Food and Agriculture Organization of the United Nations

ISSN 1020-1203

FAO WATER REPORTS

47

The AquaCrop model: enhancing crop water productivity

Ten years of development, dissemination and implementation 2009-2019

FAO WATER REPORTS

47

The AquaCrop model: enhancing crop water productivity

Ten years of development, dissemination and implementation 2009-2019

By
Maher Salman
Senior Land and Water Officer, Land and Water Division, FAO

Margarita García-Vila
University of Cordoba, Spain

Elias Fereres
University of Cordoba & IAS-CSIC, Spain

Dirk Raes
KU Leuven, Belgium

Pasquale Steduto
Former Chief of Water Service, Land and Water Division, FAO

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2021

Required citation:
Salman, M., García-Vila, M., Fereres, E., Raes, D. and Steduto, P. 2021. *The AquaCrop model – Enhancing crop water productivity. Ten years of development, dissemination and implementation 2009–2019.* FAO Water Report No. 47. Rome, FAO.
https://doi.org/10.4060/cb7392en

ISBN 978-92-5-135222-9

Contents

TABLES

FIGURES

Foreword

Water resources are linked to the global challenges of food insecurity and poverty, as well as to climate change adaptation and mitigation. In line with the Sustainable Development Goals (SDG), FAO works towards several dimensions of sustainable development, including the promotion of coherent approaches to efficient, productive and sustainable water management, from farm to river basin scales. Accordingly, FAO is enhancing well-informed on-the-ground decision-making processes on water management through projects, knowledge advancement, information-sharing and tools development, such as AquaCrop, the FAO crop-water productivity model. This model assists in assessing the effects of environment (including atmospheric CO_2 concentration) and management on crop production through the simulation of yield response to water of herbaceous crops. It is particularly suited to address conditions where water is a key limiting factor in crop production.

In 2009, FAO officially launched AquaCrop, being the result of several years of collaborative work among scientists, water and crop specialists and practitioners worldwide, bringing together previously fragmented information on crop yields in response to water use and water deficit. AquaCrop has evolved over the different versions released since its first launch, but it always balances accuracy, simplicity and robustness. This has enabled it to remain faithful to its goal, i.e., to be a dynamic tool accessible to several types of users, mainly practitioner-type end users, in different disciplines and for a wide range of applications. In addition, AquaCrop may be considered a valuable tool by research scientists for analysis and conceptualization.

After ten years of development, improvement, training and application of AquaCrop, a review and analysis of its performance and impact worldwide, including trends and challenges, have become relevant for FAO. Aware that several gaps and emerging issues remain, this assessment exercise is a first essential step towards the delineation of the future roadmap for the improvement, dissemination and proper application of AquaCrop. With that aim in mind, this report presents objective and comprehensive information and analyses on the current state, trends and impacts that the model has had on users, from a range of practitioners to the research community.

Presenting AquaCrop state-of-the-art, it is our hope that this report provides valuable information about the relevance of the tools and a guidance for the improvement and the new developments of the model, as well as for improving and extending its applications, always focusing on the progress of the management and productivity of the precious water resources.

Acknowledgements

The report “The AquaCrop Model: Enhancing Crop Water Productivity - Ten years of development, dissemination and implementation 2009-2019” is an effort of the Land and Water Division of FAO (NSL) with the contribution and valuable support of the members of the extended core group on AquaCrop model. The assessment performed in this publication is considered a prerequisite to the delineation of the future roadmap for the improvement, dissemination and proper application of AquaCrop.

The authors of this publication are Maher Salman (Land and Water Division, FAO, Rome), Margarita Garcia-Vila (University of Cordoba, Spain), Elias Fereres (University of Cordoba and IAS-CSIC, Spain), Dirk Raes (KU Leuven, Belgium) and Pasquale Steduto (Former Chief of Water Service, Land and Water Division, FAO).

The authors gratefully acknowledge the contribution of Ihab Jnad (ACSAD, Syria), Joost Wellens (University of Liege, Belgium), Lee Heng (Joint FAO/IAEA Centre, Austria), Rossella Albrizio (Consiglio Nazionale delle Ricerche, Italy), Sue Walker (Agricultural Research Council, South Africa), Theodore C. Hsiao (University of California, Davis, US) and Timothy Foster (University of Manchester, United Kingdom).

The authors acknowledge the support given by Sasha Koo-Oshima, Deputy Director, Land and Water Division of FAO.

A special thanks to James Morgan (NSL) for the design of the report.

Abbreviations and acronyms

A	Assimilation
B	Above-ground biomass
c_a	Ambient air CO_2 concentration
CC*	Adjusted green canopy cover
CCact	Green canopy cover development under limited conditions
CC	Green canopy cover
CCpot	Green canopy cover development under non-limiting conditions
CCx	Maximum value of green canopy cover
DAP	Days after planting
DP	Deep percolation
ECe	Electrical conductivity of the soil paste-extract
ECsw	Electrical conductivity of the soil water
E	Evaporation
e	Radiation use efficiency
ETa	Actual evapo-transpiration
ETc	Potential or maximum evapo-transpiration
ET	Evapo-transpiration
ETo	Reference evapo-transpiration
FAO	Food and Agriculture Organization
gb	Boundary layer conductance
GDD	Growing degree day
gm	Mesophyll conductance
gs	Stomatal conductance
HI	Harvest index
HIo	Reference harvest index

KcTrx	Basal crop coefficient
Ks	Stress coefficient
LAI	Leaf area index
NGO	Non-governmental organization
N	Nitrogen
PAR	Photosynthetically active radiation
Q1	First quartile
Q2	Second quartile
Q3	Third quartile
RO	Runoff
Rs	Solar radiation
RUE	Radiation use efficiency
TE	Transpiration efficiency
Tr	Crop transpiration
Trpot	Potential crop transpiration
T	Transpiration
VPD	Air vapour pressure deficit
wp*	Normalized biomass water productivity
WPa	Actual crop water productivity
w_p	Biomass water productivity
WP	Crop water productivity
WPm	Potential or maximum crop water productivity
WPY	Yield water productivity
Wr	Soil water content in the root zone
WUE	Water-use efficiency
Ya	Actual crop yield
Y	Crop yield
Ym	Potential or maximum crop yield
Zr	Rooting depth

1. Introduction

1.1. THE IMPORTANCE OF ENHANCING CROP WATER PRODUCTIVITY

The most outstanding feature of the climate of any given location on the Earth is its variability. There are variations in all climatic features at different time scales, from hours to seasons. Such variations are of different magnitudes depending on the parameter and on the time scale, for example, hourly solar radiation varies widely within a day, while average radiation varies little from year to year. Likewise, daily air temperature, humidity and wind speed fluctuate amply but their annual average values in one location do not vary much among years. Of all weather features, rainfall is undoubtedly the most variable at all temporal scales, and that has profound implications for agriculture. In many world areas, lack of sufficient rainfall limits agricultural production to such an extent that when long periods occur where rainfall is absent, they can even cause complete crop failure and famine. Drought spells happen in all climates, some are predictable as they occur around the same time every year, but others are uncertain and of a long duration, impacting negatively on most human activities, primarily on agriculture and food security. This is because all terrestrial plants require a continuous supply of water to grow and produce. Ensuring sufficient water under rainfed conditions is thus of at most importance.

Furthermore, when water becomes scarce, efforts are made to develop more “supply” or to manage properly the resource to reduce the “demand”. Due to various drivers (e.g., population growth, urbanization, climate change, groundwater depletion, etc.) the divide between supply and demand is continuously escalating. Priorities in water allocation often privileges domestic and industrial use before agriculture, which will always experience a progressive reduction of their allocation for irrigation. Therefore, a major response to water scarcity under irrigated conditions is to increase water productivity (produce more with less).

1.1.1. Plants and water

The relations between plants and water have been studied since very long ago. Monteith (1990) credited Woodward for the first publication on transpiration as early as in 1699 but indicated that Lawes in 1850 was among the first to explore the same subject for agricultural production. Extensive experimental studies on the use of water by crop plants were conducted more than a century ago in the Western United States of America, and de Wit (1958) was the first to synthesize past information and to establish a clear relation between transpiration and biomass production. This extensive early research is probably the basis why Tanner and Sinclair (1983) chose the title of their classical review consolidating the view that a reduction in biomass production was tied to a decrease in transpiration, and that the biomass to transpiration ratio (currently termed transpiration efficiency, TE) was a conservative parameter (it was fairly constant once normalized for climatic differences). Despite Tanner and Sinclair (1983)’s review and subsequent contributions supporting their analysis (e.g. Steduto *et al.,* 2007), it is not easy to accept the concept that regarding water use, plants are to a large extent at the mercy of their environment. This was clearly explained already in 1916 by Kiesselbach who stated that transpiration was purely a physical phenomenon, depending on the moisture supply to the leaves and on the evaporative power of the atmosphere (Monteith, 1990). Given the large gradient in water vapour between a saturated atmosphere inside the leaves and the much drier environment surrounding them, the rate of transpiration is quite significant, and large amounts of water are transported by plants from the soil to the atmosphere. As an example, a maize plant can transport an amount equivalent to its own weight in a single summer day.

1.1.2. Towards efficient use of water

Considering the tight linkage between biomass production and transpiration and the large amounts of water used by crops, interest in the issue of water limiting agricultural production has been very high, particularly in areas of limited rainfall of the arid and semi-arid world zones where production is negligible in the absence of irrigation. In such areas, the scarcity of water dictates that it should be used wisely and that the goal should be to obtain the best returns for society from the water that is available for various uses. This is how the notion of using water efficiently emerged in water-limited agriculture. To quantify the efficiency of water use, the most common term used is the water-use efficiency (WUE) which is a carbon:water ratio, defined in several ways depending on the scale of interest. Plant physiologists are interested in the exchange of water for CO_2 and define WUE as the ratio of carbon gain to water transpired, measured at the leaf or at the individual plant level. At the agronomic level the focus is on crop productivity, and WUE is defined as a ratio that has normally crop yield as the numerator with evapo-transpiration (ET) or total water supply as the denominator. Efficiency is a term that is commonly used in engineering and economics to characterize the performance of a process by determining the ratio of the output to the input for that process. In irrigated agriculture, the term WUE has also been used for a long time to evaluate irrigation performance (Israelsen, 1950), and is defined in this case as the ratio of the consumptive use (ET) to the total water input, at scales going from a particular field to a whole irrigation district or a region. The use of the WUE term to express different ratios has caused some confusion and this is why, more recently, the term water productivity (WP) has been proposed as the ratio of production (in biophysical or economic terms, expressed in weight or monetary units) over the amount of water used (normally expressed as ET in m^3) (Kijne *et al.*, 2003). Analogously to WUE, the definition of WP is scale dependent as discussed below.

1.1.3. The water balance

The process of assessing the efficiency of water use at the scale of a cropped field and at higher scales up to the basin level is governed by a fundamental process, the water balance. Considering the crop root zone, the water balance dictates that inputs from rainfall (and/or irrigation) must be balanced by losses due to surface runoff (RO), deep percolation (DP), evaporation (E) from soil, plant transpiration (T), and changes in soil water content. It is the disposition of water among all components of water balance that determines the efficiency of water use in the system under consideration. To understand the significance of efficient use of water, it is thus necessary to know the fate of the different water balance components within and outside the system under consideration. For a given field, the irrigation input is used as ET, RO, and DP, and they all may be considered losses. However, while the ET component contributes to production, RO and DP leave the field under consideration thus reducing the efficiency of irrigation. Nevertheless, at the farm scale, it is possible that the RO from one field is recovered and used in another field, and also that DP recharges the water table from where the farmer pumps to irrigate. Clearly, at scales beyond the field, RO and DP may not be true losses while ET evaporates and is lost to the atmosphere. Even though water quality deteriorates after its use, RO and DP losses are often recoverable within the basin and are reused until they reach a saline sink. It is therefore important to distinguish between water use, the total water input, and the water consumed as evaporation (ET) which has an uncertain fate and cannot be recovered within the basin. In the water accounting of agricultural systems, a distinction must be made to delineate the water depleted as ET and the actual reuse of the other components of the water balance.

1.1.4. The water productivity

In areas where the renewable water supply to crops is limited, an important goal is to use it as efficiently as possible to achieve the maximum societal benefits. Water productivity provides a metric for the assessment of the efficiency of water use but it can be defined in different ways, starting by quantifying the process by which plants trade carbon for water. As one scales from the leaf level up to the farmers' field, WP is defined as the ratio of production to water consumed as ET or of production over the total water supply. When economic or social considerations are taken into account, WP is defined as the ratio of crop value to water consumed or it may focus on some other beneficial output such as employment per unit water consumed. Getting the most out of the water supply should always be the focus without getting confused among the many definitions that have been coined for WP. Enhancing WP requires efforts in many different disciplines needed to examine the fate of WP from the production system all the way to consumers. The main avenues for improvement are explored below.

Genetic improvement, aimed broadly at drought resistance, has been the objective of much research over the last fifty years but so far, the results have not been encouraging. Much of the effort has been focused on finding traits for increased WP, seeking greater carbon gains per unit of water transpired (TE) at the leaf or individual plant levels. Early analyses (Tanner and Sinclair,1983) had pointed out that TE was highly conservative and was inversely related to the evaporative demand. Subsequent research on carbon isotope discrimination in relation to TE offered some hope of TE improvement and led to a commercial wheat cultivar with some yield advantage in dry conditions (Condon *et al.,* 2004). Finding drought resistance traits which are controlled by a few genes has proven elusive, however. Contrary to the reactions to biotic stresses, crop responses to water deficits depend on a myriad of genes modulated by an environment which varies in space and time. In fact, the progress in increasing yield and yield stability under drought has been questioned (Turner *et al.,* 2014). Nevertheless, research investments in the molecular biology of drought resistance have been very significant in the last 25 years with very little to show until now, except for thousands of published papers of limited relevance (Passioura, 2020). Conventional plant breeding, on the contrary, has contributed substantially to the improvement of WP over the years, but mostly by raising yield potential (maximum), which directly relates to the numerator of the WP ratio. It has been shown that, while the average and potential yields of the major crops have increased substantially over the years, the corresponding ET values have hardly changed for a given environment in the same time period. Duvick (2005) has shown that breeding increased the yields of maize hybrids released in 2000 by more than 40 percent over those released in 1960, suggesting an increase in WP of about the same magnitude. Breeding, which was specifically targeted to yield improvement under drought, has been less successful even though the relevance of agronomy (Acevedo and Fereres, 1993) and ecophysiology has been highlighted (Araus *et al.,* 2003). One of the most important efforts in breeding for stressed environments has been reported by Gaffney *et al.* (2015) who achieved about a six percent yield increase under water-limiting conditions in maize hybrids bred for drought resistance in a long-term program that integrated crop physiology and modelling to identify useful traits.

Agronomy has had a pivotal role in the improvement of WP until now. The increase in nutrient supply, matching planting dates and densities to the water available, weed control, and crop health measures all have contributed to the consistent yield increases over the years and therefore to the increase in WP. De Wit (1992) has shown that, when a production factor is limiting the most, an additional supply produces more the closer the other production factors are to their optimum. The upshot of that finding is that most production resources are used more efficiently with increasing yield levels, as overall growing conditions are further optimized. This is the basis for aiming at the sustainable intensification of production and emphasizes the role of good agricultural practices in increasing WP. As empirical evidence for the increase in WP, looking at the production trend over several decades of the three main cereals (wheat, rice, and maize) reported by Fischer and Connor (2018), it can be concluded that their WP must have increased roughly three times since 1960 as a result of cereal yield increases. It is important to highlight that considering WP improvement, agronomic measures not only achieve direct yield increases but can also increase the fraction of the water supply that is used effectively as transpiration. For example, high plant density and adequate nitrogen (N) supply enhance canopy development and changes the partitioning between E and T, thus reducing the E fraction of ET.

At scales beyond an agricultural field, improving WP is still a very relevant objective which must be integrated in the overall water management program. More efficient use of water in irrigated agriculture is a critical objective heavily demanded by society because it perceives irrigation as an inefficient process. The large expansion since the middle of the 20th Century makes irrigation the primary user of diverted water among all sectors of society, with more than 65 percent of total. Performance assessments of irrigation networks have yielded apparent low efficiencies in many world areas, giving the impression that there are ample opportunities for saving water. In water-limited areas, water accounting at the basin scale often does not confirm such an impression, as the reuse of apparent losses is widespread. A water balance analysis at the appropriate scale/s is thus needed before investing in reducing the recoverable losses. To evaluate the potential for improving WP, it is useful to consider that water use in agricultural systems generally occurs in sequence, following a number of chains from sources to sinks. Hsiao *et al.,* (2007) have analyzed the different chains and proposed a general framework for the assessment of the efficiency of water use of different agricultural systems. The chain of efficiencies framework allows the examination of current levels of efficiency and the identification of where, among the different steps along the chain, is most critical to improve it (Hsiao *et al.,* 2007). It is imperative that this framework is applied to any areas in need of improvement before investment decisions are made in those areas in the name of increasing WP.

In conclusion, improving WP is essential to make best use of water resources in agriculture, but it is not equivalent to saving water. While significant WP improvements have taken place over the last fifty years, there are still ample opportunities for more effective use of the limited water supply available in the different agricultural systems.

Within the toolbox needed to identify and exploit such opportunities, models for predicting crop yield response to water are indispensable for the assessment of WP.

1.1.5. Crop yield response to water

The linearity of the relation between biomass and transpiration, and the conservativeness of the harvest index within a range of water deficits, facilitated the formulation of an empirical model relating yield (Y) to ET. A few assumptions are needed to relate both parameters which, when expressed relative to their maximum or potential values, are related by a single empirical parameter which represents the rate of decline in relative Y against that of relative ET. This simple model, termed a water production function, was presented in the FAO Irrigation and Drainage Paper 33 (Dorenboos and Kassam, 1979) and it has been widely used for yield prediction as a function of ET. This approach has been very popular among professionals interested in broad yield predictions for hydrologic, agronomic and economic studies at scales above an individual farm, such as irrigation districts, regions or basins. After extensive use of water production functions, several major limitations have been revealed, primarily related to the site specificity of empirical predictions which prevent extrapolation to other environments, and to the inability to capture the differential sensitivity of yield responses to water deficits when they occur at different stages of growth.

1.1.6. Dynamic crop simulation models

As knowledge of plant physiology advanced, the simulation of crop behavior attracted many scientists interested in understanding the functioning of agricultural systems. The advent of computers facilitated the calculations needed to mimic the dynamic behavior of a crop and the integration and feedback loops needed to characterize the different processes involved in the growth, development and yield of crop plants. Several research groups in the Netherlands and the United States of America developed the first computer simulation models of crops around the late 1960's, and since that time there has been a continuous effort in developing more and more sophisticated crop models. The goals behind such efforts have been quite diverse, from identification of plant characteristics for breeding purposes, to test hypotheses about crop functioning, or to finding knowledge gaps that would guide further research. Because crops are very complex systems, models are still a simplification of reality, combining mechanistic formulations with empirical adjustments needed to match simulated to observed behavior (Loomis *et al.,* 1979). Nevertheless, the progress made in model building has been formidable and there are now many models available to simulate each of the major crops, although modelling efforts have largely remained in the research domain. The use of models for practical applications such as to assist crop management is not widespread among practitioners due to the high number of parameters that most simulation models require, and which are difficult to assess in field situations.

1.1.7. AquaCrop

Initially, crop models had their foundation on the simulation of canopy photosynthesis and were built with a high degree of complexity in order to capture the myriad of plant responses to the environment. Subsequently, a fundamental simplification was introduced by making use of the conservative relation between intercepted radiation and biomass production, termed as radiation use efficiency (RUE). Most crop models today make use of RUE to compute the simulated biomass on the basis of intercepted radiation and then simulate the harvest index to predict yield.

The use of water production functions to predict water-limited yield while effective, had obvious limitations which the FAO decided to overcome by conducting a series of consultations, starting in 2002, aimed at exploring either the use of existing simulation models or the option of building a new one. FAO decided to build a new, simpler model than those already established in the scientific community. Because the focus was on water-limited yield, it was decided that the new model would make use of another conservative relation, that between biomass production and crop transpiration, the WP. An important step was the normalization of WP for use in different environments, and it was shown that using Reference ET (ETo) as a normalizing factor, the WP was quite similar for several different crops, as published subsequently by Steduto *et al.* (2007). Thus, the new model, AquaCrop, would have a water-driven growth engine instead of a radiation-driven growth engine, which was the common approach of main models. Another important innovation was the use of canopy cover as the parameter characterizing crop growth instead of the leaf area index (LAI), which was the canopy property most commonly used in established models. AquaCrop also simulates the modulation of the response of the harvest index to water deficits in detail, an important requisite for a model that is focused on predicting yield as a function of the water supply available. The overall goal was to build a new model that would have an adequate balance among simplicity, accuracy and robustness, and that would be aimed more at a diverse range of practitioners than at the research community. Two main requisites to achieve that goal were to offer easy access by making the model as friendly as possible to users, and to minimize its complexity or to hide it from the users behind the software. The first versions of AquaCrop were released for testing around 2005, but it was in 2009 when the model was published by Steduto *et al.* (2009), together with a number of journal articles that described its performance in predicting the yield of several crops under variable water supply grown in different environments, and which are described in detail in the subsequent chapters of this publication.

1.1.8. How can simulation models assist in the assessment and improvement of WP?

Determining WP requires knowledge of production and of water consumed (ET), and there are many methods to measure or estimate WP. Two indicators of WP may be considered: one is the potential or maximum WP (WPm), which represents the maximum attainable WP and which is quantified as the ratio of yield potential (Ym) over the ET of a crop that is never short of water (maximum ET or ETc). The other WP that may be of interest is the actual WP (WPa), quantified as the actual yield (Ya) over the actual ET (ETa). For benchmarking the WP of an agricultural system under consideration, it is instructive to determine both WPm and WPa. This allows to make an assessment of the WP gap, which is the magnitude of the difference between actual and potential WP. Knowledge of the WP gap paves the way to formulate hypotheses and recommendations aimed at improving WPa and to glean other measures needed for improving the efficiency of water use.

Simulation models such as AquaCrop can provide estimates of potential yield and of ETc, thus providing both components of WPm. Additionally, if the water supply is insufficient, AquaCrop is able to compute the actual yield corresponding to the ETa that results from the available water supply, thus giving an estimate of WPa. In both cases, the estimates are the upper limit achievable for crops that would have no yield reducing factors resulting from pests, diseases or weeds. AquaCrop thus provides both WP estimates needed to assess the WP gap and this is one important model application. The alternative for a WP assessment is to estimate yields and ET either with field measurements or with estimates derived from remote sensing observations (Bastiaanssen and Steduto, 2017).

1.2. GOALS, SCOPE, STRUCTURE AND TARGET AUDIENCE OF THE REPORT

This publication has been produced ten years after the AquaCrop model was published. The model itself has been modified as different versions were released since it was first launched in 2009. From the onset of model development, FAO had the intention of building a model that could be used to assist member countries in implementing effective water management strategies and practices to sustainably intensify crop production, close yield and water productivity gaps, and quantify the impact of climate variability and change on cropping systems, among others. Even though crop models are developed in research and academic environments, given their complexity and integrated nature, AquaCrop attempted to simplify the complexity of modelling so that it could reach the major number possible of users. The focus was to provide an effective tool to help water managers and planners, extension services, consulting engineers, governmental agencies, NGOs, farmers' associations, agricultural economists, as well as research scientists.

The goal of this publication is to benchmark the results that AquaCrop has achieved in the first ten years (2009-2019), and to assess the impact that the model has had on users, from a range of practitioners in the field to those belonging to the research community. Another objective is to document the degree of usage of AquaCrop and to highlight the large diversity of model applications which was hardly envisaged when the model was being designed.

As to the structure of the report, following Chapter 1, Chapter 2 presents first a description of the three fundamental approaches in crop modelling based on carbon assimilation and on the efficiency of resource use, either solar radiation or water. It also presents a description of the current version of the AquaCrop model to provide the reader with the background on how the model is built and how it operates. The following three chapters are devoted to document in detail the use of AquaCrop in three main areas: research (Chapter 3), training and capacity development (Chapter 4), and applications on the ground (Chapter 5). Given the generalized use of publication metrics in research environments, it was possible to quantitatively assess the usage of AquaCrop and to determine some impact indicators which are commonly used in academia, as described in Chapter 3. The extensive training programs are delineated in Chapter 4, while Chapter 5 provides a summary of applications and approaches where AquaCrop has been used on the ground in projects and to assist a wide diversity of stakeholders in the management of water in agriculture.

2. Modelling crop yield response to water for enhancing water productivity

2.1. INTRODUCTION

The United Nations estimates that by 2030, almost half of the world population will be living in areas where the water demand is higher than the annual renewable fresh water resources. In those regions with water scarcity, the challenge for agriculture is to increase crop production by using less water. The achievement of 'more crop per drop' can only be accomplished by increasing the water productivity (WP).

To design strategies for improved water productivity in water-scarce regions, crop growth models are very useful. A model assumes different degrees of complexity in simulating the system, depending on the objective to achieve. Generally, a crop model is expected to be at the same time complex enough to be comprehensive in scope, and simple enough to easily access data and measurements for its parameterization, calibration and validation. Useful guidelines can be developed to improve WP by analyzing the results after running crop model simulations for different crop cultivars, different planting dates, and various irrigation and field management scenarios. Models are also good tools to study the effect of climate change on crop production.

Since existing models require a large number of variables and input parameters not easily available for the diverse range of crops and sites around the world, FAO developed the AquaCrop model balancing accuracy, simplicity and robustness. To be widely applicable, the model uses a relatively small number of explicit parameters and mostly-intuitive input-variables requiring simple methods for their determination. On the other hand, the calculation procedures are grounded on fundamental and often complex biophysical processes to guarantee an accurate simulation of the crop response to environmental and management factors.

