted on the website.(2) Additional herbaceous crops are and will continue to be calibrated. These may include common bean, millet, cassava, sweet potato, chickpea, forage crops and leafy vegetables. Some of these are among the so-called *locally-important* crops, to which particular attention will be paid. New crop sections, as well as the calibrated crop files with the calibrated parameters, will be provided on the *AquaCrop* web-page as they are finalized. (3) As part of the ongoing development of the software, special versions will be made available for use with various operating systems (e.g., Linux, Unix, etc.) and platforms for spatial analysis (e.g. GIS, DSS, etc.). For update, the user is recommended to visit the *AquaCrop* web-page periodically.

Special attention will also be given to the community of *AquaCrop* users and data and information providers. An *AquaCrop Network* is established with the purpose of sharing experience and scaling-up significant results. Particularly relevant is the scaling-up and propagation of 'training' in the use and application of *AquaCrop* and of the *Guidelines* for trees and vines, as well as of other related tools. *Face-to-face* workshops, *training-of-trainers* approaches, *distance*-and *e-learning* methods and other capacity development activities are being developed to respond to this need.

The overall goal is to reach out and engage a large community of users and potential users, and researchers with good experimental data, to enhance and expand the utilization of these tools, methods, and knowledge, and to improve them based on community input and feedback. This will ultimately lead to an augmented capacity of the users to sustainably manage water and crops while enhancing their productivity.

FAO IRRIGATION AND DRAINAGE PAPERS

1	Irrigation practice and water management, 1972 (Ar* E* F* S*)
1 Rev.1	Irrigation practice and water management, 1984 (E)
2	Irrigation canal lining, 1971 (New edition, 1977, available in E, F and S in the FAO Land and Water Development Series, No. 1)
3	Design criteria for basin irrigation systems, 1971 (E*)
4	Village irrigation programmes - a new approach in water economy, 1971 (F E*)
5	Automated irrigation, 1971 (E* F* S*)
6	Drainage of heavy soils, 1971 (E* F* S*)
7	Salinity seminar, Baghdad, 1971 (F E*)
8	Water and the environment, 1971 (E* F* S*)
9	Drainage materials, 1972 (E* F* S*)
10	Integrated farm water management, 1971 (E* F* S*)
11	Planning methodology seminar, Bucharest, 1972 (E* F*)
12	Farm water management seminar, Manila, 1972 (E*)
13	Water use seminar, Damascus, 1972 (F* E*)
14	Trickle irrigation, 1973 (E* F* S*)
15	Drainage machinery, 1973 (F* E*)
16	Drainage of salty soils, 1973 (C* E* F* S*)
17	Man's influence on the hydrological cycle, 1973 (E* F* S*)
18	Groundwater seminar, Granada, 1973 (E* F S*)
19	Mathematical models in hydrology, 1973 (E)
20/1	Water laws in Moslem countries - Vol. 1, 1973 (F* E*)
20/2	Water laws in Moslem countries - Vol. 2, 1978 (F E)
21	Groundwater models, 1973 (E)
22	Water for agriculture - index, 1973 (E/F/S*)
23	Simulation methods in water development, 1974 (E* F* S*)
24	Crop water requirements, (rev.) 1977 (C* E F S)
25	Effective rainfall, 1974 (C* E* F* S*)
26/1	Small hydraulic structures – Vol. 1, 1975 (E* F* S*)
26/2	Small hydraulic structures – Vol. 2, 1975 (E* F* S*)
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29	Water quality for agriculture, 1976 (E* F* S*)
29 Rev.1	Water quality for agriculture, 1985 (C** E* F* S*)
30	Self help wells, 1977 (E)*
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33	Yield response to water, 1979 (C* E F S)
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35	Mechanized sprinkler irrigation, 1982 (C E* F S*)
36	Localized irrigation, 1980 (Ar C E* F S*)
37	Arid zone hydrology, 1981 (C E)
38	Drainage design factors, 1980 (Ar C E F S)
39	Lysimeters, 1982 (C E* F* S*)
40	Organization, operation and maintenance of irrigation schemes, 1982 (C E* F S*)
41	Environmental management for vector control in rice fields, 1984 (E* F* S*)
42	Consultation on irrigation in Africa, 1987 (F E)
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44	Design and optimization of irrigation distribution networks, 1988 (F E)
45	Guidelines for designing and evaluating surface irrigation systems, 1989 (E)
46	CROPWAT – a computer program for irrigation planning and management, 1992 (E F* S*)
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64	Manual on small earth dams. A guide to siting, design and construction, 2010 (E)
65	Guidelines on spate irrigation, 2010 (E)
66	Crop yield response to water, 2012 (E)

Ar	–	Arabic	Multil	–	Multilingual
C	–	Chinese		*	Out of print
E	–	English		**	In preparation
F	–	French			
P	–	Portuguese			
R	–	Russian			
S	–	Spanish			

Crop yield response to water

Abstracting from the scientific understanding and technological advances achieved over the last few decades, and relying on a network of several scientific institutions, FAO has packaged a set of tools in this Irrigation and Drainage Paper to better appraise and enhance crop yield response to water.

These tools provide the means to sharpen assessment and management capacities required to: compare the result of several water allocations plans: improve soil-moisture control-practices under rainfed conditions; optimize irrigation scheduling (either full, deficit or supplementary); sustainably intensify crop production; close the yield and water-productivity gaps; quantify the impact of climate variability and change on cropping systems; enhance strategies for increased water productivity and water savings; minimize the negative impact on the environment caused by agriculture.

These tools are invaluable to various agricultural practitioners including, but not limited to: water managers and planners; extension services; irrigation districts; consulting engineers; governmental agencies; non-governmental organizations and farmers´ associations; agricultural economists and research scientists.

CONTRIBUTING INSTITUTIONS

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