The number and types of crop models present in literature is quite large and this is not surprising since there is no one universal crop model suitable for all the different systems to analyze, the objectives to achieve, the processes to simulate, the environmental boundary-conditions to define, etc. Listing the strengths and weaknesses of the various models is beyond the scope of this publication, an overview of 70 crop models is provided by Paola *et al.* (2016).

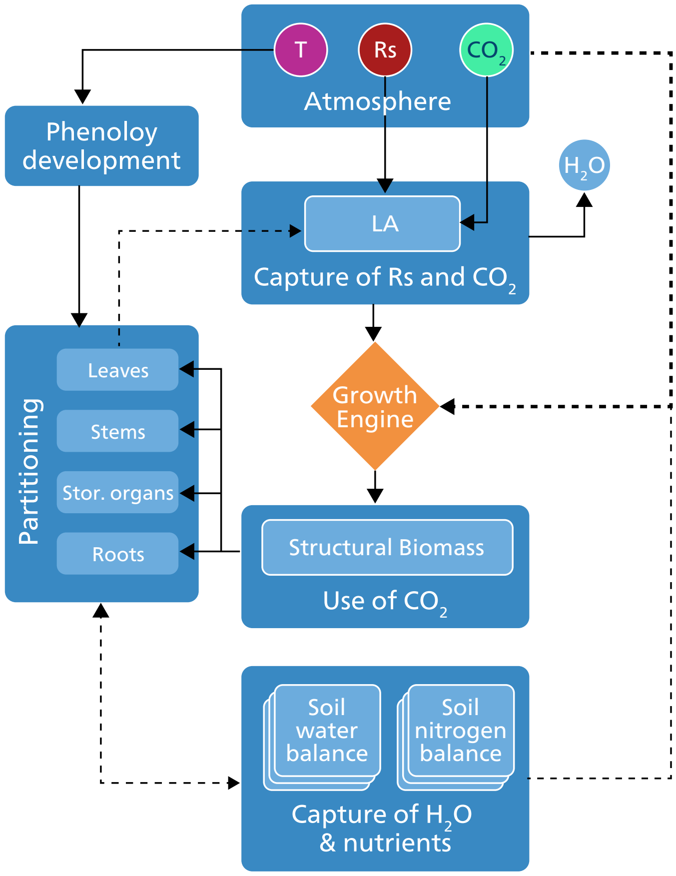
2.2. GROWTH-ENGINES OF CROP MODELS

Most crop models have many distinctive features while having also sufficient similarities, especially in certain basic physiological processes. This has induced new approaches in crop modelling development, where a modular platform implements the unifying physiological principles into a "crop template", while allowing several alternative processes to be employed. Among the unifying principles of crop growth are the processes of *capture* and *use* of solar radiation, carbon dioxide, water and nutrients. Moreover, at the heart of any crop growth model there is always a *growth-engine* that simulates the production of structural biomass from the use of captured solar radiation and carbon dioxide.

A general process-oriented crop model has a structure that integrates different components, each of them addressing part of the system being simulated. Typically, the soil-crop-atmosphere system is central to many crop models (Figure 2.1).

FIGURE 2.1

Schematic representation of a general process-oriented crop model. T=air temperature; Rs=solar radiation; LA=leaf area



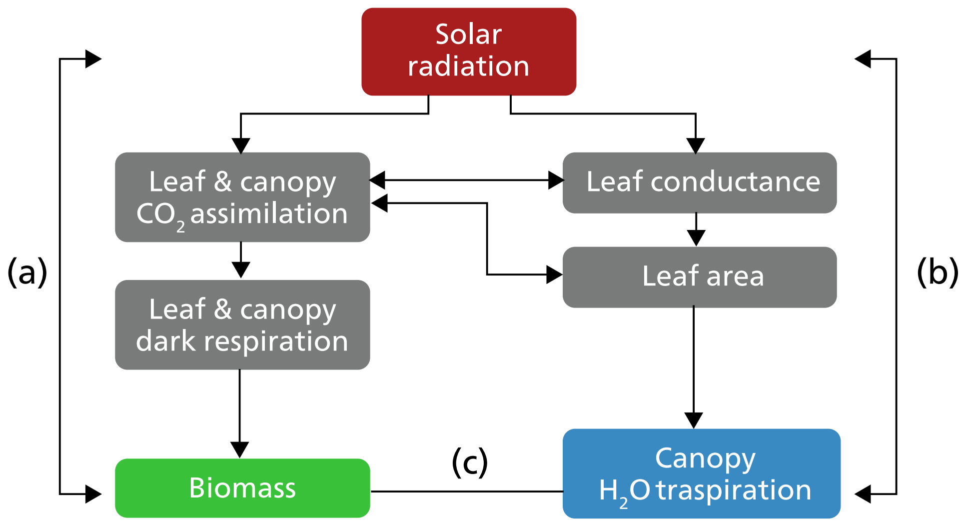
Source: Redrawn and modified from Steduto, 1997.

The crop phenological development is driven primarily by air temperature, while leaf area captures solar radiation and assimilates CO_2. The crop growth is, thus, driven by the accumulation of net carbon assimilated by leaves and transformed into biomass. The partitioning of this biomass into the various plant organs (leaves, roots, stems, storage organs) evolves accounting for the respiratory losses, together with phenological development and with the uptake of water and nutrients by the root system. While leaves assimilate carbon, they also lose water by transpiration, in turn is driven by the energy balance established at their surface.

The demand for nutrient and water for plant growth is balanced against the supply and uptake at soil level. The dynamics of mass and energy balance processes may induce stress conditions (e.g., temperature, water, nutrient, salinity, etc.), impairing growth via complex and articulated *feed-backs* and *feed-forward* mechanisms. Given the initial conditions, models integrate the rate-variables (e.g., assimilation rate) to update the state-variables (e.g., accumulated biomass) on daily time-steps. The processes involved in biomass accumulation, making use of captured solar radiation and assimilated carbon dioxide, are carried out by a specific model component (or sub-model routine) called *growth engine*.

The *growth engine* of all crop models has the solar energy (Rs) as primary driving force. However, the same solar radiation is also the primary driving force for water transpiration. Moreover, both the processes of carbon assimilation and water transpiration are occurring in gaseous phase through the same pathway (stomata). Because of the indissoluble link between carbon assimilation and water transpiration, this link is maintained while presenting the *growth engines*. Thus, for a given crop, the flows of linkages between Rs, biomass and water transpiration of its canopy can be represented as shown in Figure 2.2.

FIGURE 2.2
Flows of linkages between solar radiation, biomass and canopy transpiration



Solar radiation is the primary driving force for both biomass production (through the path a) and canopy transpiration (through the path b). These paths are one-way. A two-way link is, then, established between biomass production and canopy transpiration (through the path c). Over path (a), the underlining photosynthetic process runs the carbon assimilation by the single leaves, subsequently integrated to the whole canopy. The plant determinants of carbon assimilation are leaf conductance (the *sink-intensity* for CO_2) and leaf area (the *sink-size* for CO_2). Further, this carbon assimilation needs to account for the (leaf/canopy) respiratory losses to obtain the structural biomass. Over path (b), the underlying transpiration processes consists of leaf conductance (the *source-intensity* for H_2O) and leaf area (the *source-size* for H_2O). The path (c) shares the common features of paths (a) and (b).

Almost all *growth-engines* of the different crop models can be grouped into three main categories, depending on the hierarchy of processes and scales involved: (i) *carbon-driven growth-engine*, (ii) *solar-driven growth-engine*, and (iii) *water-driven growth-engine*. Some crop models have an internal switch that allows using more than one engine. For example, CropSyst, a cropping system simulation model developed by Washington State University, can switch between the *solar-driven* and the *water-driven growth-engines*, according to the most limiting resource.

2.2.1 The carbon-driven growth-engine

In the carbon-driven growth-engine, growth is based on the carbon assimilation by the leaves photosynthetic process. Maintenance and growth respiration of the various organs is accounted for to obtain biomass. Thus, the *carbon-driven growth-engine* follows path (a) as highlighted in Figure 2.2.

The advantage of this type of *growth-engine* is the excellent subdivision in hierarchical levels of system organization (e.g., organs, plant, crop), where the higher-level responses result from the integration of the lower-level processes. In other words, its structure is heuristic, mechanistic and explanatory, in which the processes have sound physical and physiological basis. For instance, the effects of leaf angles, of location latitudes and crop-row orientation, of diffuse and direct light, of elevated CO_2, of leaf carboxylation capacity, and other low-hierarchy processes are best investigated with this type of *growth-engine*.

The disadvantages of this type of *growth-engine* are ascribed to the variability of response observed at lower hierarchical level. For instance, the photosynthetic response function to photosynthetic active radiation is described by hyperbolas parameterized by the initial slope (or apparent quantum yield) and the maximum value of photosynthesis obtained at full light saturation. These two parameters are sensitive to temperature, nitrogen content, CO_2 partial pressure, leaf age, light history on the leaf, etc. Some of these variable changes along the different layers of the canopy profile following a much more complex structure than what is implemented in these models. Furthermore, if a new cultivar needs to be simulated, its experimental parameterization is quite demanding, timewise and resource-wise.

Most significant, however, are the uncertainties introduced by the maintenance and growth respiration processes. A first uncertainty is due to the derivation of gross photosynthesis, which is estimated in the presence of light (an intrinsic limitation). Furthermore, there is quite inconclusive evidence of the appropriateness of the respiration coefficients used. These uncertainties could lead to large errors in growth rates, especially in the presence of large biomass.

The models that use the *carbon-driven* engine include all the *growth-engines* of the Wageningen crop models (Bouman *et al*. 1996; van Ittersum *et al.*, 2003), among which are BACROS (BAsic CROP Simulator); SUCROS (Simple and Universal CROp Simulator); ARID CROP (BACROS with water-limited conditions); WOFOST (WOrld FOod STudies); MACROS (Modules of an Annual CROp Simulator); PAPRAN (Production of Arid Pasture limited by RAinfal and Nitrogen); SWACROP (Soil WAter and CROp Production); SWAP (Soil Water Atmosphere Plant); and many others. Some of these models are oriented more toward "understanding and explaining" (e.g., BACROS, SUCROS, ARID CROP) while others focus more toward "applications" (e.g., WOFOST, MACROS, PAPRAN). To this same group belong also the *growth-engines* of the American CROPGRO (CROP GROwth) crop-template model-series for soybean (SOYGRO), peanut (PNUTGRO), fava bean (BEANGRO), tomato (TOMGRO), and other crops (Boote *et al.*, 1998, 2002).

2.2.2 The solar-driven growth-engine

Although the solar radiation remains the primary driving force for all *growth-engines*, the term *solar-driven* is reserved here for the specific case when the crop model derives the biomass directly from the intercepted solar radiation through a single synthetic coefficient. In this type of *growth-engine*, there are no lower hierarchical processes expressing the intermediary steps necessary to simulate the biomass accumulation. This does not mean that the underlying processes are ignored (but rather that they are synthetically incorporated into a coefficient called radiation use efficiency (RUE or e). The *solar-driven growth-engine* still follows the path (a) highlighted in Figure 2.2 as in the *carbon-driven* growth engine, but bypassing the intermediary steps (i.e. leaf & canopy CO_2 assimilation, and leaf & canopy dark respiration).

This approach was based on the pioneering work of Monteith (1977), who demonstrated that cumulative seasonal light interception for several crops grown with adequate soil water supply was closely related to biomass production. He formalized and fully established the experimental and theoretical grounds for the relationship (e) between accumulated crop dry-matter and intercepted radiation, pointing to this approach as robust and theoretically appropriate to describe crop growth. Sinclair and Muchow (1999) reviewed the theoretical analysis, the experimental determination and measure of RUE, as well as summarized (with critical analysis) all literature values for a large number of crops.

The advantages of this type of *growth-engine* are in the robustness of the RUE relationship, remaining substantially constant under non-stressed conditions and for a large portion of the crop season, and in the relatively easy-to-derive values. One disadvantage of this type of *growth-engine* is ascribed to the inconsistent variability of e observed among crops, locations and years.

The main models that use the solar-driven *growth-engines* include those in the CERES (Crop Environment REsources Synthesis; Ritchie *et al.*, 1985) family, now DSSAT. Additionally, EPIC (Erosion Productivity Impact Calculator; Jones *et al.*, 1991), STICS (Simulator mulTIdisciplinary for Crop Standard; Brisson *et al.*, 2003), CropSyst (Cropping System simulation model; Stöckle *et al.*, 2003) and APSIM (Agricultural Production Systems sIMulator; Keating *et al.*, 2003).

2.2.3. The water-driven growth-engine

Referring to the initial structure of the linkages between solar radiation, biomass and transpiration, and the underlying processes depicted in Figure 2.2, it is possible to show that the *water-driven growth-engine* avoids the path (a) of the previous two engines (the *carbon-driven* and the *solar-driven*) adopting a completely new approach, corresponding to the path (c), as highlighted in Figure 2.2.

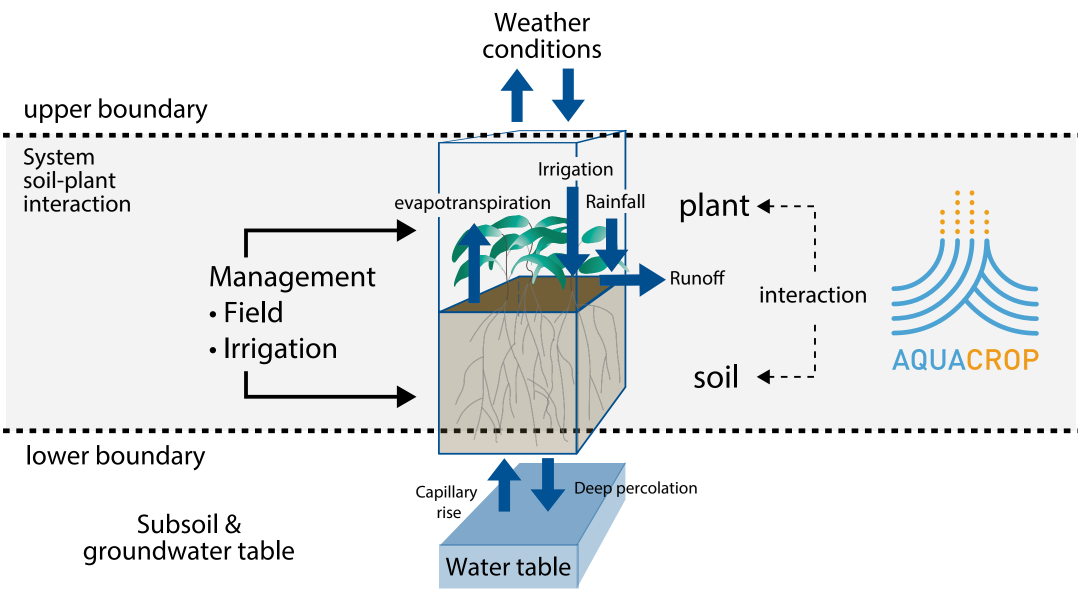
This approach has been initially highlighted by de Wit (1958), who showed the tight relationship between cumulative seasonal transpiration of crops, grown with adequate soil water supply, and biomass production. Furthermore, he was able to normalize for the different climatic conditions, from year to year and from location to location, by dividing crop transpiration for the evaporative demand of the atmosphere.

To the *water-driven* group belongs only one of the two *growth-engines* of CropSyst and of APSIM. This type of engine has been little explored in modelling due to the difficulties encountered in determining actual canopy transpiration. Nevertheless, advances in instrumentation technology allow nowadays more reliable determinations of evapo-transpiration (ET) and of the separation between E and T. The water-driven growth engine is at the core of the AquaCrop model, as it was concluded that the growth-engines best suited for the FAO Crop Water Productivity program is the water-driven. It appeared the most robust and most promising of the three growth-engines illustrated for the purposes of building a new model.

2.3. THE AQUACROP MODEL

AquaCrop is a crop water productivity model which describes the interactions between the plant and the soil as the primary system (Figure 2.3). From the root zone, the plant extracts water and nutrients, which allows the canopy to grow, the root zone to expand and the crop to produce biomass and yield. Field and irrigation management are considered in the model since they affect the soil-plant interaction. The model can be downloaded from FAO website at: http://www.fao.org/aquacrop/en/

FIGURE 2.3
The part of the reality between the upper and lower boundary described by AquaCrop



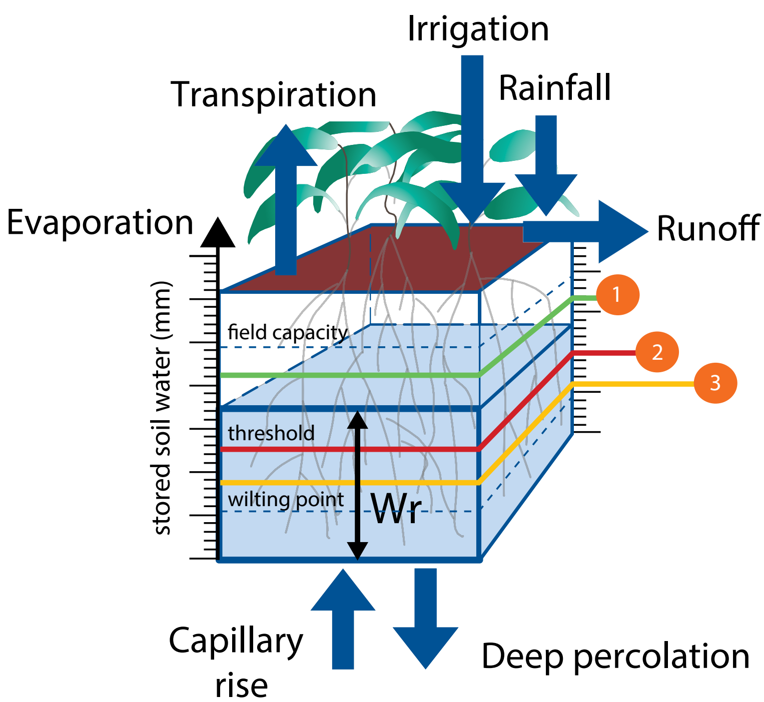
The described system is linked to the atmosphere through the upper boundary which determines the evaporative demand (ETo) and supplies rainfall, CO_2 and heat units for crop development. Water that cannot be retained in the root zone, drains from the system to the subsoil and the ground water table through the lower boundary. If the groundwater table is shallow, water can move upward to the system by capillary rise.

2.3.1. Soil water balance

To keep track of the soil water content in the root zone (Wr) and the corresponding soil water stress, AquaCrop updates the soil water balance at each daily time step. In a simplified way, the root zone can be depicted as a reservoir (Figure 2.4). AquaCrop considers three thresholds for the water content in the root zone. When the water content (Wr) drops below a threshold, crop water stress starts to develop, which respectively (1) slows down canopy expansion growth, (2) reduces transpiration and (3) triggers early canopy senescence. The lower the soil water content below the threshold, the stronger the water stress.

FIGURE 2.4

The root zone depicted as a reservoir, with indication of the 3 thresholds below which (1) leaf expansion growth starts to affect canopy development, (2) stomata closure starts to affect crop transpiration, and (3) early canopy decline is triggered



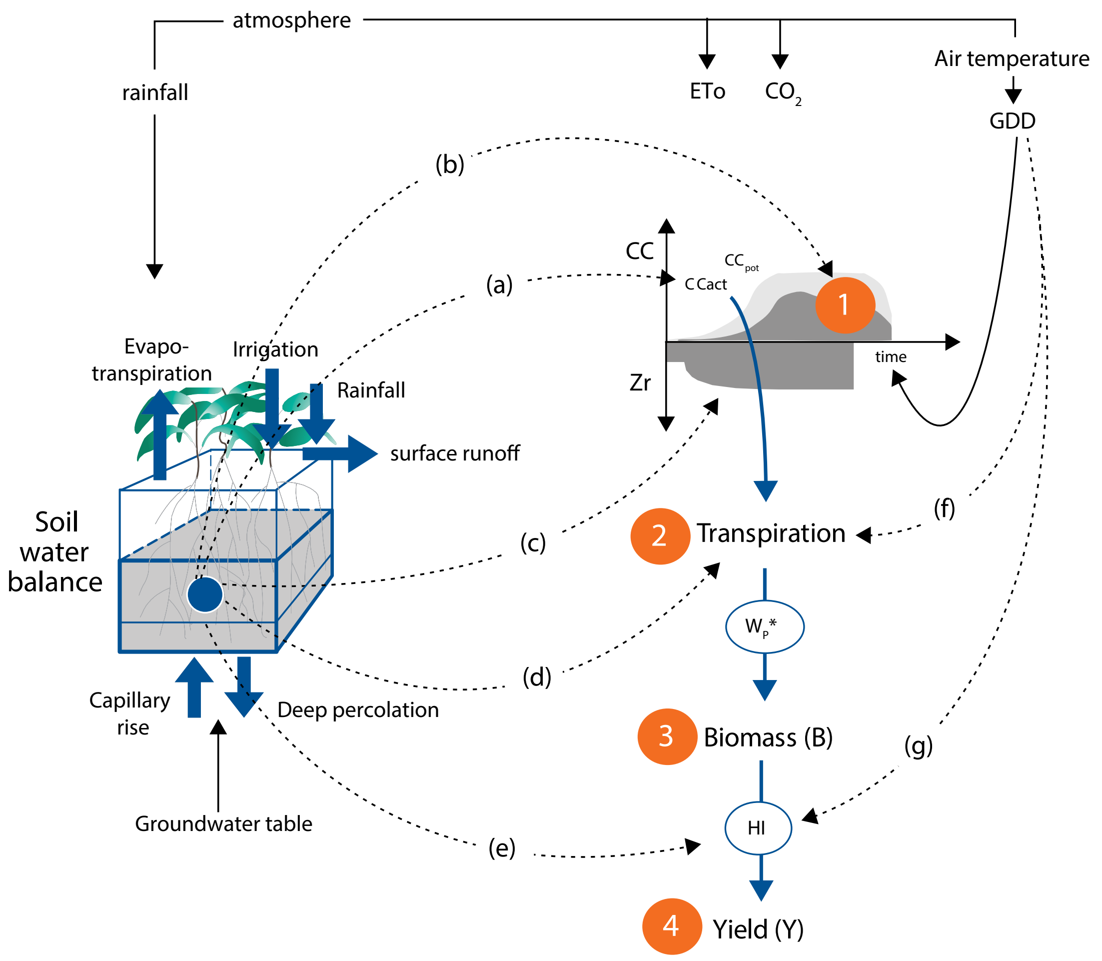
To describe accurately the retention, movement and uptake of water in the soil profile, AquaCrop divides the soil profile into small compartments with their own soil physical characteristics. As such the one-dimensional vertical water flow and root water uptake can be solved at each time step by means of a finite difference technique.

2.3.2. Simulation of crop development and production

The simulation of crop development and production is based on fundamental and often complex biophysical processes to guarantee an accurate simulation of the crop response in the plant-soil system. AquaCrop simulates crop production in four steps that are easy to understand, and which makes the modelling approach transparent. The four steps, which run in series at each daily time step, shown in Figure 2.5, consist in the simulation of:

1. Development of the green Canopy Cover (CC)
2. Crop transpiration (Tr)
3. Above-ground biomass (B)
4. Crop yield (Y)

FIGURE 2.5
Calculation scheme of AquaCrop



CC is green canopy cover; Zr, rooting depth; ETo, reference evapo-transpiration; w_p*, normalized biomass water productivity; HI, harvest index; and GDD, growing degree day. Water stress: (a) slows down canopy expansion, (b) accelerates canopy senescence, (c) decreases root deepening but only if severe, (d) reduces stomatal opening and as such affects transpiration, and (e) affects the harvest index. Cold temperature stress (f) reduces crop transpiration. Hot or cold temperature stress (g) inhibits pollination and reduces HI.

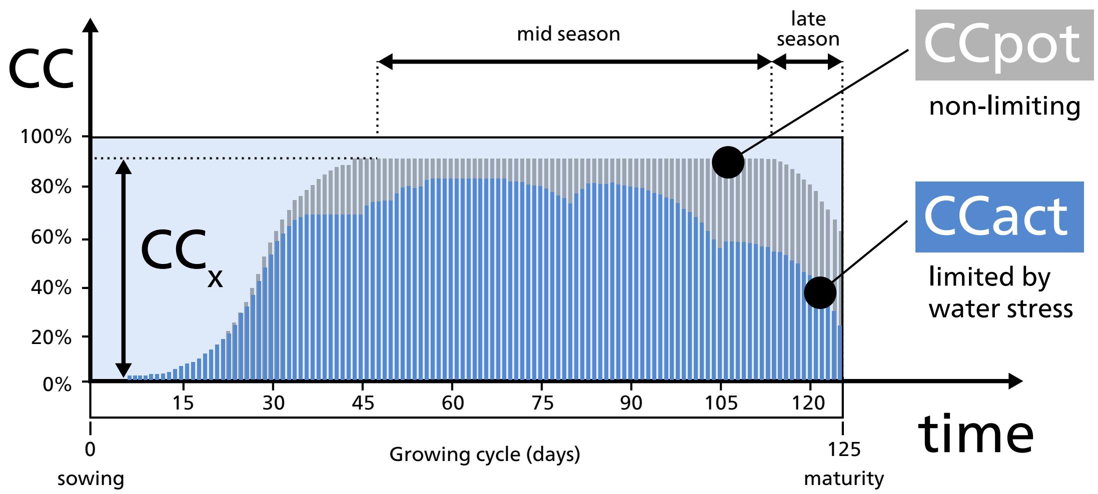
2.3.3. Crop development

Development of green canopy cover (CC)

In AquaCrop, foliage development is expressed through green canopy cover (CC) and not via Leaf Area Index (LAI) as many other models. The green canopy cover (CC) is the fraction of the soil surface covered by the canopy. It ranges from zero at sowing (0 percent of the soil surface covered by the canopy) to a maximum value (CCx) at mid-season which can be 100 percent when a full canopy cover is reached (the soil surface is completely covered by the canopy).

Under non-limiting conditions, canopy development is simulated for the first half of the growth curve by an exponential growth equation. For the second half of the growth curve, CC follows an exponential decay. At mid-season, once the maximum canopy cover (CCx) is reached, CC remains constant. In the late season, the green canopy cover declines due to natural senescence. (CCpot in Figure 2.6).

FIGURE 2.6
Canopy development under non-limiting (CCpot) and limited (CCact) conditions



When running a simulation, the actual canopy development might be quite different from the development under non-limiting conditions (CCact in Figure 2.6). By adjusting daily, the soil water content in the soil profile, AquaCrop keeps track of the stresses which might develop in the root zone. When the water content in the root zone drops below the canopy expansion threshold, the growth of the canopy will slow down and finally stops completely when the water stress becomes too strong. If water stress becomes severe also early canopy senescence will be triggered. In this way, water stress may prevent CCx to be reached and might result in a smaller canopy size.

Expansion of the root zone

At sowing or planting, the effective rooting depth is minimal. In a well-watered soil, the root zone will expand till the maximum effective rooting depth is reached. When water stress affects stomatal closure, not only crop transpiration but also the expansion of the root zone will slow down. Root deepening is also limited in soil layers with low penetrability and when the sub-soil at the front of root zone expansion is very dry.

Crop development adjustment to the temperature regime

The development of the green canopy cover and the deepening of the root system are simulated as a function of time in AquaCrop. When running AquaCrop in growing degree days (GDD), heat units (°C) accumulated during the day are used to adjust the expansion of the canopy cover and the deepening of the root system. If the average air temperature is below the crop base temperature, no heat units can be accumulated during that day and crop growth is halted.

2.3.4. Crop transpiration

For well-watered conditions, crop transpiration (Tr) is basically proportional to CC, but with an adjustment for inter-row micro-advection and sheltering effect by partial canopy cover. The adjusted green canopy cover (denoted as CC*) is used to calculate transpiration. The proportional factor is a basal crop coefficient (Kc_{Trx}) for full canopy cover (CC = 1). When there is no stress-induced stomata closure, crop transpiration (Tr_{pot}) is calculated by multiplying the reference evapo-transpiration (ETo) with the term [Kc_{Trx} CC*]. ETo is a measure of the evaporative demand of the atmosphere, and determines the rate of crop transpiration and soil evaporation. The term [Kc_{Trx} CC*] is proportional to the simulated canopy cover and hence varies throughout the life cycle of the crop in correspondence with the natural canopy development and encountered stresses.

Water stress does not only affect CC but might also affect directly crop transpiration. Water shortage in the root zone will trigger stomata closure, resulting in a reduction of crop transpiration. Deficient aeration conditions in a waterlogged root zone affects transpiration as well. Finally, crop transpiration is also reduced by cold stress, when there are insufficient heat units. The effects of those stresses on transpiration are simulated by multiplying Tr_{pot} with various stress coefficients (Ks). In the absence of stress, each Ks is equal to one. When a stress starts to build up, the corresponding Ks becomes smaller than one and might even finally reach zero when the stress is complete and transpiration is halted.

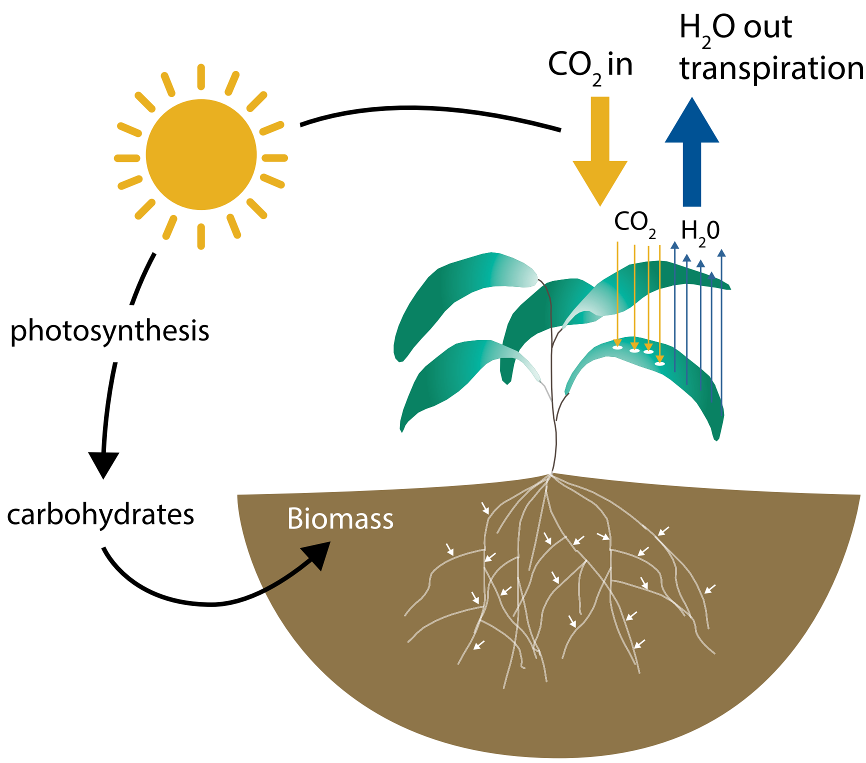
2.3.5. Above-ground biomass (B)

By separating evapo-transpiration (ET) into crop transpiration (Tr) and soil evaporation (E), AquaCrop avoids the confounding effect of the non-productive consumption of water (E).

When plant stomata are open, green plants take up carbon dioxide (CO_2) from the atmosphere and transport it through the stomata to the interior of the leaves. Simultaneously water vapour (H_2O) is removed from the leaves by transpiration to the atmosphere through the stomata. In the plant cells, CO_2 is converted to carbohydrates by a photosynthesis process in the presence of sunlight (Figure 2.7). The carbohydrates are the building stones for the total plant biomass (roots, leaves, stems, flowers, fruits, etc.).

FIGURE 2.7

Simplified presentation of the photosynthesis process whereby CO_2 and available water are converted to carbohydrates which are the building stones for the total plant biomass



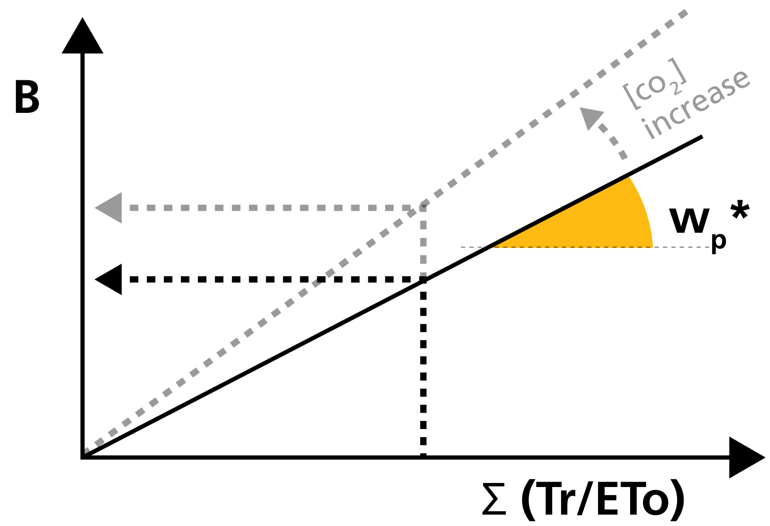
Since CO_2 uptake and water vapour removal uses the same pathway (stomata), there exists hence a direct link between biomass production and crop transpiration. The conceptual equation at the core of the AquaCrop, states that biomass production (B) is proportional to the cumulative amount of water transpired (ΣTr). The proportional factor is the biomass water productivity (w_p). In AquaCrop, w_p is normalized for variations in evaporative demand (represented by ETo) which makes the normalized biomass water productivity (w_p*) valid for diverse locations and seasons (Figure 2.8). The w_p* is also normalized for the CO_2 concentration of 369.41 ppm in the reference year (2000). As atmospheric CO_2 concentrations increases, w_p* increases (Figure 2.8).

2.3.6. Crop yield (Y)

AquaCrop simulates the above ground biomass (B) which integrates all photosynthetic products assimilated by the crop during the season. By using a reference Harvest Index (HI), which is the fraction of B that is the harvestable product, crop yield (Y) is obtained as the product of B times HI. Water and temperature stresses during the growing cycle might alter HI from its reference value (HIo). The adjustment of HI to water deficits depends on the timing and extent of water stress during the crop cycle. Severe water stress, cold or high temperature during pollination might also trigger an adjustment of HI.

FIGURE 2.8

Linear relationship between the cumulative amount of water transpired, normalized for the effect of the climatic conditions Σ(Tr/ETo), and the biomass production (B), with indication of the proportional factor wp*



2.3.7. Salt balance

To keep track of soil salinity and the corresponding soil salinity stress, a salt balance has been incorporated in AquaCrop which is updated daily. Salts enter the soil profile as solutes with the irrigation water or through capillary rise from a shallow groundwater table. The extent to which salts accumulate in the soil depends on the quality and quantity of the irrigation water, the frequency of wetting, the adequacy of leaching, the magnitude of soil evaporation and crop transpiration, the soil physical characteristics of the various layers of the soil profile, and the salt content and depth of the groundwater table. Salts are transported out of the soil profile (leached) by drainage.

The indicator for soil salinity in a well-watered soil is the average electrical conductivity of the soil paste-extract (ECe) in the root zone during the growing cycle. When ECe drops below its threshold, soil salinity stress slows down the canopy expansion, reduces the maximum canopy cover (CCx) that can be reached, and induces some canopy decline during the crop cycle, resulting in a reduced canopy cover (CC) and reduced crop transpiration. Crop transpiration is also affected directly by salinity stress as a result of a partial closure of the stomata.

Canopy development and crop transpiration might be further affected if next to salinity stress, also water stress starts to affect crop development and production. In the presence of water stress, the electrical conductivity of the soil water (EC_{sw}) is considered in AquaCrop, since soil salinity stress increases when the soil dries out. The high salt concentration in the limited amount of the remaining soil water, results in a stronger effect of soil salinity on crop development and production.

2.3.8. Management

Temperature, water and salinity stresses affect crop development and production. AquaCrop simulates also the effect of irrigation and field management on the canopy development, crop transpiration, biomass production and yield.

Irrigation management

The water application amount, salt content and irrigation interval alter the water and salt balances of the root zone, thus affecting crop development and production. By running different simulations with variable irrigation schedules, the simulated crop yield and yield water productivity (WP_Y) might provide valuable information about the performance of the irrigation schedule, and indicate the way forward to optimize crop yield and/or the yield water productivity.

Field management

Various types of field management are considered in AquaCrop: soil fertility, field surfaces practices, mulches, and weed management.

Soil fertility

To keep the model relatively simple, AquaCrop does not simulate nutrient balances to predict soil fertility limitations. Instead, AquaCrop employs an indirect approach by offering semi-quantitative options to assess the effect of the fertility regime on canopy development and biomass water productivity.

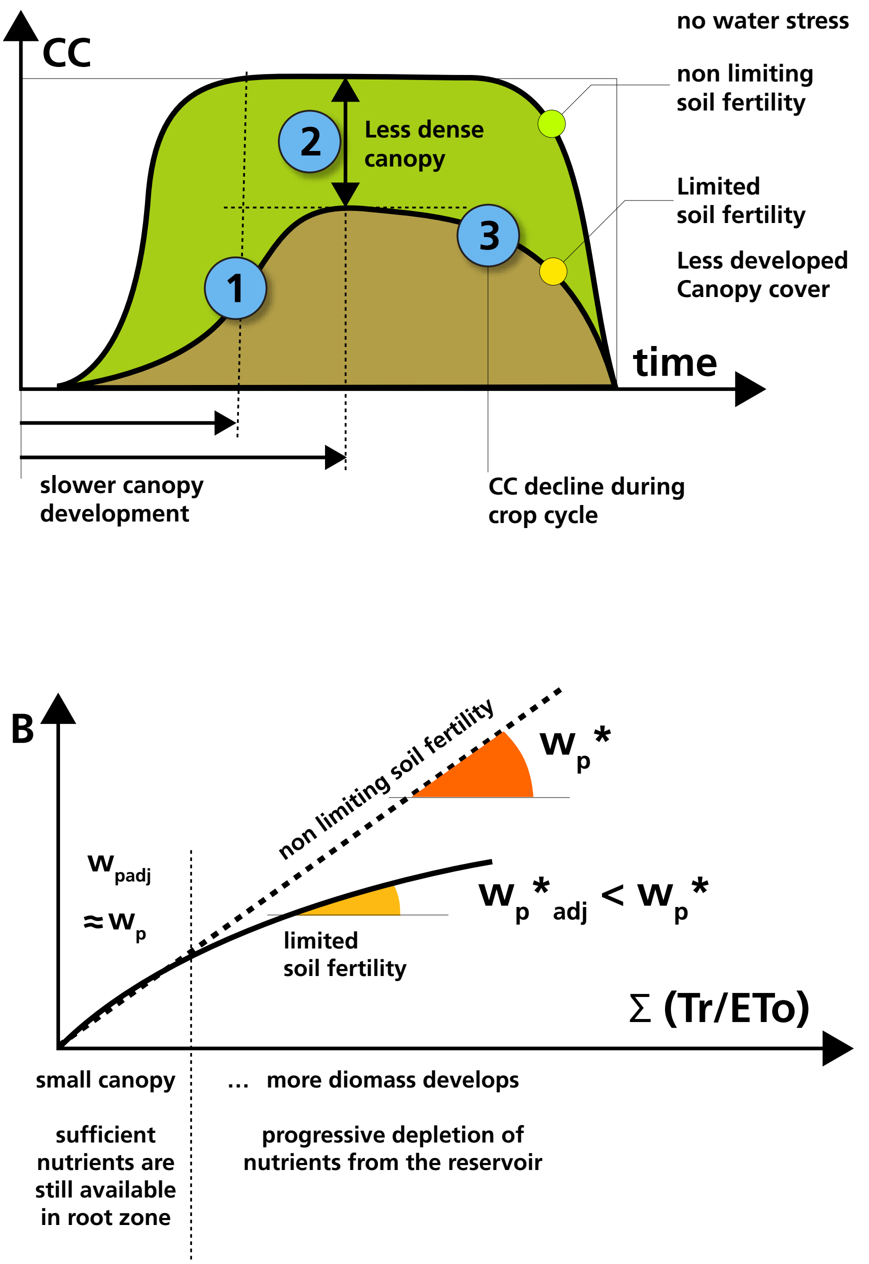
The effect of soil fertility stress on canopy development is simulated in AquaCrop by mimicking its effects as observed in the field (Figure 2.9a): (i) slower canopy development, i.e. requiring more time to reach maximum canopy cover (CCx); (ii) less dense canopy cover (lower CCx); and (iii) a faster the canopy cover decline once CCx is reached at mid-season.

Mineral nutrient stress, particularly lack of N, can also reduce the biomass water productivity (w_p*). Because the reservoir of nutrients gradually depletes when the crop develops, the effect of soil fertility on the adjustment of w_p* is not linear throughout the season (Figure 2.9b). As long as the canopy is small, the daily biomass production will be rather similar to the daily production for non-limited soil fertility. This is the case early in the season when sufficient nutrients are still available in the root zone and the uptake of N is limited. If the crop does not experience water stress, the canopy will further develop during the season but this will result in a progressive depletion of nutrients from the soil pool, and this reduces w_p* with time (Figure 2.9b).

Soil fertility ranges from non-limiting to poor, with increasing reductions in w_p*, leaf expansion rate, CC and green canopy senescence as the fertility level decreases.

FIGURE 2.9

The effect of soil fertility stress on: (a) canopy development (CC), and (b) biomass water productivity (wp *)



Field surface practices

The part of rainfall lost by surface runoff is simulated by considering the amount of daily rainfall, the soil type and field surface practices. By specifying the crop type, and cultivating practices such as sowing in straight rows or along contour lines, AquaCrop increases or decreases accordingly the surface runoff at run time. AquaCrop blocks surface runoff in the presence of tied ridges. Soil bunds around paddy rice fields, does not only block surface runoff, but allows also storing excess of water on top of the field.

Mulches

Mulches can be composed of organic plant materials, synthetic materials consisting of plastic sheets, or any other material that reduces soil evaporation. Depending on the type of mulches and the fraction of the soil surface covered by mulches, a reduction in soil evaporation is simulated.

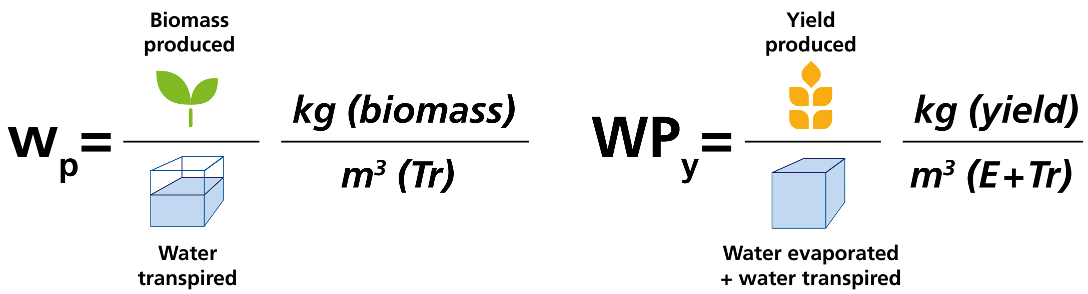
Weed management:

Weeds affect crop development and production through competition for the available resources: light, water, and nutrients. AquaCrop simulates in a simple way the effects of weed competition by affecting crop canopy cover and transpiration.

2.3.9. Biomass water productivity (wp) versus yield water productivity (WPY)

In AquaCrop, a distinction is made between biomass water productivity (w_p) and yield water productivity (WP_Y). The w_p refers to the amount of biomass that can be obtained with a certain quantity of water transpired. The WP_Y is the ratio of crop yield to evapo-transpiration. It is expressed as kg yield per m^3 of water evapo-transpired. Yield (instead of B) is used since it is often the output in which one is most interested in. Evapo-transpiration (ET) instead of crop transpiration is used since soil evaporation is unavoidable and needs to be considered as well at field level (Figure 2.10).

FIGURE 2.10
The biomass water productivity (wp) versus yield water productivity (WPY)



WP_Y, which is an output of AquaCrop when running simulations, is typically used as an indicator to assess the performance of a system. AquaCrop uses WP_Y to identify the environments in which (or management strategies by which) the yield per unit water consumed (ET) can be maximized. This type of performance indicator is useful under conditions of scarcity of water resources.

One way to increase WP_Y, and as such the production of more marketable yield per unit of water evapo-transpired in the field, consist in reducing soil evaporation (which is in the denominator of the equation). Reducing soil evaporation, which is a non-productive consumption of water, can be achieved by mulches or by switching from traditional irrigation methods to drip irrigation, which only partially wets the soil surface. By running AquaCrop with and without the interventions, the increase in WP_Y can be quantified.

AquaCrop can also be used to quantify the effect of other irrigation, field and crop management strategies on WP_Y (more crop per drop) in water-scarce regions. Examples of strategies that can be analyzed by AquaCrop are the effect of selecting a more suitable crop and/or cultivar for the region, altering the time for seeding/planting, adjusting the planting density to the rainfall and soil fertility, introducing deficit irrigation, limiting surface run-off of valuable rainwater from the field, improving weed management, etc.

2.3.10. Simulation of the effects of climate change

Climatic change projections include elevated atmospheric CO_2 concentrations ([CO_2]), warming temperatures and changes in precipitation pattern and amount. The elevated [CO_2] increases the biomass water productivity (w_p*), and results in a higher biomass production per unit of water transpired (Figure 2.8). Crops, differentiated between C3 and C4 types, will benefit from this CO_2 fertilization in future years if soil fertility is not a constraint. On the other hand, the altered weather conditions in future climate are likely to induce more heat and water stress, which both affect mainly canopy development and reduce crop transpiration. The structure of the AquaCrop model allows to assess the combined effected of increased temperature and ETo, altered rainfall patterns and elevated atmospheric CO_2 concentrations.

2.3.11. Model inputs

To be widely applicable, AquaCrop uses only a relatively small number of explicit parameters and mostly intuitive input-variables that can be determined by simple methods. Inputs consist of weather data, crop and soil characteristics, and a description of field and irrigation management practices that define the environment in which the crop will develop. Soil characteristics are divided into soil profile and groundwater characteristics.

A calculator, which derives the reference evapo-transpiration (ETo) from imported weather station data by means of the FAO Penman-Monteith equation, is incorporated into AquaCrop. For automatic adjustment of the w_p* to the year of simulation, AquaCrop's data base contains historical time series of mean annual atmospheric CO_2 concentrations, as well as the expected concentrations for future years according to several scenarios.

FAO has calibrated crop parameters for the major crops and provides them as default values in the model. After selecting a crop, only the cultivar specific crop parameters need to be adjusted when selecting a cultivar different from the one considered for crop calibration.

The user can make use of indicative values of the hydraulic characteristics of the various soil layers 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.

3. AquaCrop – Research development, improvement and application

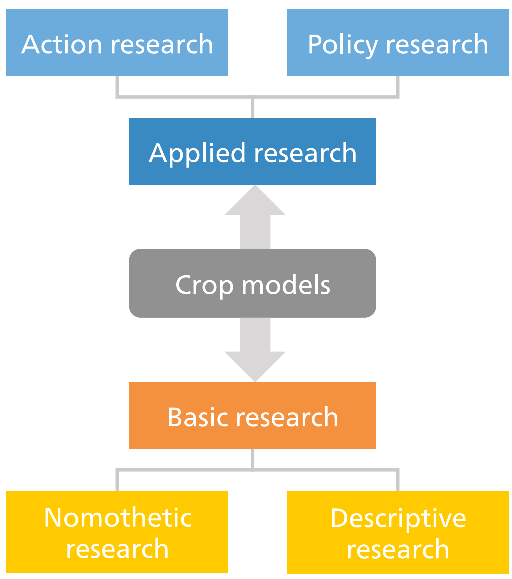
3.1. ANALYSING AQUACROP IMPACT ON RESEARCH – METHODOLOGY

3.1.1. The importance of assessing the impact of AquaCrop on research

Why is it needed to assess the AquaCrop impact on research? Is there any precedent of assessment for AquaCrop or any other model?

Crop models are increasingly being applied in research, teaching, crop systems and natural resources management and policy advisory at present. The relevant role of crop modelling in research is well-known (Seligman, 1990), evolving from a marginal activity to a tool now used routinely for research, encouraged as it greatly enhances the efficiency of field research through extrapolation beyond the limits of the site, season and management (Robertson and Canberry, 2010). From model development up to its application (Figure 3.1), these tools ensure the integration of basic research from different disciplines and allow the identification of the major system drivers and the knowledge gaps. In this way, crop models provide relevant information for defining research priorities and policies. Thus, these tools are contributing to more targeted and efficient research. Although crop models remain the best quantitative repository of knowledge on crop functioning, the readiness of models to support this task can be debated (Stöckle and Kemanian, 2020). Reviewing the performance of crop models should bear in mind that there is always room for improvement of models, which appears as a necessary condition for progress.

FIGURE 3.1
Different research ways to implement crop models to achieve different types of knowledge



Source: based on Oquist, 1978.

Despite the importance of assessing the impact of crop models on research to point out future efforts and actions, only a few studies have attempted to review and analyze it. The most comprehensive work has been performed by Robertson and Carberry (2010).

Through a review of published literature in Australia, New Zealand, Europe and North America, they documented the evolving role of crop modelling in agronomy research, analyzing trends, motivations and regional differences. Reynolds *et al.* (2018) also reviewed the use and impact of crop modelling on the international research centers of the CGIAR (Consultative Group on International Agricultural Research). Focusing on a specific crop model, Timsina and Humphreys (2006) carried out a comprehensive literature review to show and evaluate the applications of CERES-Rice (Alocilja & Ritchie, 1988) and CERES-Wheat (Ritchie and Otter-Nacke, 1985) in Asia, aiming at applying lessons learned to make research more effective. The overall performance of the CERES-Wheat, -Maize and -Rice models was also reviewed in depth by Basso *et al.* (2016). Similarly, the performance of the APSIM model (McCown *et al.,* 1995) in the Semi-Arid Tropics was assessed by Wolday and Hruy (2015) through a comprehensive review. Also, McCown *et al.* (2002) summarized the use of APSIM in Australian dryland cropping research and farm management intervention and its change over time. Notwithstanding these efforts, the impact of a specific model on research has not been exhaustively analysed to date in its different applications and with full geographical coverage.

AquaCrop model, since its launch in 2009, has been increasingly used by the research community for different purposes, including its own improvement and new developments. As in the case of other crop models, its impact on research and trends and challenges have not been assessed so far. Assessing impact is about identifying and evaluating change. The awareness of these impacts opens a discussion with a common understanding of issues, challenges and interventions needed. This information is crucial to set a clear roadmap for the improvement and new developments of AquaCrop, as well as for improving its implementation and extending its applications. Impact analysis is one step in a process that will allow a better model implementation for achieving its original objective, i.e., simulating the effects of environment and management on crop production.

In this Chapter, the challenge of assessing the impact of the AquaCrop model on research during the first ten years since its launch (2009-2019) is addressed by answering the following set of questions:

On the scope of research activities and institutions involved

How many research works on AquaCrop have been published? How fruitful are the research activities on AquaCrop in comparison with other crop models? How has the number of publications evolved geographically? Is there any trend? What are the institutions with higher research activity?

On the relevance of research publications

In which journals have AquaCrop research works been published? What is their impact factor? How many citations do they have? What are the most relevant research works?

On the topic trends in focus

What are the main topics of the research publications on AquaCrop? Is there any trend over time or geographically? What have been the main applications of the model? What are the main issues in the implementation of AquaCrop? For which crops has the model been implemented? To what extent has AquaCrop been globally validated for those crops?

3.1.2. Methodology for the analysis

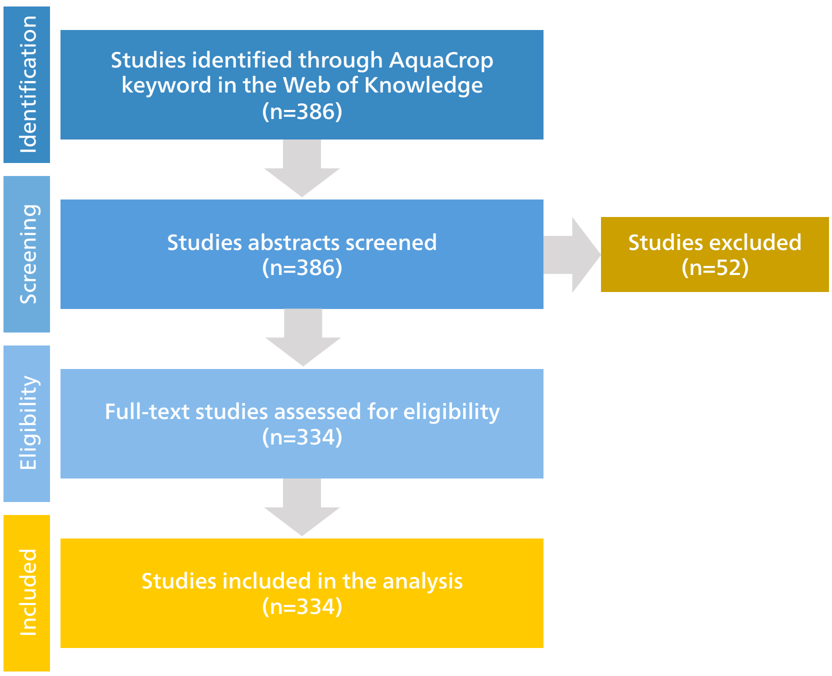
How was the impact of AquaCrop on research analyzed?

The guiding questions proposed were answered by performing a comprehensive and systematic review of the available scientific literature on AquaCrop. The review involves a rigorous approach comprising the collection, analysis and synthesis of all studies on AquaCrop from 2009 to 2019, as described below.

Collection

The bibliographic search procedure used to select the individual studies to be included in this analysis was based on targeting the search to scientific articles published in journals, books or conference proceedings indexed in the Web of Science. It should be noted that most of the publications in the Web of Science are articles in academic journals. The literature search included publications from 2009 to 2019, i.e., the first ten years since the AquaCrop launch. It was broad and inclusive, identifying the original studies through a search by theme using the keyword ‘AquaCrop’. The abstracts of the studies identified through the keyword search (386 publications) were screened to exclude those works that were not really concerned with AquaCrop (Figure 3.2). Furthermore, the full texts of the pre-selected studies were assessed for eligibility. After this process, the number of articles included in this study was finally 334, and their references were listed in the AquaCrop Zotero public library, which can be accessed online (https://www.zotero.org/groups/368553/aquacrop_publications).

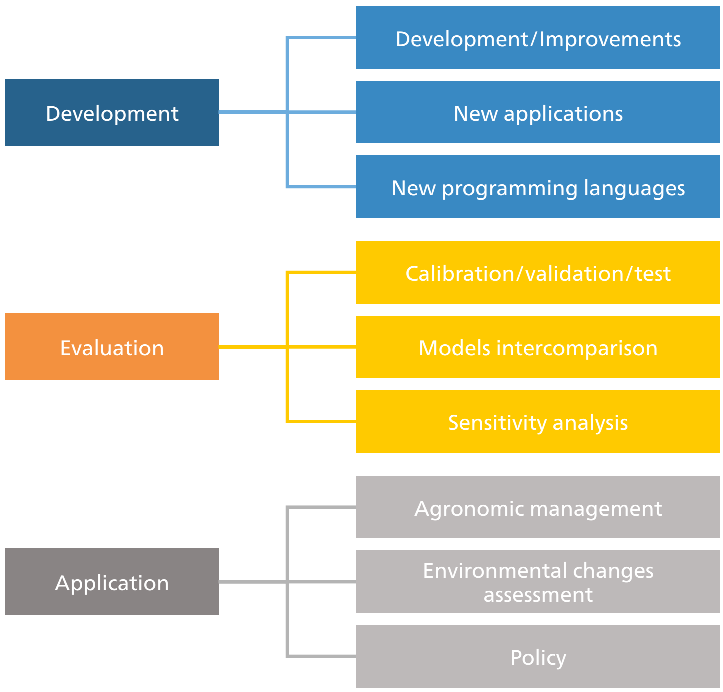
FIGURE 3.2
Selection procedure of studies for inclusion in the review



Analysis and synthesis

The selected studies were analyzed and some general information, including some data about the scope and relevance of the publications, were recorded in an Excel database created for the systematic review of the impact of AquaCrop on research. This information includes publication year and journal, number of citations, the affiliation of the lead author(s), geographical coverage and crops simulated. Due to the large number of topics covered by these publications, 52 different keywords were assigned to describe the focus of the studies in the database. Based on all this information, the articles were classified as having a main focus on model development, evaluation, or application. Further classification was performed for each category, as presented in Figure 3.3. In particular, development papers were classified as model development/ improvements, new applications and new programming languages. In turn, the sub-categories for the evaluation studies were calibration/validation/test, models intercomparison and sensitivity analysis. Finally, other three sub-categories were considered for the applied articles, specifically, agronomic management, assessment of environmental change, and policy.

FIGURE 3.3
Categories and sub-categories of classification for the studies selected based on the main topic



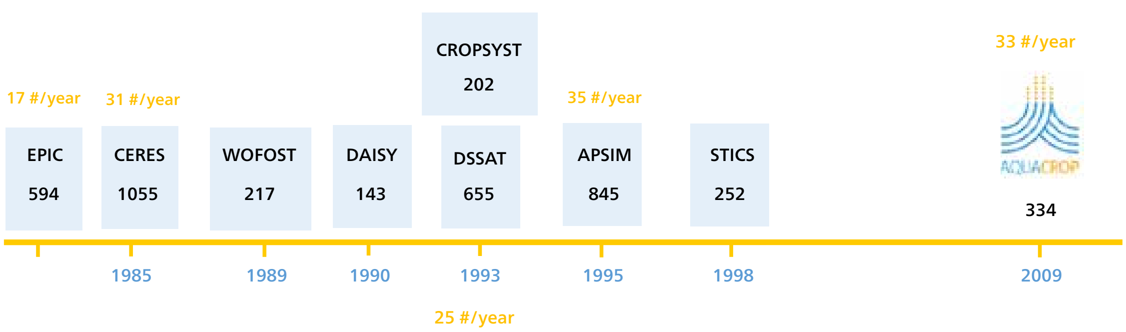
In addition to the keywords of the studies' topics and the classification of their main focus, the approach to other relevant cross topics was recorded in the database for subsequent analysis. These topics were the performance of crop calibration and sensitivity analysis, the use of the fertility, salinity, and groundwater features, the combination of AquaCrop with other tools and the application of the model in economic analysis. In the case of the studies that performed crop calibration, the values of the main crop parameters were extracted and compiled in the Excel database. This allowed the analysis of their variability, consistency, reliability and quality, and led to proposed recommendations for future actions.

3.2. SCOPE OF RESEARCH ACTIVITIES AND INSTITUTIONS INVOLVED

How many research works on AquaCrop have been published? and how fruitful are the research activities on AquaCrop in comparison with other crop models?

The number of research publications found which were devoted to AquaCrop or involved its use was large, specifically 334 publications in the first ten years from its launch. This figure indicates that the model was well received by the scientific community who devoted considerable effort to its use. When the annual publication rate is used as an indicator, the magnitude of AquaCrop research activities becomes more evident. The purpose of this ratio is to help visualize the scientific activity about the model considering the launch year, relative to other models. The indicator value for AquaCrop is 33 publications per year, which is a high value compared to that achieved by other crop models widely recognized by the international scientific community (Figure 3.4). AquaCrop was second only to the APSIM model (McCown *et al.*, 1995) with an indicator value of 35 publications per year. Other models with a high number of publications, such as CERES (Ritchie and Otter, 1985), DSSAT (Jones, 1993) and EPIC (Williams *et al.*, 1983) models with 1055, 655 and 594 publications from their launch to 2019, respectively, have a lower average annual rate of publications than AquaCrop (Figure 3.4). The number of publications for each model was determined through a search in Web of Science by theme using the name of each model as keyword. In this case, screening was not performed, so the reported values of the other models might have been overestimated, suggesting even greater relevance of the AquaCrop model in the scientific literature field. It can be concluded that AquaCrop caught the attention early of the scientific community and is currently one of the most commonly used models in agricultural research.

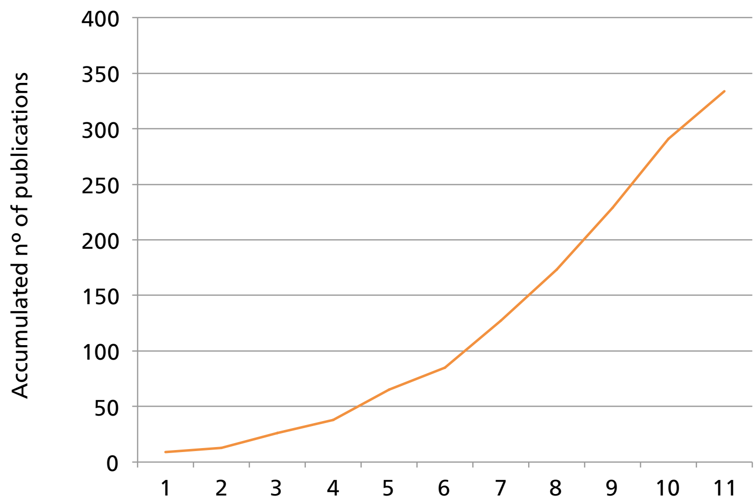
FIGURE 3.4
Main crop models and their launch year, the number of scientific publications from their launch to 2009 (inside the boxes) and some ratios of the number of publications over the number of years since its launch (in yellow)



In 2009, the core papers on AquaCrop (Steduto *et al.*, 2009; Raes *et al.*, 2009; Hsiao *et al.*, 2009; Farahani *et al.*, 2009; Garcia-Vila *et al.*, 2009; Heng *et al.*, 2009; Geerst *et al.*, 2009; Todorovic *et al.*, 2009) were published in the special issue of the Agronomy

Journal devoted to the symposium entitled: "Yield Response to Water: Examination of the Role of Crop Models in Predicting Water Use Efficiency" at the 2007 International Annual ASA–CSSA–SSSA meeting. From these eight articles, the first papers specifically devoted to AquaCrop, onwards, the number of publications increased exponentially until 2018 (Figure 3.5). In that year, 62 scientific studies were published, the highest number since 2009, being 50 publications per year the average value of the last 5 years.

FIGURE 3.5
Accumulated number of scientific publications devoted to AquaCrop model since its launch (2009)



How has the number of publications evolved geographically? Is there any trend?

Analysing the geographical coverage, the highest percentage of studies were conducted in Asia (42 percent), followed by Europe, with 23 percent of the publications (Figure 3.6). The second position of Europe is in line with findings by Robertson and Carberry (2010), who observed that 22 percent of the agronomic research was devoted to crop modelling in Europe from 2002 to 2009, a significantly higher percentage compared with North America or Oceania. It is noteworthy that Africa ranks third (19 percent of the publications), ahead of America (15 percent of the publications), despite of the standstill of agricultural research intensity ratios in Africa (Roseboom and Flaherty, 2016). This may be linked to the fact that FAO has made a significant effort in AquaCrop dissemination and training in this continent, as discussed below in Chapter 4.

Additionally, Figure 3.7 visualizes how the publication record has evolved over time in each geographical region. As this figure illustrates, the exponential increase in the number of publications, observed in Figure 3.5, was led by Asian countries from 2014. Stagnation in the number of publications per year can be appreciated in the other regions from then on. The growing leadership of Asian countries, China in particular, is in line with the fact that China agricultural R&D efforts remains high on the policy agenda, with continuing investments to rise (Chen *et al.*, 2012).

FIGURE 3.6
Percentage of research studies on the AquaCrop model conducted in each continent

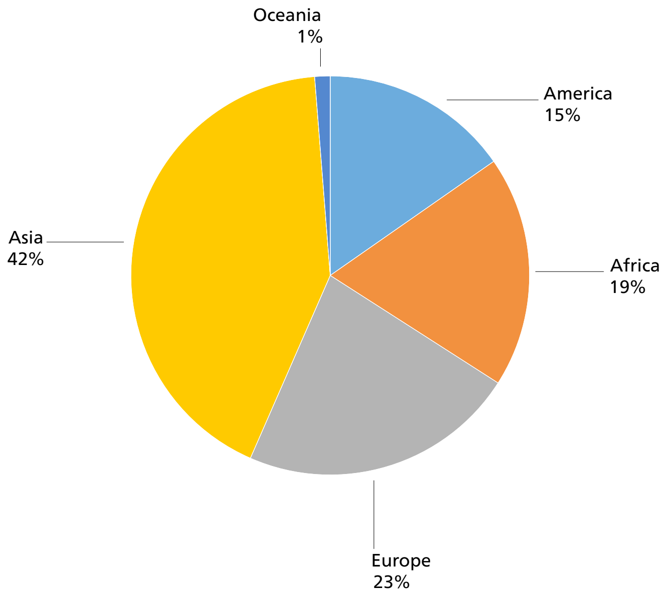
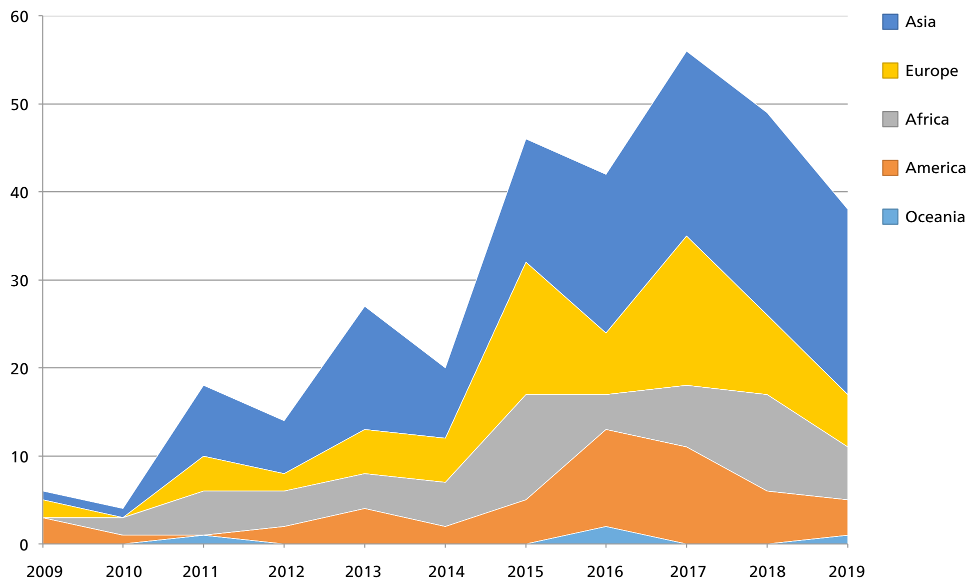


FIGURE 3.7
Area graph showing the evolution of the number of research studies on AquaCrop model conducted in each continent from 2009 to 2019



Despite the leadership of Asian countries, the use of AquaCrop in agricultural research has achieved good geographic coverage, as presented in Figure 3.8. This map shows the number of publications per country, from 2009 to 2019. AquaCrop model has been implemented in 64 different countries across the world's five continents, in very different agro-ecological zones. It emphasizes the broad geographical coverage in Asia and Africa, where at least one scientific study based on AquaCrop has been carried out in 44 percent and 33 percent of the countries, respectively. These figures indicate the scope of the research activities on the model, not focusing only on specific environmental conditions or being used by a small research community.

FIGURE 3.8
Number of research publications on AquaCrop model in each country around the world (The size of the circle represents the number of publications in these countries)

The analysis of the records shows increasing use of AquaCrop in Chinese agricultural research, the country with the highest number of publications on it, specifically 14 percent of total (Figure 3.9). The second one is another Asian country, Iran (8 percent of publications), followed by Italy, United States of America, Ethiopia and Spain, with around 5 percent of publications each of them. The proliferation of AquaCrop articles in Iran and Ethiopia may be attributed in part to the training efforts that have been made in these countries by FAO, as will be shown in Chapter 4.

Analysing the evolution of the publications number in these counties over time, it is noticed that China and Iran are the only ones which have an increasing trend in publications number (Figure 3.10). No clear time trend is seen in the number of publications per year in other countries.

FIGURE 3.9
Percentage of research publications on AquaCrop model for the countries with the greatest number of publications

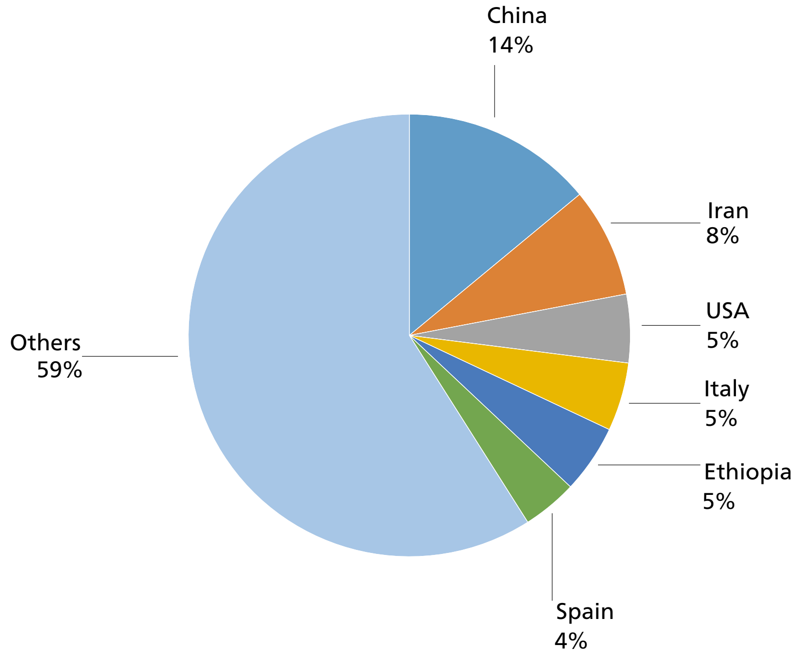
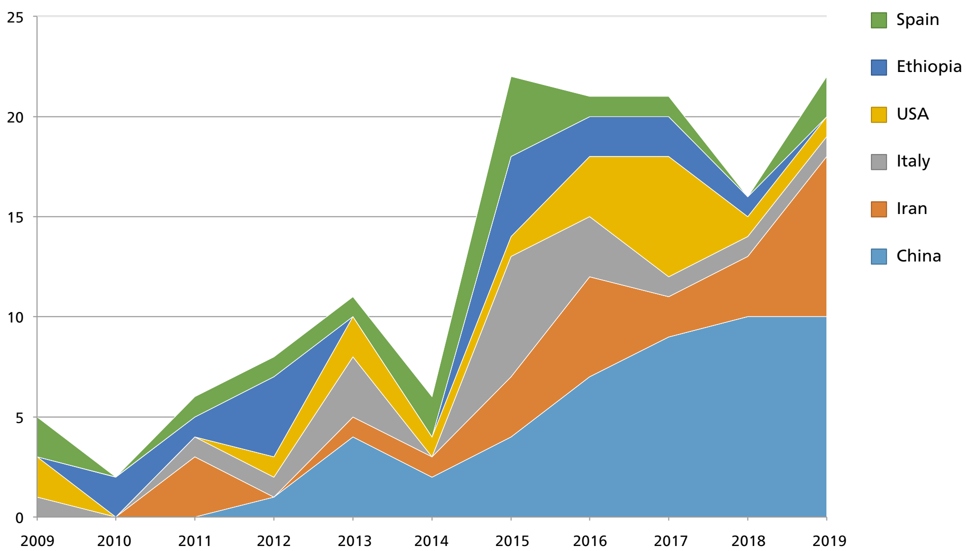


FIGURE 3.10
Evolution of the number of publications per year on AquaCrop model for the countries with the greatest number of publications



What are the institutions with higher research activity?

On the basis of the analysis of the affiliation of the lead author(s), a total of different 188 institutions appear leading the studies on AquaCrop. Once again, this figure gives a clear idea of the magnitude of model scope, being the lead institutions around three times the number of countries where a research study on AquaCrop was conducted, i.e. 64 countries. Universities represent 69 percent of all institutions, and research institutes are 26 percent of those (Figure 3.11). On the other hand, international organizations, such as FAO or CGIAR, lead 3 percent of the publications. Table 3.1 presents the top institutions leading at least four publications (19 institutions in total), with the KU Leuven (Belgium) being clearly more active (14 publications). This is not particularly surprising, as one of the AquaCrop developers is affiliated to this university. In the top eight institutions with at least five publications, four European, two Asian and two African institutions are found.

FIGURE 3.11
Percentage of different typologies of institutions to which the lead authors of the publications are affiliated

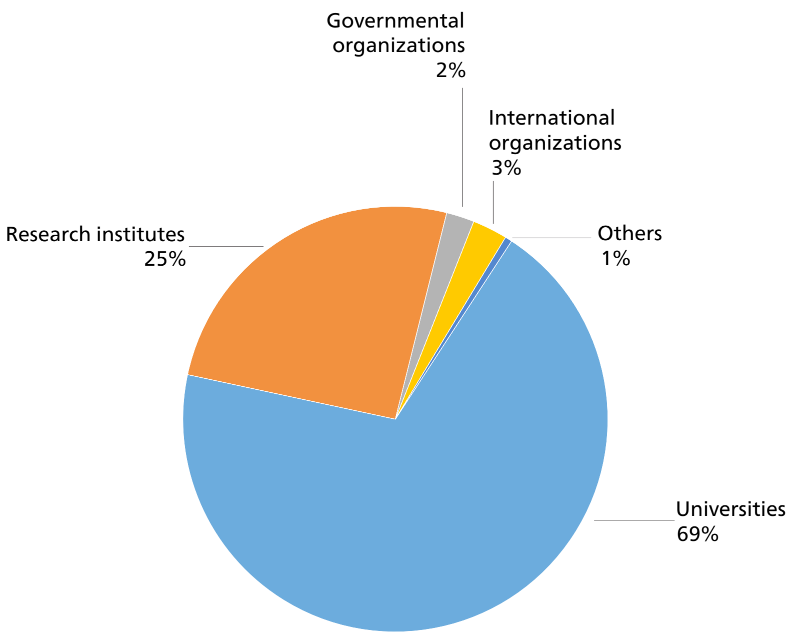


TABLE 3.1
List of institutions leading the higher number of publications on AquaCrop model (affiliation of the lead author).

Institution	Number of publications
KU Leuven (Belgium)	14
Asian Institute of Technology (Thailand)	7
Mekelle University (Ethiopia)	7
China Agricultural University (China)	6
University of KwaZulu-Natal (South Africa)	6
University of Twente (Netherlands)	6
University of Belgrade (Serbia)	5
University of Cordoba (Spain)	5

Institution	Number of publications
Chinese Academy of Sciences (China)	4
CSIRO (Australia)	4
IFAPA (Spain)	4
Islamic Azad University (Iran)	4
Northwest A&F University (China)	4
Shiraz University (Iran)	4
Tsinghua University (China)	4
University of Florida (United States of America)	4
University of Liège (Belgium)	4
University of Lisbon (Portugal)	4
Wageningen University (Netherlands)	4

To compare the institutional use of AquaCrop against that by two of the crop models with the highest number of publications, APSIM and DSSAT, the 'Analyze results' feature of the Web of Science has been used. This has generated a list of institutions ranked by record count based on a search query, i.e. the model name. For AquaCrop, the top-three institutions are present only in 15 percent of the publications, while for APSIM and DSSAT they are in 67 percent and 45 percent of the publications, respectively. Looking at the geographical distribution of the institutions involved in their publications, it is found that the top-three countries bring together 44 percent, 96 percent, and 71 percent of the publications on AquaCrop, APSIM and DSSAT, respectively. These figures provide further evidence of the scope of the research activities on the model, not being led by a small number of institutions linked to a geographic area.

3.3. RELEVANCE OF RESEARCH PUBLICATIONS

In which journals have AquaCrop research works been published? and what is their impact factor?

One critical issue of the relevance assessment of the research studies on AquaCrop model is the analysis of publication sources. This review revealed that these studies have been published in a wide variety of sources of publication, specifically, in 134 different peer-reviewed international journals, conference proceedings or books. About 98 percent of them are specialized journals, instead of general scientific ones. Figure 3.12 shows the percentage of research studies published in each journal category based on their aim and scope. Most of the publications (35 percent) can be found in journals ranked in the 'Water Resources' category (InCites Journal Citation Reports). This category covers resources concerning a number of water-related topics, including irrigation and drainage science and technology. AquaCrop was designed to simulate the yield response of herbaceous crops to water. It is therefore not surprising that a slightly larger number of publications can be found in the 'Water Resources' category than in the 'Agronomy' or 'Agriculture' categories (33 percent), the most common ones for research studies on crop modelling. It is also noteworthy the high percentage of publications in 'Environmental Sciences' (16 percent) and 'Meteorology and Atmospheric Sciences' (7 percent) journals. These figures indicate the scope and relevance of the model in different scientific communities, AquaCrop being not limited to the agronomy/agriculture area.

FIGURE 3.12

Percentage of research studies on AquaCrop model published in each journal category based on their aim and scope

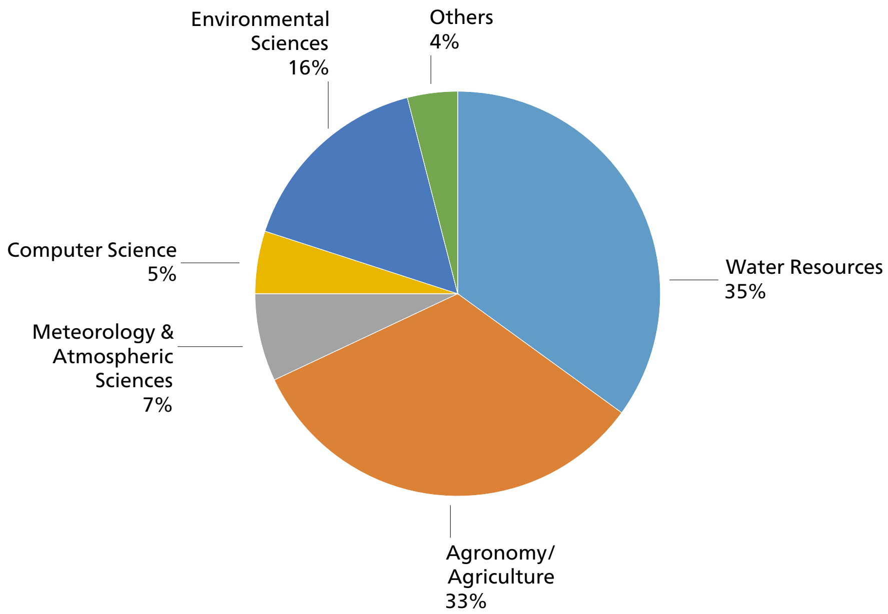
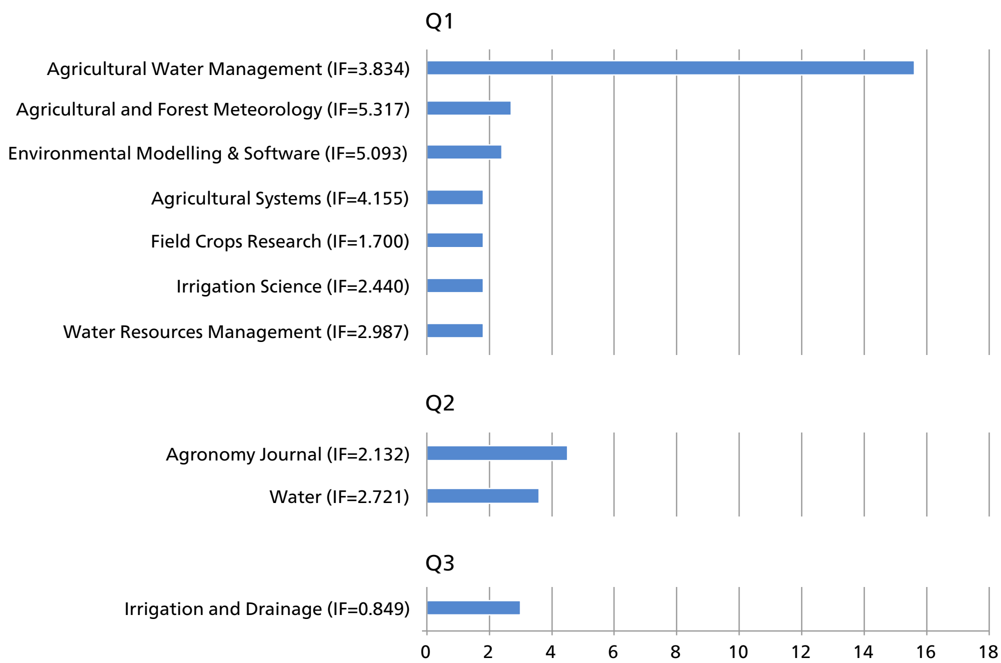


Figure 3.13 presents the ten journals where nearly 40 percent of the papers have been published. The top journal in terms of number of publications is Agricultural Water Management, a renowned publication source in the agronomy and water resources fields, with 52 articles representing 16 percent of the full record. Seven out of the top ten journals are ranked among the top 25 percent of journals in the list of its subject category (Q1; InCites Journal Citation Reports), a measure of the scientific influence of scholarly journals. On the other hand, the impact factor of these journals is high (Figure 3.13), another measure of the importance or rank of a journal. In this regard, Nature Climate Change, which covers the most significant research on the causes and impacts of global climate change (5-year Impact Factor= 25.170; first journal in the 'Meteorology and Atmospheric Sciences' category), has published two studies that have implemented AquaCrop. These works are part of the joint effort made by the modellers community involved in the 'Agricultural Model Intercomparison and Improvement Program' (AgMIP), whose ultimate goal is to significantly improve crop models for assessing the sustainability of agricultural systems at local and global scales. Another relevant study of the AgMIP that involved AquaCrop use was published by Nature Plants (5-year Impact Factor= 13.338), the third journal in the 'Plant Science' rank.

FIGURE 3.13

Percentage of articles on AquaCrop model published in the top ten journals in terms of number of publications. IF: Journal Impact Factor (InCites Journal Citation Reports). Q1: First quartile, the top 25 percent of the IF distribution. Q2: Second quartile, between top 50 percent and top 25 percent of the IF distribution. Q3: Third quartile, between top 75 percent to top 50 percent of the IF distribution.



How many citations do the AquaCrop research publications have? and what are the most relevant ones?

Regarding the number of citations, another indicator of the impact and quality of the research, the 334 publications on AquaCrop model accumulate 6021 citations over the indicated period. This citation level (20 citations per publication on average) is comparable to that other crop models with a longer haul, such as DSSAT, with 22 citations per publication on average (Citation report of the Web of Sciences). Table 3.2 presents the twenty most cited journal articles, including their main topic that later are analyzed in bulk for the full record (Chapter 3.4). As might be expected, the core articles of AquaCrop where their concepts, principles and main algorithms are described (Steduto *et al.*, 2009 and Raes *et al.*, 2009) are the most cited ones (541 and 361 citations, respectively). However, alongside these articles is an applied research study on the impacts of the expected temperature increase on wheat production at the global scale (Asseng *et al.*, 2015, with 457 citations). This multi-model exercise carried out under the framework of the AgMIP was published in the renowned journal of Nature Climate Change. A similar study can also be found in eighth place with 98 citations (Liu *et al.*, 2016). Nevertheless, the majority (70 percent) of the top-20 most cited articles are devoted to crop calibration (maize, cotton, sunflower, wheat, barley, quinoa and sugar beet). Thus, in addition to the two climate change impacts articles, only one applied research study (García-Vila and Fereres, 2012) is among the 20 highest cited papers (89 citations), which combines AquaCrop with an economic model to optimize the irrigation management at farm level. On the other hand, in the fifteenth and seventeenth places, there are a global sensitivity analysis of the model (Vanuytrecht *et al.*, 2014a) and a review of the model version 4.0 (Vanuytrecht *et al.*, 2014b).

TABLE 3.2
Number of citations and main topic of the top-twenty most cited research articles on AquaCrop model

Reference	Topic	Number of citations
Steduto *et al.* (2009)	Core article	541
Asseng *et al.* (2015)	Climate Change-Multi model	457
Raes *et al.* (2009)	Core article	361
Hsiao *et al.* (2009)	Crop calibration	261
Heng *et al.* (2009)	Crop calibration	187
Farahani *et al.* (2009)	Crop calibration	135
Todorovic *et al.* (2009)	Crop calibration	112
Liu *et al.* (2016)	Climate Change-Multi model	98
Andarzian *et al.* (2011)	Crop calibration	97
Araya *et al.* (2010)	Crop calibration	96
Geerts *et al.* (2009)	Crop calibration	94
Abedinpour *et al.* (2012)	Crop calibration	90
Garcia-Vila and Fereres (2012)	Model application	89
Iqbal *et al.* (2014)	Crop calibration	83
Vanuytrecht *et al.* (2014)	Global sensitivity analysis	73
Garcia-Vila *et al.* (2009)	Crop calibration	73
Vanuytrecht *et al.* (2014)	AquaCrop review	70
Stricevic *et al.* (2011)	Crop calibration	70
Mkhabela and Bullock (2012)	Crop calibration	68
Katerji *et al.* (2013)	Crop calibration	66

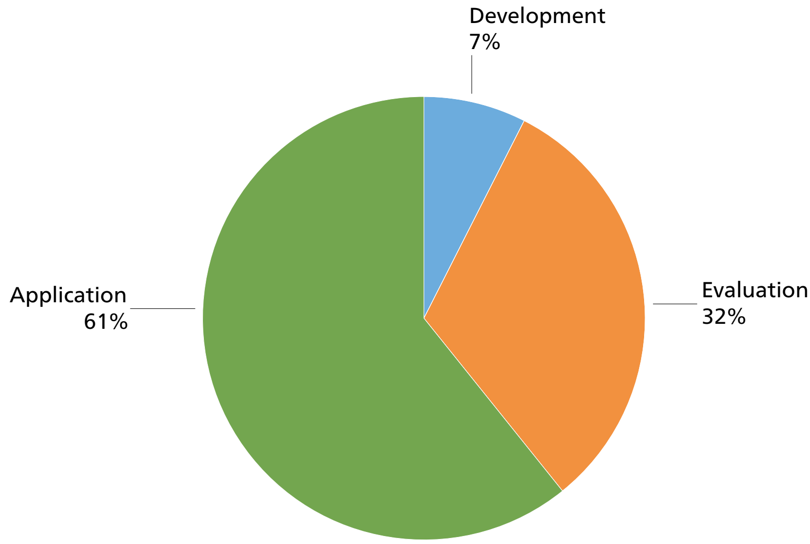
4.3 TOPICS TRENDS IN FOCUS

What are the main topics of the research publications on AquaCrop? Is there any trend over time or geographically?

Based on all the information compiled about the AquaCrop publications during the indicated period, the articles were classified in terms of their main focus on model development, evaluation, or applications. Results showed that AquaCrop practical application studies dominate, representing 61 percent of the articles (Figure 3.14). This contrasts with the data observed by Robertson and Carberry (2010) in analysing the role of crop modelling in agronomy research. They found that in Europe and America about one-third of modelling articles were devoted to application, reaching 50 percent in Australia and New Zealand. Thus, it can be concluded that the research on AquaCrop model is more practically oriented than for other crop models. This is in line with the main goal of AquaCrop which was built to be primarily a planning tool and to assist management decisions.

The number of publications devoted to evaluating the model is also high (32 percent; Figure 3.14). There has been a significant effort to properly assess the model performance and calibrate it before its implementation in these publications. By contrast, the short life of the model is reflected in the limited number of articles devoted to its further development or improvement (7 percent).

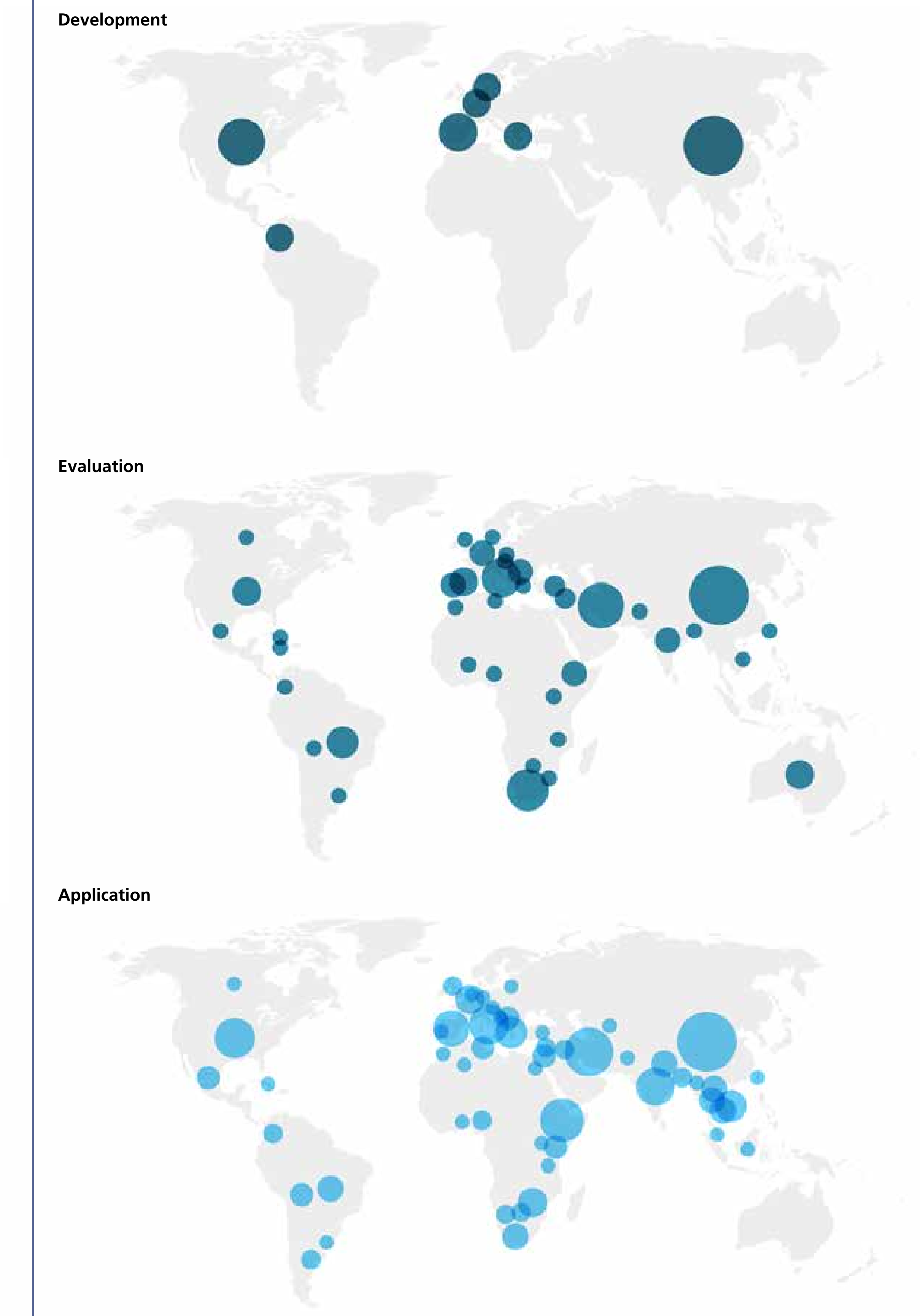
FIGURE 3.14
Percentage of publications on AquaCrop model devoted to its development, evaluation and application



When looking at the geographical distribution of the studies in terms of their main focus, a more diverse picture is observed for the evaluation and application categories than for development (Figure 3.15). AquaCrop has been evaluated and implemented in many countries around the world with different agroecological conditions and diverse levels of agricultural research development. On the contrary, the model development and improvement works are concentrated in a few countries which also have high agricultural research intensity ratios. Whereas the initial developments were carried out by European and North American researchers, worthy of note is the recent momentum in the research on AquaCrop improvement coming from China.

Analyzing the studies' typologies within the development category, most of them are focused on model development or improvement (6 percent of publications; Figure 3.16). Besides the articles presenting the algorithms behind the model (e.g. Raes *et al.*, 2009; Vanuytrecht *et al.*, 2014b), the new developments are mainly oriented towards remote sensing data assimilation for improving the model predictions providing the missing spatial information required (e.g. Kim and Kaluarachchi, 2015; Jin *et al.*, 2016), a trend among the modellers communities. Only a small percentage of the publications (1 percent; Figure 3.16) present new applications, such as AquaCrop-GIS (Lorite *et al.*, 2013), which facilitates the generation and management of inputs and output files and presents the results within a geographic information system. Also, AquaCrop has been programmed in other computer languages, such as MATLAB (Foster *et al.*, 2017) and R (Camargo Rodriguez and Ober, 2019), which represent less than 1 percent of the studies (Figure 3.16).

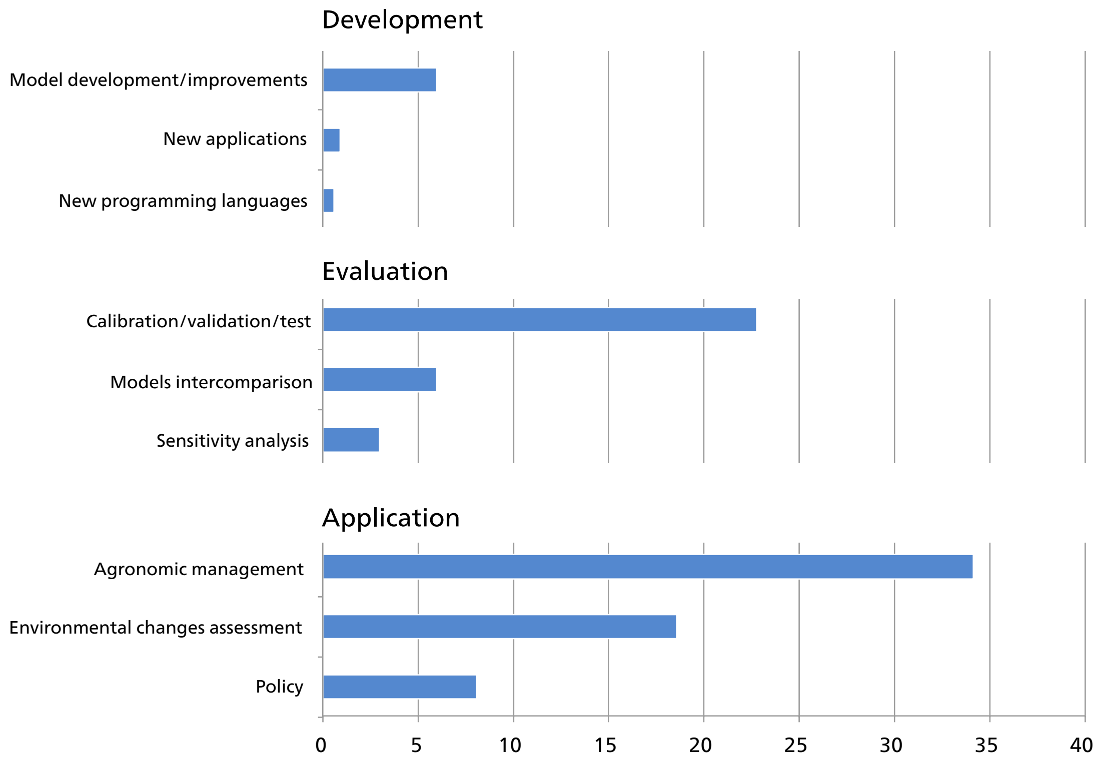
FIGURE 3.15
Number of research publications in each country around the world on AquaCrop model within each primary topic category. The size of the circle represents the number of publications in these countries



The evaluation category is dominated by studies oriented to the calibration, validation or test of the model for different crops around the world (23 percent of the publications, Figure 3.16). More specifically, in these articles, the target is to validate crops already parameterized for new, specific conditions (e.g. Toumi *et al.,* 2016), to improve the parameterization already proposed (e.g. Garcia-Vila *et al.,* 2019) or to calibrate the model for a crop not yet parameterized (e.g. Wellens *et al.,* 2013). A great effort has been made to parameterize AquaCrop for many different crops, as will be discussed further. However, despite these efforts, it is worth noting that the parameterization process proposed by Hsiao *et al.* (2012) has not been followed in a number of cases. Nevertheless, assessing the accuracy and goodness of fit of the parameters published in these studies is not the target of this publication, but it should be addressed in the future. In a small percentage of publications (6 percent, Figure 3.16), researchers try to improve agricultural models, including AquaCrop, based on their intercomparison and evaluation (e.g. Teodorovic *et al.,* 2009; Eitzinger *et al.,* 2013). Another aspect covered by this category is the sensitivity analysis which was conducted in a reduced number of studies (3 percent of publications; Figure 3.16) with the aim of quantifying the relative effect of model parameters on intermediate or output variables (e.g. Vanuytrecht *et al.,* 2014a; Silvestro *et al.,* 2017). Parameters might be ranked for their sensitivity, providing guidelines for efficient model calibration.

The applied research that was implemented with the AquaCrop model was classified in terms of whether the model was applied to agronomic management, environmental changes assessment or policy. As crop models are designed to predict crop responses, it is perhaps not surprising that agronomic management was the focus of many applications (34 percent; Figure 3.16), although there is a notable growing emphasis on environmental changes assessment and policy dimensions, as was also observed by Robertson and Carberry (2010). Much of the AquaCrop modelling work was devoted to the analysis of crop response to certain agronomic management condition, mainly irrigation related practices (e.g. Geerts *et al.,* 2010; Araya *et al.,* 2016), sowing density and date (e.g. Nyakudya *et al.,* 2014; Tsegay *et al.,* 2015), fertility practices (e.g. Shrestha *et al.,* 2013; Akumaga *et al.,* 2017) and salinity management (e.g. Kumar *et al.,* 2014; Mondal *et al.,* 2015). This has led to using AquaCrop to find optimum management practices in specific environments, generally to maximize yields. In some cases, AquaCrop-based decision support systems have been developed (e.g. Zinyengere *et al.,* 2011; Wellens *et al.,* 2017), but the model has been used as a research tool rather than for its inclusion in decision support tools. Another important AquaCrop application is evaluating the impact of changing environmental features (19 percent of publications; Figure 3.16). This is a particularly important issue, as the world's food production resources are already under pressure from climate change. The main focus of these studies is to forecast the effects of global climate change (81 percent of the environmental changes assessment studies; e.g. Voloudakis *et al.,* 2015; Moursi *et al.,* 2017) or to perform a drought severity evaluation (16 percent of them; e.g. Vergni *et al.,* 2015; Martins *et al.,* 2018). Furthermore, in the context of a global need to effectively prioritize political interventions to enhance crop productivity, while protecting natural resources, AquaCrop is being implemented increasingly as a tool to analyse hypothetical scenarios and rational policymaking (8 percent of the publications, Figure 3.16). In this regard, water footprint studies have taken the leading role (e.g. Zhuo *et al.,* 2016; Karandish and Hoekstra, 2017). Notwithstanding the wide range of AquaCrop applications identified in the research literature, it is noteworthy the absence of a new promising application field, plant breeding, where AquaCrop might accelerate turnarounds in breeding programs.

FIGURE 3.16
Percentage of publications on AquaCrop model devoted to each sub-category of topics.

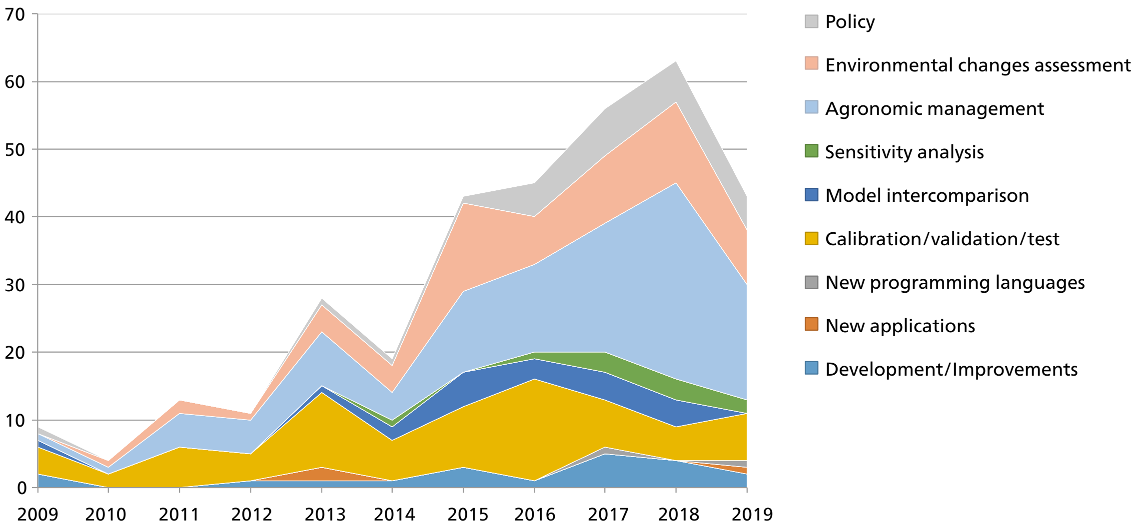


Looking at the evolution over time of the different topics' categories (Figure 3.17), as expected, increasing use of AquaCrop in applied research can be observed, with a strong emphasis on agronomic management. Other applications, such as those included in environmental changes assessment and policy categories, have strongly burst into the AquaCrop publications in recent years. In turn, models intercomparison and sensitivity analysis publications have also recently emerged. By contrast, the studies devoted to calibration/validation/test of AquaCrop, have stabilised after the initial growth. Regarding model development, the latest improvements lead by remote sensing data assimilation have fuelled this category after the initial developments.

Given the relevance of applied research on AquaCrop, the analysis of its geographical coverage may be of interest. As shown in Figure 3.18, no clear geographical patterns were found among the publications belonging to the categories of agronomic management, environmental changes assessment, and policy. Hence, one can note a great diversity of AquaCrop applications in all regions of the world.

FIGURE 3.17

Area graph showing the evolution of the number of research studies on AquaCrop model in each topic sub-category from 2009 to 2019



In addition to the topic categories, the keywords assigned to describe the focus of each study in the database have been analyzed with the aim of identifying the trending topics. Figure 3.19 shows the most important found in the AquaCrop publications, being model calibration and validation, the main issue addressed (20 percent of publications). This is in line with the significant effort made to implement the model worldwide, as noted above. Nevertheless, a slight decline in these studies number in favour of other topics can be observed in the last few years (Figure 3.20). It is noteworthy that the most prominent model application is the analysis of the climate change impacts, being covered by 17 percent of the publications (Figure 3.19), which is ahead of other relevant topics such as irrigation management (13 percent of the publications). It should not be forgotten that the assessments of climate change impacts and adaptation are right at the top of the policy agenda, driving the use of crop models in research. Studies using the model assess the water footprint rank fourth, but with a substantially smaller percentage of publications (four percent). The accurate water balance performed by AquaCrop turns it into an excellent tool to assist this trending matter in the last five years (Figure 3.20). The model application for evaluating mulching use and for optimizing sowing dates also stands out (4 percent of the publications each), above other model uses. While the sowing date assessments have been present since the model launch, mulching related applications have strongly burst recently (Figure 3.20).

FIGURE 3.18
Number of research publications in each country around the world on AquaCrop model within each topic sub-category of application studies category. The size of the circle represents the number of publications in these countries

Agronomic management

Environmental changes assessment

Policy

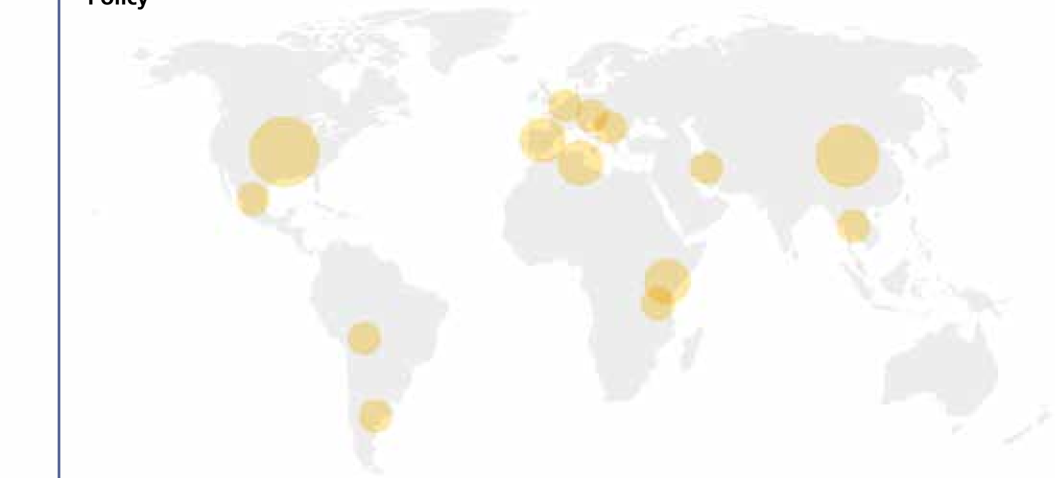


FIGURE 3.19

Percentage of publications on AquaCrop model devoted to the main topics

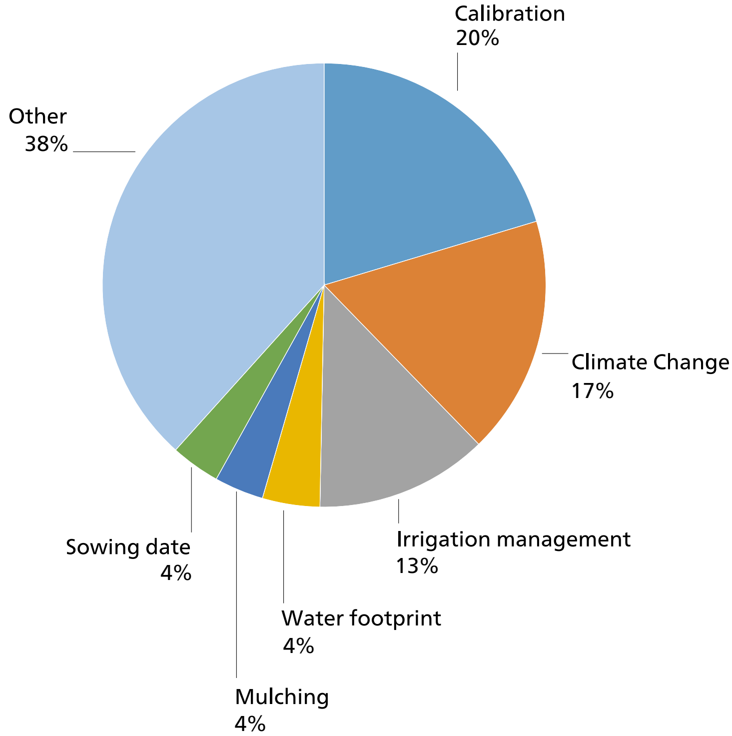
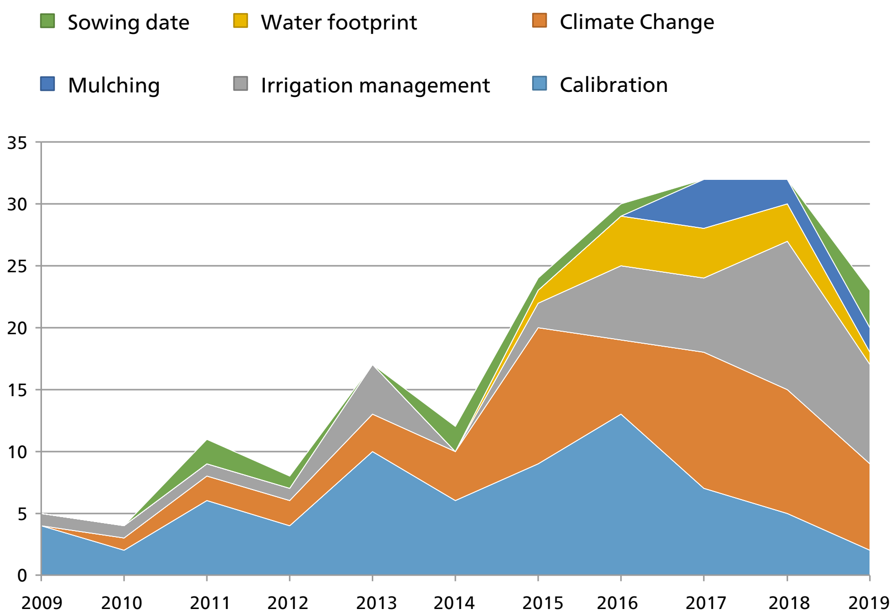


FIGURE 3.20

Area graph showing the evolution of the number of research studies on AquaCrop model in each main topic from 2009 to 2019



The geographic distribution of the main topics beyond model calibration (specifically, climate change, irrigation management and water footprint) is presented in Figure 3.21. The impacts of climate change on crop production and the opportunities for adapting to these changes have been assessed worldwide. On the contrary, both irrigation management and water footprint studies have been mainly conducted in water scarce regions, which was to be expected. Although water scarcity affects every continent and is among the main problems faced in many areas, the model implementation for these purposes is mostly concentrated in Europe and Asia.

Since most of the publications involve more than one subject matter, the secondary topics are analyzed here and termed cross topics. Regardless of the main topic, in two thirds of the articles, a model calibration/validation process has been carried out (Figure 3.22). The parameters adjustment has primarily conducted manually, while only two percent performed an automatic calibration through an algorithm (e.g. Bayesian, nested) (e.g. Mohammadi *et al.,* 2016; Huang *et al.,* 2018). Only in four percent of the calibration studies, this process has been complemented with a sensitivity analysis (e.g. Salemi *et al*. 2011; Razzaghi *et al.,* 2017). These results highlight once again the major efforts made to evaluate model performance for different crops under diverse environmental and management conditions. On the contrary, a limited number of studies have used the fertility (e.g. Shrestha *et al.,* 2013), salinity (e.g. Hassanli *et al.,* 2016) and groundwater (e.g. Goosheh *et al.,* 2018) features, accounting for nine, four, and two percent of all publications, respectively (Figure 3.22). Furthermore, of the studies that have used the fertility module only 39 percent have performed a local soil fertility calibration, even though it is considered a prerequisite before conducting any fertility-limited simulation. In the light of the limited testing of these three features of AquaCrop, these model applications should be further tested to ensure model accuracy and robustness. Finally, given the growing interest in the development of decision support systems, it would be instructive to analyse the coupling of AquaCrop to other models. While in 16 percent of the articles AquaCrop has been implemented coupled with another model or tool (e.g. Tsakmakis *et al.,* 2017; Li *et al.,* 2018), only in four percent of the studies, an economic analysis has been made (e.g. Garcia-Vila and Fereres, 2012; Vilvert *et al.,* 2018; Figure 3.22). After reviewing these publications, it could be concluded that there is still a long way to go to reach the full potential of AquaCrop as part of a decision support tool, with most studies so far focusing more on operational or tactical than on strategic decision making.

For which crops has the model been implemented? To what extent has AquaCrop been globally validated for those crops?

The widespread use of AquaCrop has resulted in an increased model application for a wide variety of crops. In the AquaCrop crop database, there are 15 different crops with default values for the crop parameters, which have been obtained conducting a calibration/validation process against experimental data. In Annex I of the AquaCrop reference manual, indications of the thoroughness of the calibration/validation process are provided with respect to optimal and water stress conditions, as well as with respect to the coverage of major production areas of that crop around the world (Raes *et al.,* 2018). Nevertheless, the literature review on AquaCrop from its launch to 2019 reveals that the model has been implemented in 46 different crops. This means that AquaCrop is being used for a great diversity of crops, triple those initially included in the AquaCrop

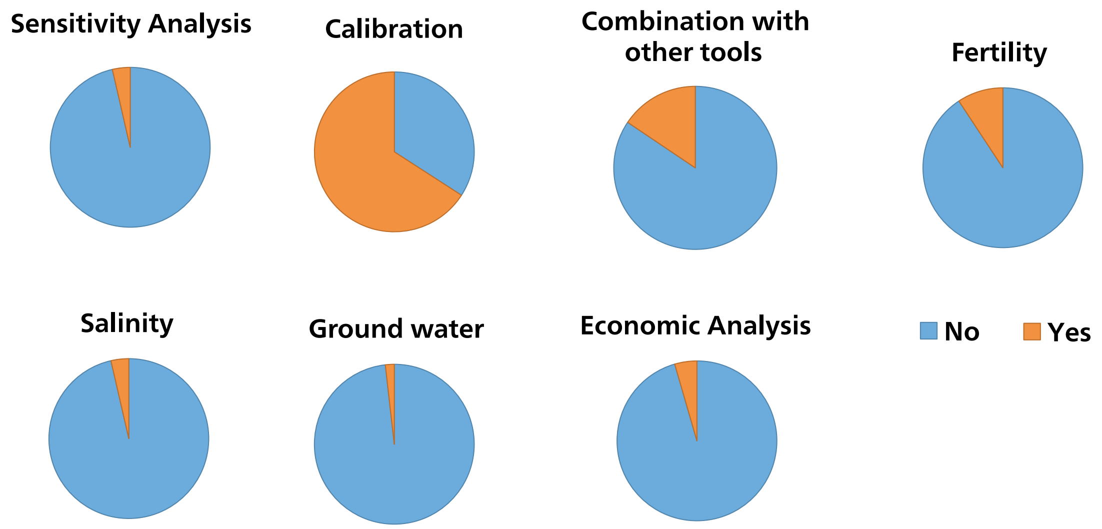
FIGURE 3.21
Number of research publications in each country around the world on AquaCrop model application for each topic. The size of the circle represents the number of publications in these countries

Climate change

Irrigation management

Water footprint

FIGURE 3.22
Percentage of publications on AquaCrop model that cover the cross topics specified



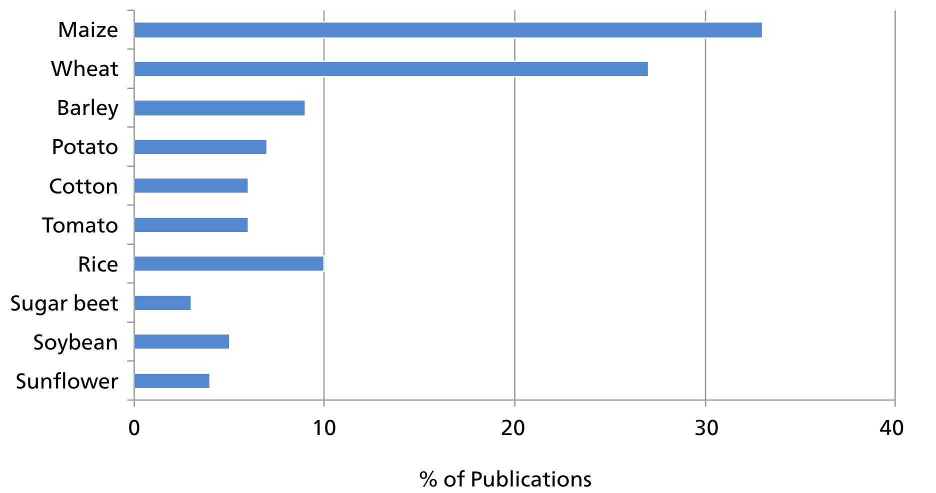
database. Unfortunately, clear information about the parametrization process of all these crops is not fully available in the literature. In fact, the crop parameters of only 37 crops are reported, at least partially. As discussed earlier, a critical review of the calibration processes performed in these studies and of their results is required to assess the quality of the proposed parameters needed to simulate the crops outside those in the AquaCrop database.

An in-depth analysis of crop diversity in AquaCrop research literature indicates that cereals are the target crops in most studies (87 percent of the publications, Table 3.3). Cereals do not only stand out for the number of publications but also for their diversity, as ten different cereals are found in the literature (Table 3.3), both major cereals (such as maize, wheat or rice) and minor ones (e.g. tef or millet) or even pseudo-cereals (e.g. quinoa). It is necessary to bear in mind that although 81 percent of the articles focus on a single crop, some studies perform simulations for several crops (e.g. Delgoda *et al.*, 2016; Gobin *et al.*, 2017). In second position, pulses, vegetables and tuber crops are present in a similar proportion (8-10 percent of the publications). The wide variety of grain legumes (7 crops) and vegetables (8 crops) should be highlighted since the crop models have not traditionally addressed them. It is surprising that fodder crops (e.g. Moursi *et al.*, 2017; Stricevic *et al.*, 2017) and even tree crops (e.g. Rallo *et al.*, 2012; Qin *et al.*, 2016) have been attempted to simulate with AquaCrop even though the model is designed for use only in herbaceous, annual crops. Figure 3.23 presents the top-ten crops in terms of number of publications. Maize (33 percent of the publications) and wheat (27 percent) top the list followed by rice (10 percent), the three world's most popular food crops.

TABLE 3.3
Percentage of publications on AquaCrop model devoted to each crop type

Crops types	N° of crops	% of publications
Cereals	10	87
Vegetables	8	10
Pulses	7	10
Tuber crops	4	8
Fiber crops	1	6
Oil crops	2	5
Sugar crops	2	3
Tree crops	7	3
Fodder crops	4	2
Other crops	1	0.3

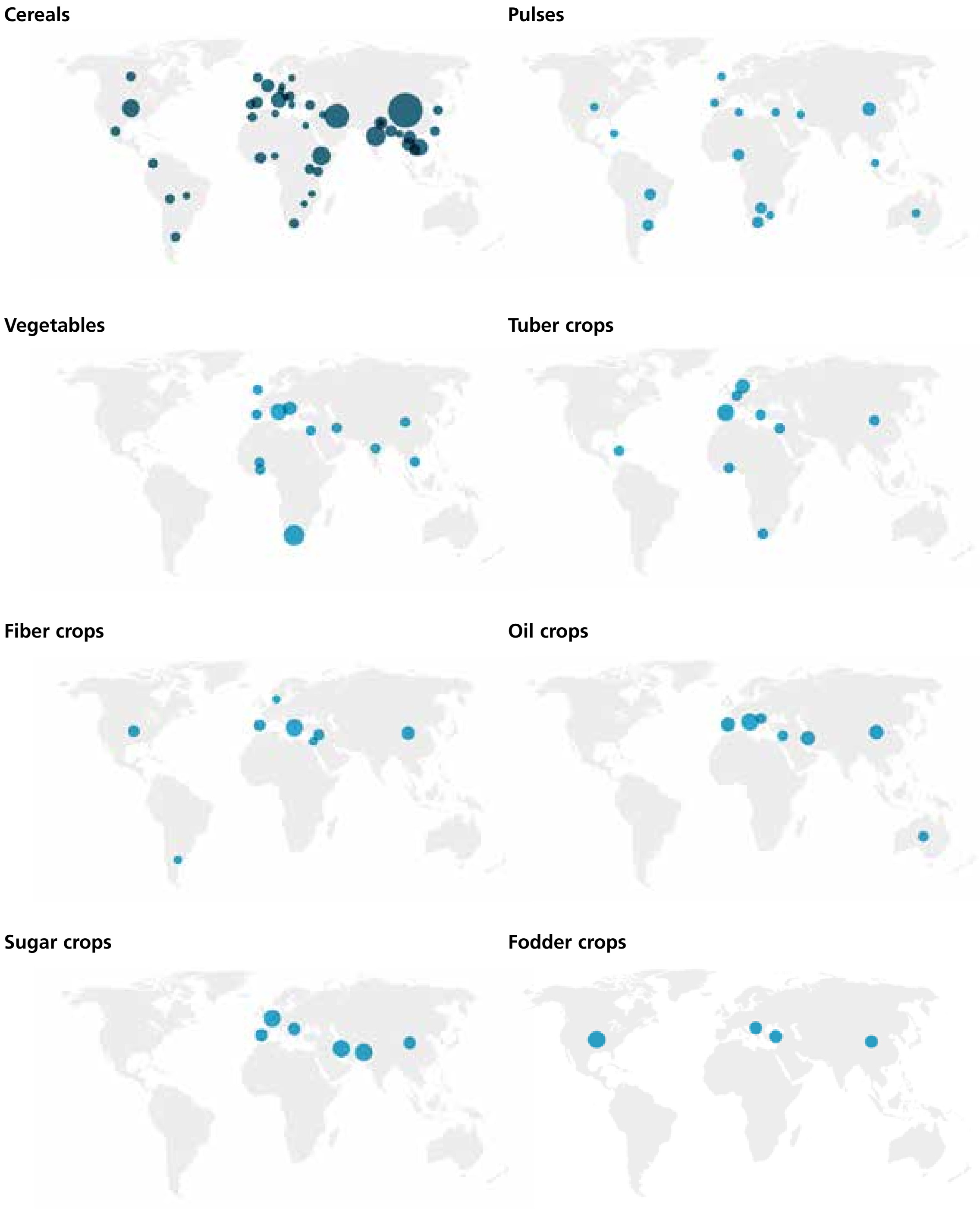
FIGURE 3.23
Percentage of publications on the AquaCrop model devoted to the top-ten crops in terms of number of publications



Regarding the geographic distribution of the studies addressing each crop type, cereals and pulses have been simulated under many diverse agro-ecological and socioeconomic conditions (Figure 3.24). This is not the case of industrial crops for which the model has been implemented mainly in Asia and Europe and leaving behind large producing regions in both America and North Africa. On the other hand, vegetables and tuber crops are almost wholly absent in America and have a limited presence in Asia compared to cereals. There are no crop models that cover all crop types and have been evaluated in all regions, so perhaps future efforts should be concentrated on the parameterization and evaluation of crops in their main producing areas.

FIGURE 3.24

Number of research publications on AquaCrop model devoted to each crop type in each country around the world. The size of the circle represents the number of publications in these countries



©FAO/Hoang Dinh Nam

©FAO/Laura Mullera

4. AquaCrop – Training and dissemination

Research and capacity building are steppingstones toward better water management in agriculture. Beyond its knowledge products, e.g. reports, guidebooks, manuals, FAO also focuses on capacity building for sustainable development, mostly in developing countries and emphasizing the Sustainable Development Goals (SDGs). Capacity building is a complex concept, being defined by FAO's strategy on Capacity Development (2010) as "the process whereby individuals, organizations and society as a whole unleash, strengthen, create, adapt and maintain capacity over time" (FAO, 2012). In particular, one of the key objectives of the FAO Land and Water Division is to enhance the ability of countries to generate demand-driven knowledge on water management in agriculture and to translate that information into action.

Sustainable crop and water management requires significant and well targeted investments in training that bolster capacities. AquaCrop model is an effective tool to identify optimal crop and water management strategies under different scenarios. Thus, AquaCrop training and dissemination activities are in themselves an effective adaptation measure to global change always through the prism of sustainable development. Since the model launch in 2009, FAO has perceived its potential beyond research and has made substantial efforts towards making this tool accessible and usable to a diverse set of practitioners working for extension services, governmental agencies, non-governmental organizations, farmer associations and other stakeholders.

In this chapter we present how the knowledge and experience on AquaCrop have been transferred to all potential users. Ten years of experience in training and dissemination of AquaCrop can provide a valuable perspective on capacity building and reveal which should be the future roadmap.

4.1. STRATEGIES OF TRAINING AND DISSEMINATION

What have the strategies of training and dissemination of AquaCrop been? and what are the training materials produced?

All the efforts carried out by FAO for the training and dissemination of AquaCrop were guided by the following principles based on FAO's strategy on Capacity Development (FAO, 2012):

- Capacity building is primarily an endogenous process that should be demand-driven. Thus, the training and dissemination actions should be led by national stakeholders from conception to evaluation with the FAO support.
- Considering that capacity building is related to different dimensions (people, organizations, and the enabling environment), the activities should be targeted not only the individuals but also organizations.
- There is no easy one-size-fits-all solution. All the activities should be tailored to the particular context and adapted to the varying capacities across countries.
- Activities should occur within an interdisciplinary approach, including crop production, water and soil resources management, meteorology and climatology, strengthening multidisciplinary expertise and networking.
- Activities should not be targeted solely at the scientific or academic community, but also at practitioners working for extension services, governmental agencies, farmer associations, etc.

- Participation of women in all the activities should be promoted and supported.
- Encouraging active networks of individuals and institutions by engaging with early –career to mid-career technicians and by fostering south-north and south-south research networks should be pursued.

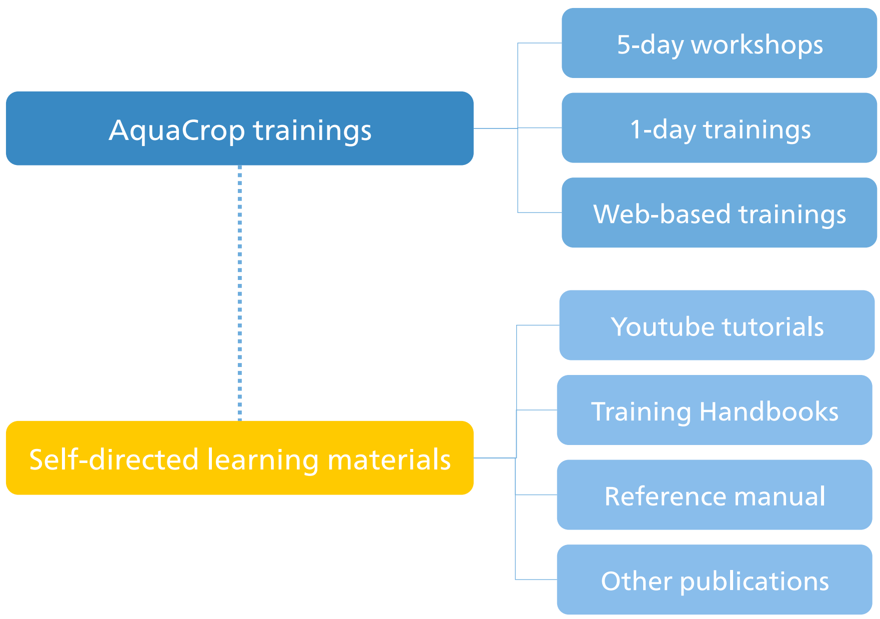
Following the guiding principles presented above, the training and dissemination strategy of AquaCrop has been based on a flexible process of learning and continuous adaptation to the new demands. A wide range of training and dissemination activities have taken place across the world since the model launch (workshops, training courses, participation in conferences and seminars, etc.). At the beginning of crop modelling, the training process started with one-to-one training sessions and was kept in relatively closed circles within academic environments. Further on, around the beginning of AquaCrop development, other established models started to offer structured courses of several days of duration with lectures and hands-on sessions (Boote *et al.*, 2015). In the case of models, such as EPIC (Williams *et al.*, 1983), and CropSyst (Stöckle *et al.*, 2003), short and reduced (for one to ten people) training sessions were provided at the promoter research sites (Boote *et al.*, 2015). APSIM (McCown *et al.*, 1995) has different modalities of training courses. The reduced version consists of a two-day training focused on the operational aspects of the model, which has been conducted in Australia at the developers' site. On the other hand, five-day APSIM workshops for 15–20 persons in countries where Australian international agricultural research projects (mainly in Africa and Asia) have been carried out. These courses usually consist of three days of hands-on sessions covering the theoretical principles and the processes simulated by the model and two days of working groups to address local issues and illustrate potential model applications.

The AquaCrop training program was launched by FAO immediately after the release of the first version of the model. It followed a somewhat different approach by conducting five-day workshops around the world, in most cases under the framework of development or technical cooperation projects, as discussed in detail below. Teaching was focused on use and applications of the model considering that most of the participants had no experience in crop models. In many regions, especially in developing countries, few professionals have crop modelling skills. In a few cases, there are trainees who wanted to learn about another crop model that they use, and specifically designed to simulate the crop response to water. They are interested in seeing how AquaCrop addresses the soil-plant-atmosphere system and is implemented in some specific contexts. Henceforth the focus will mainly be on this training course modality, not forgetting that other forms of training have been conducted, such as one-day workshops or training sessions included in the undergraduate and graduate programs of some universities.

Web-based training approaches have also been explored by the AquaCrop modellers group, as in the case of other models such as CropSyst. An example of this is the MOOC on the irrigation techniques organized by the University of Liège ("Les Techniques d'Irrigation" on www.fun-mooc.fr and online.jobsatskillscampus.be), which includes several modules that address the AquaCrop model. Furthermore, more recently, several e-trainings on AquaCrop were conducted in 2020 as a consequence of the COVID-19 pandemic, but they will not be covered in this publication. As communication technology capacity is increasing around the world, even in remote locations, these types of remote learning should be further explored. On the other hand, despite advance workshops have not been sufficiently covered during the first ten years of the model, two advanced trainings were held in Lebanon in 2018, which were targeted to technicians proficient in the use of AquaCrop and focusing on climate change impacts in crop production. Ultimately, there are several learning opportunities that should be explored to reach the greatest number of users in the most effective and efficient ways possible.

Self-directed learning materials also need to be a focus within the AquaCrop training and dissemination activities, since they are essential capacity building tools and complementing other training forms. These materials include a series of 43 YouTube tutorials (https://www.youtube.com/playlist?list=PLzp5NgJ2-dK7H85cyEmGc8KSodqm8gCf2) presenting AquaCrop. Each tutorial focuses on a specific aspect and peculiarity of the model and its applications. Two AquaCrop training handbooks, 'Book I. Understanding AquaCrop' and 'Book II. Running AquaCrop', are also available on FAO Website (http://www.fao.org/aquacrop/resources/traininghandbooks/en/). After introducing the model in the handbook I, the second handbook focuses on the practical part of how to run simulations with AquaCrop, explained step by step and illustrated with a set of exercises. Furthermore, all the model details, algorithms and applications can be found in the AquaCrop Reference Manual (http://www.fao.org/aquacrop/resources/referencemanuals/en/), as well as in other, extensive publications such as Steduto *et al*. (2012).

FIGURE 4.1
AquaCrop training formats and typologies of self-directed learning materials produced by FAO



What are the objectives, contents and structure of the AquaCrop workshops?

The overall objective of the AquaCrop workshops is to develop the capacity of practitioners, technicians and researchers in relevant domains in the use of AquaCrop. On this basis, and in addition to the context-driven targets to answer the specific needs of supporter projects or programs, the specific objectives are to:

1. introduce the participants to AquaCrop, its operation, inputs requirements and potential applications;
2. achieve a skilled management of AquaCrop by the participants towards enhancing their capacity to improve water management and crop water productivity;
3. identify possible paths of action towards implementation of AquaCrop in the professional activities of participants; and
4. serve as a platform for exchanging views among participants on the main water management constraints in their areas, and on the potential applications of AquaCrop to solve water-related problems.

The preparation process for any workshop was critically important. In general, a four-step approach was implemented to design and conduct successfully the AquaCrop workshops: (1) identification of target audience, knowledge gaps, training needs and main target for the implementation of the model; (2) detailed program design, costs and scheduling; (3) training conduction; and (4) training evaluation, which is used to assess the effectiveness of the activities and to identify future improvements.

Beyond the agricultural research and academic institutions, the common target audience of training courses of other crop models, a great effort has been made in AquaCrop to engage technicians working in governmental and non-governmental agencies, especially those dealing with agricultural water management. Information about the background of the participants and their prior experience in crop modelling was key to design the contents of each workshop. Thus, the core knowledge and skills gaps were identified during the planning process.

The five-day training programs were designed jointly with the national actors following a template that included few lectures on the general principles of the different model components combined with hands-on use of the model through practical exercises, i.e. using a 'blended learning' approach. Thus, the training in these workshops was task-oriented, where participants learn by doing, providing ample opportunities to talk and interact with the trainers and among themselves. Feedbacks at the start of every morning were appreciated to assess how far participants had progressed and to solve any problems that may have arisen in the previous sessions. The AquaCrop Training Handbooks have been used as a guide and support materials in most workshops. Despite the program template, it should not be forgotten that the training contents are dynamic, context-driven, and country-specific. Participants were encouraged to bring their own site-specific data (i.e. climate, soil, and crop development, phenology and management) in order to carry out some study cases exercises which would be directly relevant to their situations.

Regarding the trainers, in addition to the original model developers, other professionals with an in-depth knowledge of AquaCrop, teaching skills, mentoring potential and field experience have been involved in the workshops as instructors. All of them took an active role to assist the participants in model running and/or other AquaCrop-related concerns that they had. It should be highlighted that the presence of more than one trainer in some AquaCrop workshops with expertise in different topics added substantial value. Another important goal of AquaCrop courses has been to train individuals with the potential to become future trainers of AquaCrop in their countries. Accordingly, all the training materials (e.g. PowerPoint presentations, scripts, etc.) were shared with the trainees with the expectation that they were useful to help train other potential users when they return to their home institutions.

4.2. SCOPE OF TRAINING AND DISSEMINATION

How many AquaCrop workshops have been carried out? Is there any trend? What are the main institutions involved in these activities?

Monitoring and evaluating the scope of the training and dissemination activities on AquaCrop model during the first ten years from its launch is extremely challenging. The traceability of the long-term effects is complex and the impacts are difficult to quantify. Nevertheless, this section attempts to shed light on this matter using a reduced number of indicators for learning and future actions.

In 2009, after the model launch, the first four AquaCrop trainings belonged to a series of workshops on "Capacity Development for Farm Management Strategies to Improve Crop-Water Productivity using AquaCrop" organized jointly by FAO and the UN-Water Decade Programme on Capacity Development (UNW-DPC) in collaboration with local partners in Burkina Faso, Iran, China, Egypt and South Africa (Ardakanian and Walter, 2011). With this initial effort, 146 participants from 58 different countries characterized by their high potentials to improve water use efficiencies were trained. Similar workshops have been conducted around the world, amounting to a total of 67 training courses conducted from 2009 to 2019. Except for 2019, on average, five workshops per year were organized (Figure 4.2). The latter year has been marked by a huge effort made in capacity building, by conducting 16 training courses attended by over 400 participants. This is in line with the special attention paid to capacity development in the irrigation and drainage world in recent times.

The organization of most of the AquaCrop workshops has been led by FAO (61 percent of the workshops), the Joint FAO/IAEA[1] Centre (12 percent), and the Arab Center for the Studies of Arid Zones and Dry Lands (7 percent). Other institutions, such as universities (e.g. KU Leuven, IAV Hassan II[2]), cooperation agencies (e.g. VLIR-UOS[3], Australian Aid, etc.) and other UN organizations (e.g. ESCWA) also had a major role in their planning and coordination.

What has the geographical coverage of the trainings? How many people have been trained? Is it possible to link the training efforts with the impact on research?

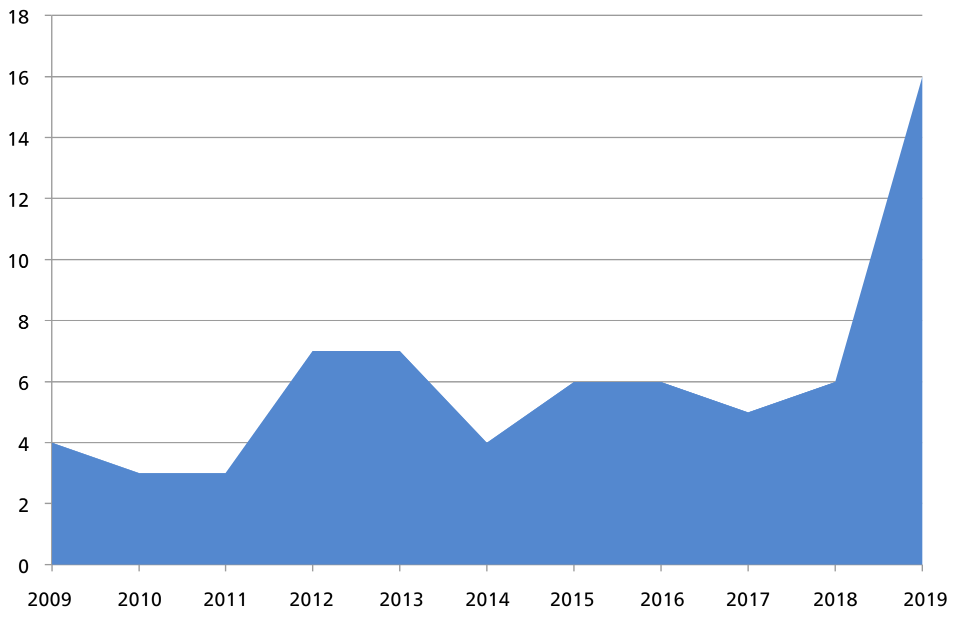
While trainees have come from many more countries, AquaCrop workshops have been conducted in 40 different countries around the world (Figure 4.3). Analyzing the geographic coverage, the highest number of trainings were organized in Asia (48 percent), especially in the Near East region, followed by Africa, with 23 percent of the workshops (Figure 4.4). In America, a significantly lower number of workshops (9 percent) can be observed despite the capacity building needs identified in this region

1 International Atomic Energy Agency

2 Agronomic and Veterinary Institute Hassan II

3 Flemish Inter-universities Council- University Development Co-operation

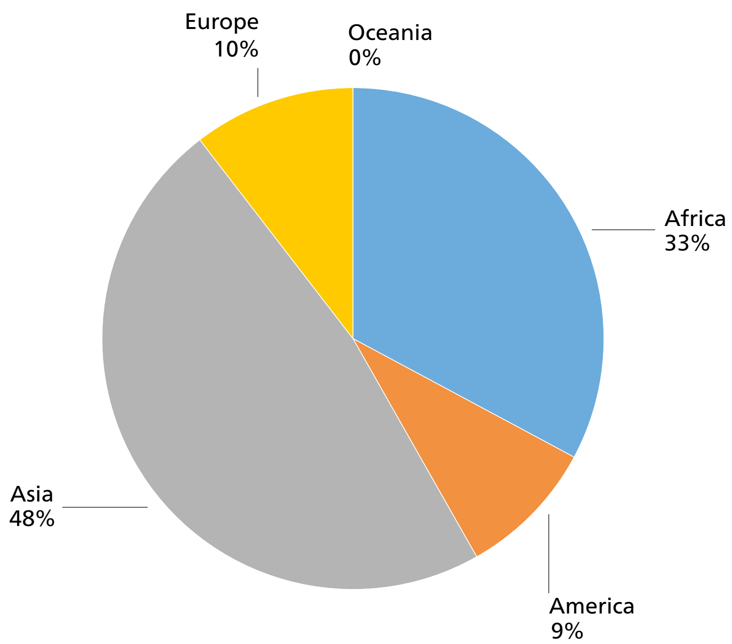
FIGURE 4.2
Evolution of the number of AquaCrop workshops per year from 2009 to 2019 (The dotted line represents the annual average number of workshops without considering 2019)



(Bormann *et al.*, 2016). Meanwhile, Oceania is the only continent where AquaCrop trainings have not yet taken place. Jordan, Lebanon and Morocco, all countries under water scarcity, are the countries where the highest number of workshops has been conducted, attended by trainees of different nationalities.

FIGURE 4.3
Number of AquaCrop workshops conducted in each country around the world (The size of the circle represents the number of workshops in these countries)

FIGURE 4.4
Percentage of AquaCrop workshops conducted in each continent



The number of participants in each workshop ranged from 8 to 55 persons, 23 on the average at any one time, a large number being sometimes a limitation for effective learning. It should be borne in mind that only 46 percent of the trainings involved participants of a single nationality (Figure 4.5). Indeed, up to more than ten nationalities participated in some workshops (13 percent). Mindful that promoting networking is one of the most important ways to boost capacity building, the training courses have been good opportunities to set networks of collaboration North-South and South-South. The multi-nationality of workshops has resulted in better geographic coverage than the one shown by the analysis of the training locations (Figure 4.3). In this regard, more than 1 500 individuals from 113 different countries were trained over the analysis period of ten years. These figures are a clear indicator of the extent of the capacity development activities performed. Figure 4.6 shows the number of people trained in the use of AquaCrop model in each country around the world. Wide territorial coverage is especially observed in Africa and Asia, where practitioners and/or researchers from 87 and 81 percent of their countries, respectively, have been trained. Meanwhile, in America, more than half of the countries (65 percent) have been subject of some training activity. This has meant that 44 and 41 percent of the trainees were Africans and Asians, respectively (Figure 4.7), while only 11 percent Americans. Perhaps in the future, the training actions should be expanded in America, not to leave anyone behind.

FIGURE 4.5
Percentage of AquaCrop workshops concerning the number of nationalities involved

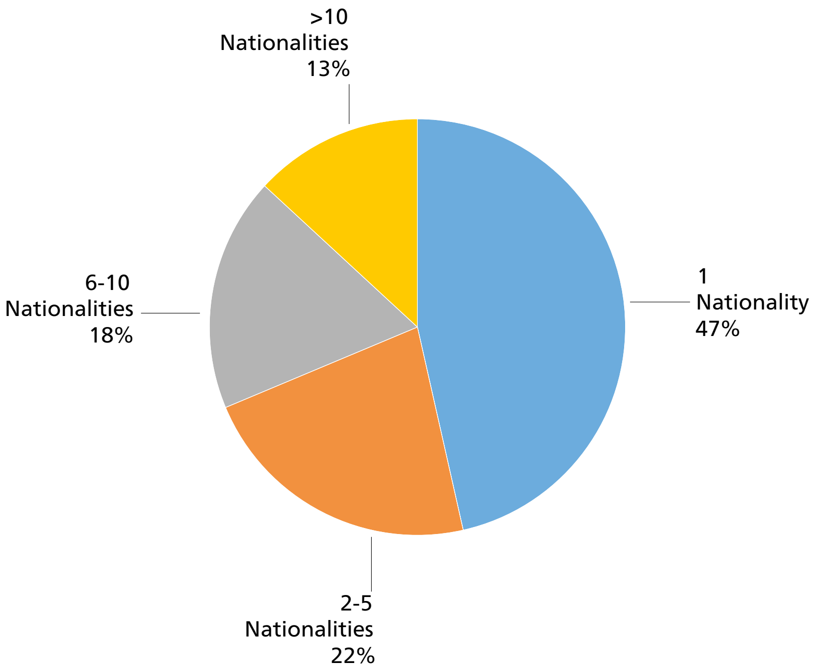
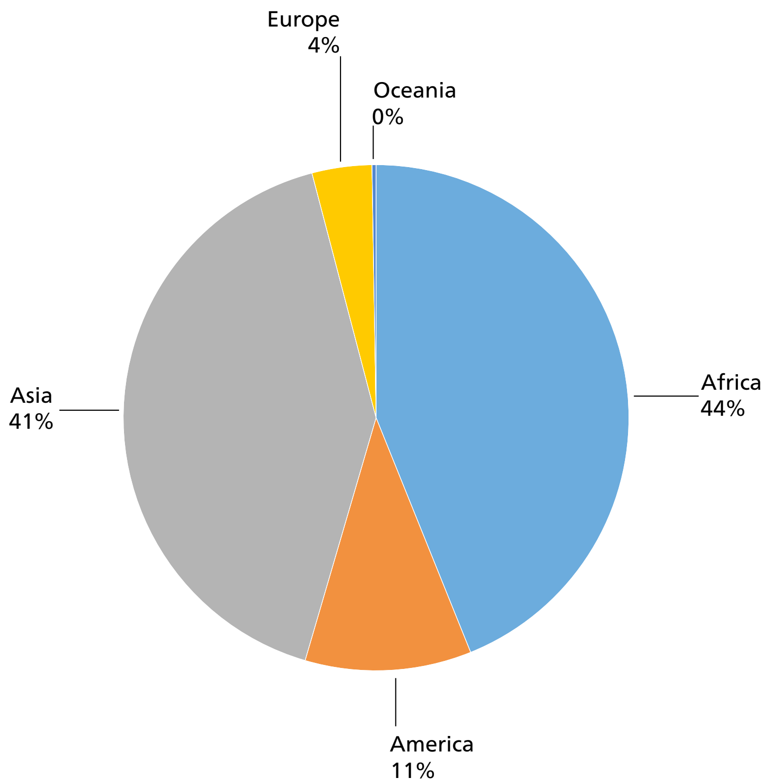


FIGURE 4.6
Number of people trained in the use of AquaCrop model in each country around the world (The size of the circle represents the number of people in these countries)

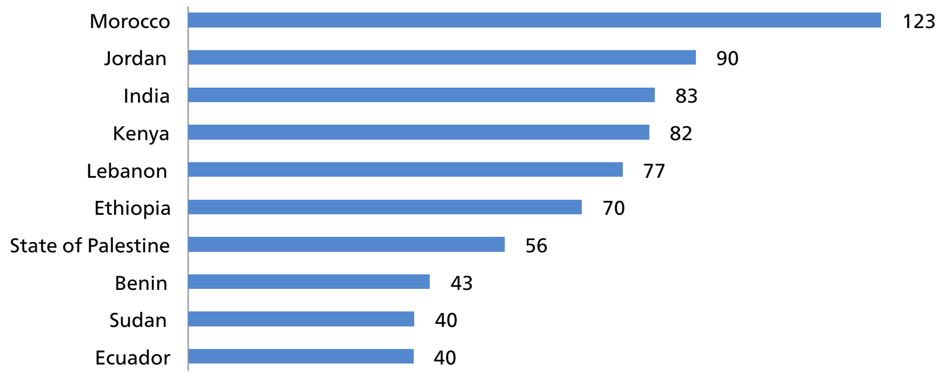
FIGURE 4.7
Percentage of people trained in the use of AquaCrop model in each continent



When analyzing the top ten countries with the highest number of participants in the AquaCrop workshops, Morocco is the first in the rank with 123 trainees (Figure 4.8). Along with Sudan, other three sub-Saharan countries (Benin, Ethiopia and Kenya) are included in the list. The major training efforts performed in these countries may be reflected in the number of research publications on AquaCrop, particularly in the case of Ethiopia (Figures 3.9 and Table 3.1). Regarding Asian countries, except for India (third position in the rank), the greatest number of trainees are from the Near East region (Jordan, Lebanon and Palestine). On the other hand, Ecuador is the only American country present in the top-ten list with 40 trainees.

Although very often possibilities to improve agricultural water management are available, they cannot be applied in countries where they are needed, as appropriate capacity development is still missing (Ardakanian and Walter, 2011). In this regard, the AquaCrop training and dissemination activities carried out during the first ten years from its launch have largely contributed to reduce the knowledge gap in the area of crop modelling between developed and developing nations. AquaCrop workshops were clearly valued positively by the participants, meeting their objectives. Nevertheless, capacity building is not a one-off intervention, but a continuous process of upgrading that includes learning-by-doing, reflection and adaptation as key elements (Mbabu and Hall, 2012). Thus, there is a need for continued support and training in AquaCrop. The experience gained hitherto can provide ideas for improvements and new approaches in future. The further training and dissemination activities planning is essential at this stage, outlining a road map in light of the previous experience.

FIGURE 4.8
Number of people trained in the use of AquaCrop model in the top-ten countries in terms of number of trainees



5. AquaCrop on the ground

As is well known, agricultural systems face three main challenges through sustainable intensification of agricultural production: feeding a growing population, providing a livelihood for farmers, and improving environmental sustainability. This leads to the need to enhance agricultural productivity sustainably, producing more with less, to meet increasing demand while preserving and enhancing the livelihoods of small-scale and family farmers (FAO, 2017). There is a continuing explosion in the amount of published information from every research field that is contributing to address these challenges. However, the problem of managing all of this knowledge, treated in many occasions as independent components, becomes more difficult (Jones *et al.,* 2016). In this regard, crop models can play an important role in systemization and integration of all this new knowledge.

In line with the above, AquaCrop is a useful tool for a wide variety of applications that can contribute to coping with these challenges. The model can be used as a tool to assist in tactical and strategic decision making, such as pre-season and in-season agricultural management decisions, and to inform planning and policy at regional or national level (Steduto *et al.,* 2009). Several examples of the implementation of AquaCrop for on-farm decision-making can be found in many projects conducted around the world. In turn, governmental agencies increasingly require plans for best management practices as well as tools for yield forecasting and for assessing the impact of the changing environment. These needs have also driven the implementation of AquaCrop on the ground through different types of projects. In this regard, in some cases, the model's biophysical outputs have been combined with economic models to support decisions for optimal policies. Nevertheless, it should be borne in mind the cautions and limitations in AquaCrop use, associated with its complexity level and degree of evaluation.

Based on these considerations, this chapter aims at providing an overview of the projects carried out by FAO and other institutions at country, regional and global level, in which AquaCrop has been implemented to support decision making at farm and policy levels. To get a better understanding of the model implementation on the ground from its launch to 2019, a survey was conducted among the members of the extended core group of AquaCrop. Aggregate data on the main characteristics of the projects led by FAO are presented in the first part of this chapter, while those conducted by other institutions are shown subsequently. Although this information provides a better picture of the projects' typology, it is not fully representative of all projects in which AquaCrop has been used, being only a first attempt to shed light on this important matter.

5.1. FAO PROJECTS – OBJECTIVES AND SCOPE

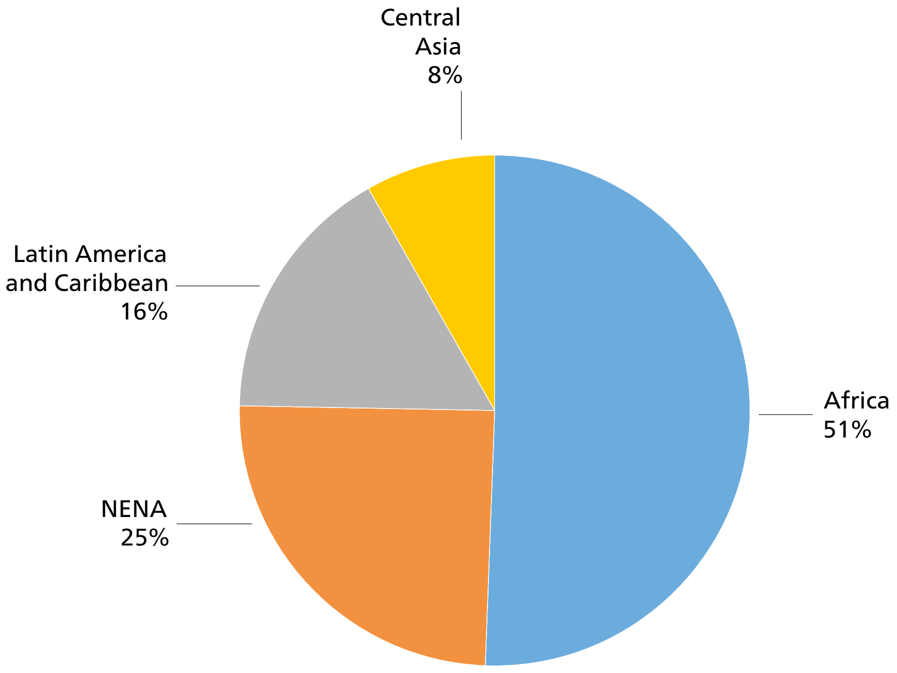
FAO projects that have implemented AquaCrop: What is the geographical coverage of these projects? What are their main objectives?

Achieving FAO strategic objectives (FAO, 2019) is a challenging and complex task. FAO works to address the issues and problems identified for each strategic objective through its core functions, among which is working in partnership with a wide range of institutions, including international and regional organizations, governments, universities, civil society and the private sector (FAO, 2019). Projects at country, regional and global levels have enabled to join forces effectively among all these institutions for addressing these challenges. In this context, AquaCrop has been implemented as a tool for improving water management in agriculture in several projects around the world.

Through a survey performed, fourteen projects led by FAO and the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture were identified. From its launch in 2009, AquaCrop has been implemented on a continuing basis through projects whose duration ranged from two to five years, averaging three years. The projects are all at different stages, but 64 percent of the projects have already been completed, nonetheless. Most of them have been financed by United Nations programmes and/or development aid agencies (e.g. SIDA[4] and SDC[5]), and have engaged a wide diversity of stakeholders, such as governmental agencies, farmers associations, academia and civil society organizations.

The majority of documented FAO projects operated at the regional level (50 percent), followed by those implemented at national level (36 percent), and at global level (14 percent). Regarding regional distribution, 43 percent of the projects focus their activities in Africa, 21 percent in the Near East and North Africa (NENA region), 14 percent in Latin America and Caribbean and 7 percent in Central Asia (Figure 5.1). The special attention paid to Africa and the NENA region in terms of training activities (see Chapter 4) is also revealed in the high level of activities on the ground. These projects

FIGURE 5.1
Percentage of projects led by FAO and the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture documented in this review paper which have implemented in each region.



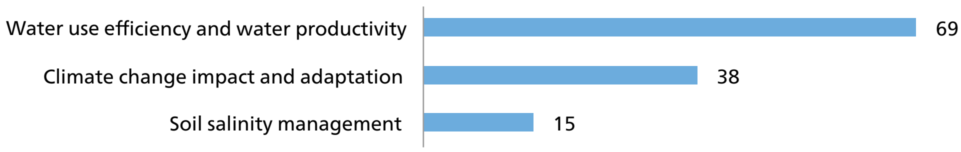
[4] Sweden's government agency for development cooperation
[5] Swiss Agency for Development and Cooperation

involve 46 different countries around the world (Figure 5.2), continuing to focus the field activities on the agricultural problems of the least developed countries. The highest number of projects (five) has been conducted in Morocco, where, similarly, a great deal of training activities has been carried out (Figure 4.8).

FIGURE 5.2
Geographical distribution of projects led by FAO and the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture documented in this review paper

The majority of FAO projects documented in this review paper are comprehensive water-related projects that apply AquaCrop for various purposes. The projects objectives range from improving irrigation management to enhance water productivity and water-use efficiency, and to monitoring water resources for the assessment of climate change impacts and adaptation strategies. More specifically, the activities with AquaCrop were mainly focused on three topics (Figure 5.3): improving water-use efficiency and water productivity (69 percent of the documented projects), climate change impact and adaptation (38 percent) and soil salinity management (15 percent). Thus, as in the case of the research publications on AquaCrop (see Chapter 3), the most prominent model applications are irrigation management and climate change impacts. This shows just how the research activities on AquaCrop have been translated into concrete actions on the ground to support decisions made by farmers and policy makers. An example of the two main types of AquaCrop implementations on the ground through an FAO project can be found below.

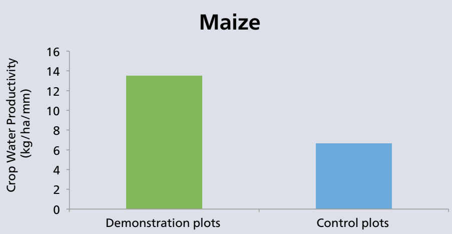
FIGURE 5.3
Typology of projects led by FAO and the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture that have implemented AquaCrop

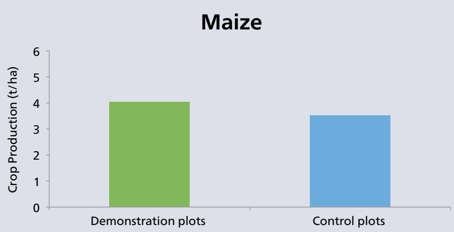


BOX 1
Improving Irrigation Water Productivity in Small-scale African Irrigation Schemes

In Africa, even though irrigation has the potential to largely increase agricultural productivity, food production is mostly based on rainfed agriculture. Therefore, boosting the performance of irrigated agriculture in Africa, particularly in small-scale irrigation, would be important for the economic development of the continent. FAO, through its project 'Strengthening Agricultural Water Efficiency and Productivity on the African and Global Level', has piloted a new approach to boost crop water productivity (WP) in small scale agriculture in three pilot irrigation schemes (Ben Nafa Ka Cha, Burkina Faso; Al Haouz, Morocco; and Mubuku, Uganda). This approach was designed with four components: (1) Diagnosis and benchmarking of current agricultural productivity levels and of farming practices at farm level for major crops; (2) Evaluation of potential and attainable yields (Ym and Ya, respectively); (3) Identification and delineation of optimal farming practices required to improve the WP; and (4) Implementation of optimal farming practices in order to demonstrate their impact. The AquaCrop model played an important role in this pathway, as it was used to: (1) obtain an independent estimate of Ym and Ya (using long-series of weather data); (2) identify possible causes of yield level gaps (among actual yields, Ym, and Ya) and management options to reduce the gaps where feasible; and (3) quantify the potential impact of implementing the proposed pathways in the improvement of yield and WP.

The optimal management strategies identified with the support of AquaCrop were implemented in demonstration plots to provide effective means for their dissemination. The main practices implemented were: (1) improved irrigation scheduling by matching applications to crop needs instead of following a rigid calendar; and (2) improved mineral fertilization by adjusting the timing and amount of the application of fertilizers to the crop needs. Three outputs were analysed as the result of the improvement strategy: yield, irrigation water amounts, and water productivity. Here, as an example, the results obtained in the maize demonstration plots in Mubuku Irrigation Scheme (Uganda) are presented. The irrigation WP of maize increased from 6.7 to 13.5 kg/ha/mm, on top of a significant irrigation water savings (221 mm) and a modest yield gain (0.5 t/ha) in the demonstration plots. An extensive description of project results may be found in Salman *et al.* (2020).

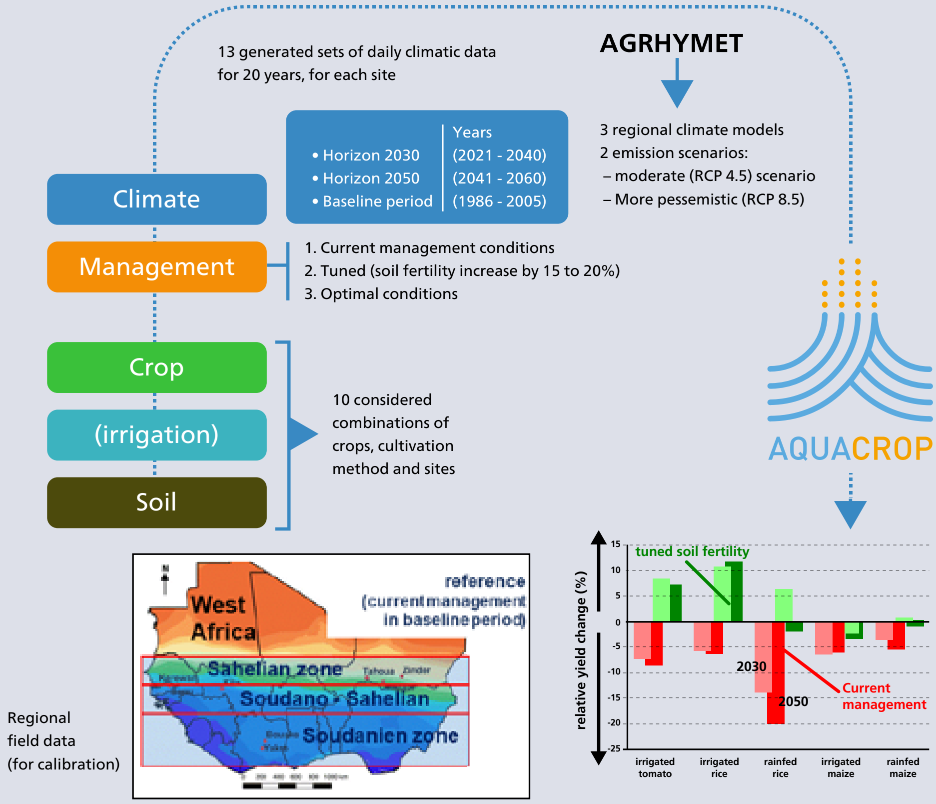




BOX 2

Adapting irrigation to climate change

The West Africa region is particularly threatened by climate change due in part to its high dependence on rainfed agriculture. A quantitative assessment of the impacts of climate change on the four main crops in the region was conducted using AquaCrop to simulate crop yields under current conditions and future climatic scenarios using two Intergovernmental Panel on Climate Change (IPCC) emission scenarios. This assessment was carried out under the framework of the FAO project 'Adapting irrigation to climate change (AICCA)' (http://www.fao.org/in-action/aicca/en/), with the support of IFAD (International Fund for Agricultural Development).



With reference to current management conditions for the baseline period ________

The main findings of the analysis of the relative yield change are:

- Crop yield is expected to fall by 5 to 20% with current management conditions;

  Cultivation of current sorghum cultivars could become impossible in the Sahelian zone.

- Improving soil fertility by at least 15 to 20%, could lead to an increase in crop yields of 5 to 14% for irrigated tomato, as well as irrigated and rainfed rice (C3 crops).

Enhancing soil fertility (to benefit optimally from CO_2 fertilization) is key to improving the yields of irrigated C3 crops.

Supplementing rainfed agriculture with irrigation, as a strategy to enhance yields, can only be effective with the improvement of soil fertility.

When assuming optimal management conditions, yield could double.

5.2. PARTNERS' PROJECTS – OBJECTIVES AND SCOPE

Partners' projects that have implemented AquaCrop: What are the main leading institutions? What is the geographical coverage of these projects? What are their main objectives?

Beyond FAO's initiatives, AquaCrop has also been implemented to address the challenges of agricultural systems through many other projects all over the world. This section attempts to complement the view of FAO's work with AquaCrop on the ground using the information compiled by the performed survey. As stated above, this is a small sample of the multitude of projects that have surely made use of the model in the first ten years since its launch.

A greater number of projects led by institutions other than FAO have been identified and documented. Specifically, 32 projects were identified, most of them under the leadership of academic and research institutions (81 percent of the projects), followed by other UN agencies (e.g. ESCWA[6]) and international cooperation institutions (e.g. GIZ[7]). Notwithstanding the strong research focus of the institutions that lead most of these projects, numerous stakeholders such as governmental agencies, international organizations, farmers associations and the private sector were also involved. The primary funding agency was the European Commission (53 percent of the projects) followed by a variety of financing institutions including development aid agencies (e.g. SIDA[8], Wallonie-Bruxelles International, etc.) and international organizations (e.g. the World Bank). An increasing tendency concerning the number of projects is observed despite the inter-annual variability, being 75 percent of the projects already completed. Their duration ranged from one to five years, averaging three years.

In contrast to the FAO projects, there is a balance between the number of projects conducted at regional (44 percent of the projects) and country level (41 percent). Another noteworthy difference is that there are no regional projects in Africa (where the majority of the FAO projects took place; Figure 5.1) and in Central Asia, with the main focus on Europe (64 percent of the regional projects, Figure 5.4). Only projects at national and global level have been conducted in these regions. Analyzing the records more in detail, the projects have involved 60 different countries around the world (Figure 5.5). European countries lead the list of the countries where a higher number of projects have been conducted, headed by Spain with 14 projects.

As with the FAO projects, optimal water management in agriculture is the main target of most other projects. In addition to the objectives pursued by the FAO projects, agriculture digitalisation, water-energy nexus and yield forecasting clearly emerge. Figure 5.6 presents the percentage of projects that addressed each of the main topics. Enhancing water-use efficiency and water productivity continues to be the most prominent model application (44 percent of the projects documented), while climate change impact and adaptation (22 percent) have tended to lag behind yield forecasting applications (28 percent). It is not surprising since seasonal forecast of crop yield plays a critical role in decision making for many stakeholders. Nevertheless, the link between the research on AquaCrop (see Chapter 3) and the actions on the ground is still evident

[6] United Nations Economic and Social Commission for Western Asia

[7] The German Society for International Cooperation

[8] Sweden's government agency for development cooperation

FIGURE 5.4
Percentage of projects led by institutions other than FAO which have implemented AquaCrop

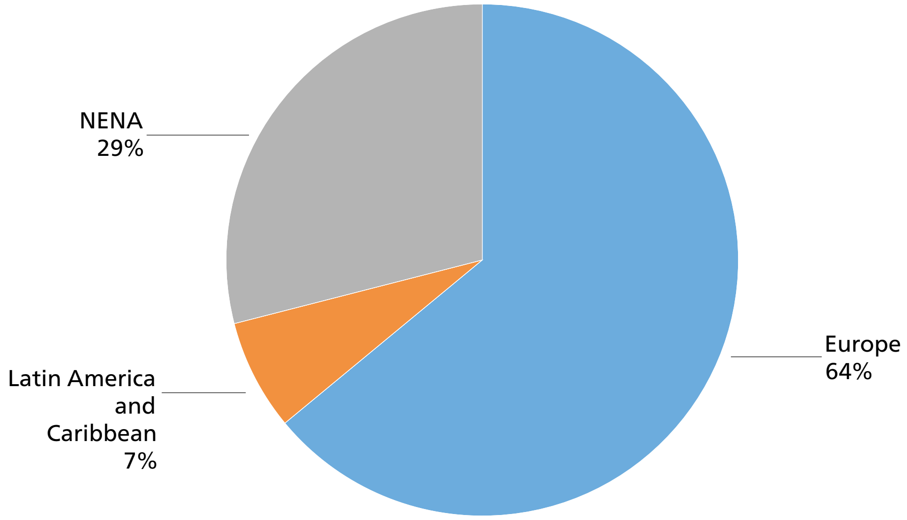
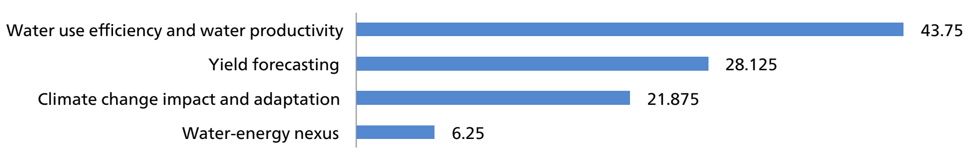


FIGURE 5.5
Geographical distribution of projects led by institutions other than FAO which have implemented AquaCrop

in all these projects. An example of the two main types of AquaCrop implementations on the ground through a partners' project can be found below.

FIGURE 5.6
Percentage of projects led by institutions other than FAO that have implemented AquaCrop



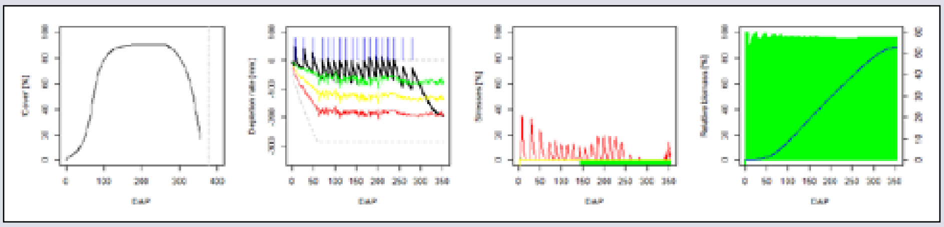
Despite the high number and diversity of projects that have implemented AquaCrop, there are still many potential applications that have not been fully explored and exploited. Furthermore, many parts of the world could benefit from AquaCrop applications to tackle the challenges of their agricultural systems, thus there remain substantial opportunities for future implementation projects.

BOX 3

AquaCrop for optimal irrigation calendars: the case of sugarcane in Senegal

The *"Compagnie Sucrière Sénégalaise"* (CSS) was looking for a decision support tool to improve their productive water management. With almost unlimited water resources from the Senegal river for its around 13.000 ha of irrigated sugar-cane, the company wanted to economize their water (and pumping) consumption, and act as a responsible and exemplary water manager for the region (Sall *et al.*, 2021). An applied research and development project, jointly funded by the University of Liège (Belgium) and the CSS, was put in place to see how AquaCrop could be of help.

A common sugar-cane campaign constituted of 32 irrigations of 48 hours applying 200 mm; or a seasonal total gross irrigation of 6.400 mm. Through AquaCrop simulations, different water related stresses were observed: between 100 and 150 days after planting (DAP) development stress due to lack of water and as from 200 DAP stomatal closure due to over-irrigation. This resulted in around 20% of biomass losses. After calibration and validation (Wellens *et al.*, 2020), an optimal and easy applicable irrigation calendar was expanded for sugar-cane in AquaCrop, with intervals varied between 14 and 21 days, and net irrigation depths of 80 mm are to be applied during lapses of 24 hours. When using these proposed irrigation calendars, only 18 irrigation events of 80 mm are required, resulting in a total gross irrigation of 2.880 mm, when considering an irrigation efficiency of 50% (Boss and Nugteren, 1974). The figure below demonstrated the beneficial effects of this optimal irrigation calendar: almost 4.000 mm of irrigation water saved for a 100% relative biomass production.



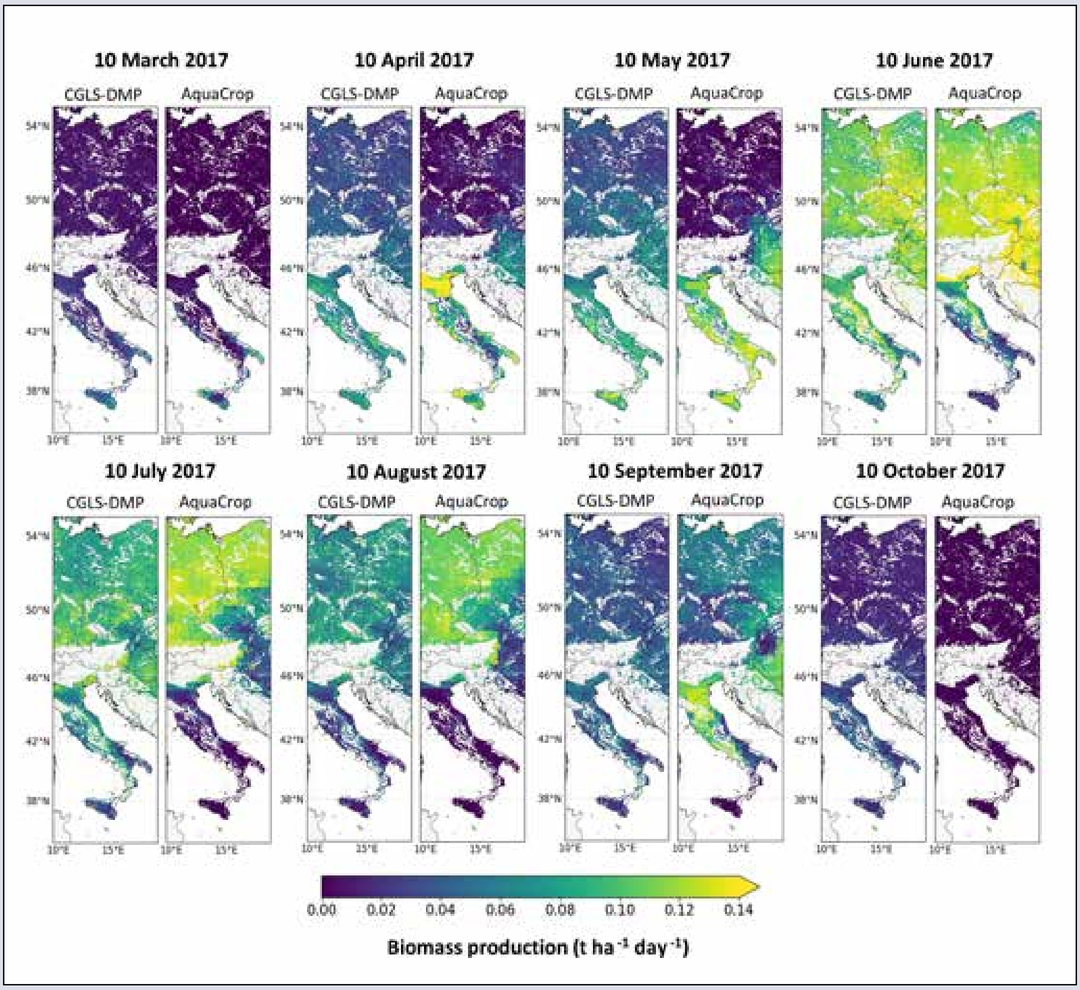
CSS is starting to gradually change his irrigation siphons (larger diameters to deliver the required discharge) in order to put these irrigation calendars in place in more and more plots. Its ambition is to also transfer this experience towards the surrounding irrigated rice and horticulture fields.

BOX 4

A regional AquaCrop version to simulate crop biomass and soil moisture

A spatially distributed version of AquaCrop was developed to simulate agricultural biomass production and soil moisture variability over Europe (de Roos *et al.*, 2021). This work is part of the Horizon 2020 project SHui 'Soil Hydrology research platform underpinning innovation to manage water scarcity in European and Chinese cropping systems' (https://www.shui-eu.org/). The AquaCrop model is parameterized with a generic C3-type of crop. A parallel processing is implemented to run the model regionally, with meteorological input data from MERRA-2 and soil characteristics based on HWSDv1.2 at 1-km resolution. The model has been evaluated at a resolution of 30 arcseconds (~1 km), with various satellite products and in situ soil moisture data. Daily crop biomass production has been evaluated with the Copernicus Global Land Service dry matter productivity. The model was able to capture spatial as well as temporal trends.

Website: https://ees.kuleuven.be/project/shui-regionalaquacrop/



Daily biomass production for different days of the year 2017. For each day, the left and right images respectively show the evaluation product CGLS-DMP and the simulated AquaCrop biomass.


©FAO/Daniel Hayduk

6. Conclusions – Impacts, challenges and the way forward

What have been the main impacts of the efforts made to develop, implement and disseminate AquaCrop?

The principles for the effective management of water in agriculture are well established, and the pathways to translate them into actions have also been delineated. Nevertheless, the magnitude of the task and the difficulties on the ground make it difficult to bridge the gap between current and near optimal situations in most areas. AquaCrop has been developed by FAO to assist stakeholders in the improvement of water use and productivity in agricultural systems. This publication attempts to assess the impact of AquaCrop model in its first ten years of usage on research and its applications, on training, and on development projects.

Regarding research activities, despite the fact that AquaCrop has been developed more recently than most established crop models, it has been very well received in academic circles, as shown by the large number of publications that have used it (33 per year). This rate makes it the second model of all those utilized by the modelling research community in the past decade. This success is somewhat impressing given that the model was built with the aim of assisting a diversity of stakeholders beyond researchers. However, the relative simplicity of AquaCrop and its friendly software interface have attracted many researchers since the model was launched, mostly with an applied focus. AquaCrop has been implemented in 64 different countries across the world's five continents, in very different agro-ecological zones. The publications were divided into three categories of model development, evaluation and application; and it was found that more than 60 percent of publications were devoted to applications. The research activities have made substantial contributions in diverse areas, leading to further calibration and validation of the model for other major and minor crop plants which had not been calibrated originally with the model. In fact, the original calibration files provided with AquaCrop cover 15 different crops, while new calibration studies have been published for an additional 19 major crops and 12 minor crops, albeit many based on limited experimental data. Another important positive outcome from the published research was the identification of simulation issues which required model improvements which will be provided in subsequent AquaCrop versions.

The extensive model tests performed by the research community and published in refereed international journals in the ten-year period provided clear proof of the robustness of the water driven approach adopted by AquaCrop, and generally showed good to very good agreement between the simulated and measured results in many different environments and for various crops. As to the type of applications developed in the publications, there was a balance between agronomic and environmental issues, the latter mostly related to water and climate change. Evidently, the focus of AquaCrop on the simulation of water-limited yield has made this model particularly suitable to tackle a diverse suit of issues related to water.

Regarding training and dissemination, given the interest of FAO to assist a diversity of stakeholders in tackling water-related issues in food and agriculture, a strong training and dissemination effort was implemented even before the model was formally published in international journals. Active networks of individuals and institutions were encouraged by engaging with early-career to mid-career professionals, by using opportunities provided by technical cooperation projects, and by fostering south-north and south-south networks. Training efforts went well beyond the academic community, focusing mainly on professionals working in the public administration, extension specialists, consulting engineers, and technicians working for farmers associations. The standard training module has been a five-day workshop which covered limited fundamental information but mostly hands-on applications, including those relevant to course participants. Nevertheless, other approaches, such as one-day short courses, lectures, seminars, participation in professional meetings, have been followed. Self-directed learning materials have also been produced such as the 43 YouTube tutorials, manuals, and a comprehensive FAO publication to provide essential fundamentals to those interested in using the model (Steduto *et al.,* 2012). Between 2009 and 2019, a total of 67 workshops have been conducted in 40 countries with participants from all over the world. Training was concentrated in areas of water scarcity such as the Near East and North Africa region. The majority of the training workshops were organized by FAO but other organizations were involved as well, including universities, governmental institutions, and NGOs. A total of more than 1500 participants from 113 countries have been trained in AquaCrop.

Actions on the ground, which have used the AquaCrop model as a tool to achieve certain objectives in research and development projects, have also been witnessed. These actions deal primarily with development-oriented projects led by FAO and other international institutes, examining in detail a sample of 15 projects led by FAO and of another 32 projects mostly led by academic or by international cooperation institutions. The overarching objective of most projects has been the improvement of water management in agriculture. A diversity of approaches was taken to implement solutions and for capacity development aimed at dealing with topics such as water productivity, yield forecasting, climate change and adaptation, and the food-water-energy nexus, among others.

What are the main challenges in AquaCrop development, improvement and application?

The AquaCrop model was built with several major considerations in mind. Firstly, to concentrate on the simulation of water-limited yield driven by a water-driven growth engine. Secondly, to simplify its make-up relative to the main, research-oriented and established models. Furthermore, a users' friendly software was deemed necessary to ensure openness, easy understanding of its functioning, and to engage a variety of stakeholders who were not familiar with crop modelling. As with any simulation model, AquaCrop started with many limitations which have only been partially addressed by the release of more than five new, improved versions of the model. One simplification that has worked well is the use of canopy cover to characterize canopy size and growth instead of the leaf area index. The computation of canopy transpiration based on a robust, thoroughly tested soil water budget, and the use of the well-known Penman-Monteith equation for quantifying evaporative demand, are at the core of the reliable biomass predictions. The introduction of harvest index adjustments in response to the dynamics of water stress has given support to water-limited yield predictions. Nevertheless, many challenges remain for improving AquaCrop performance.

The model has been thoroughly tested for only a few of the major crops, and more rigorous testing is needed for some of the crops for which the proposed parameters have been derived from a handful experiments. The present lack of interest in field data collection which is essential to model parameterization is a limiting factor to model improvement. Even in the case of the 15 crops of the AquaCrop parameter data file, there are some inconsistencies which need to be corrected. This is even more evident in the published calibration studies of additional crops, where a comparison among the parameters proposed in different studies of the same crop exhibit major differences, often unjustified from what is known of the crop physiology. The model was designed for use with herbaceous crops and cannot simulate the yield response to water of perennial crops such as fruit trees and vines.

AquaCrop simulations provide the maximum yield that may be achieved with a given supply of water. It is well known in agronomy that most of the time, factors other than water co-limit yield. This became evident in field studies in developing countries where measured yields were substantially less than simulated yields, a fact that could not be explained by water alone. In those cases, the primary co-limiting factor was soil fertility, particularly nitrogen supply. Given the difficulties associated with building a nitrogen budget module in terms of parameter values, a simple soil fertility module was devised, which appears to work well, but that needs substantial more testing to confirm its validity in different agronomic environments.

Salinity is a major environmental problem in water limited environments. AquaCrop has a salinity module to compute a daily soil salinity budget along with its robust soil water budget. The impact of soil salinity on yield is simulated using long-term empirical functions relating soil salinity to yield. This is a topic where research activities have been limited in recent decades and as a result, the yield predictions are oversimplified and untested. The impact of soil spatial variability on yields under salinity conditions in the real world makes it difficult to verify the simulations under salinity conditions. Nevertheless, more testing of the simple AquaCrop module is needed and perhaps an alternative formulation of yield response to salinity is also needed. The recent addition of a weed module that simulates the impact of weed growth on yield in the latest AquaCrop version is yet another attempt to call the attention to factors other than water affecting crop performance, giving the opportunity to explore via simulations the role of a weed invasion on crop yield predictions.

What is the way forward for the improvement, dissemination and proper implementation of AquaCrop?

Improvement of the AquaCrop model following some of the indications discussed above is a necessary condition but not at all sufficient to extract the potential that the model has in assisting efforts to improve agricultural water management and water productivity. Given that the current version has proven reliable for yield forecasting of the major herbaceous crops and that researchers appear interested in continuing to refine and propose improvements, the foundations of the model are quite solid. FAO will continue to be the repository of the AquaCrop model and to coordinate its use worldwide by different stakeholders.

Further efforts must prioritize, on one hand, more training and capacity development exploring new formats (e.g. on-line trainings, topic focused courses, etc.) to extend its use, while on the other hand, more projects on the ground are badly needed to implement different applications and to assist different stakeholders in making water management decisions. To optimize the returns on capacity development and on efforts on the ground to implement the use of AquaCrop, there is a need for closer coordination between the training activities and those devoted to model applications on the ground. A follow-up program of trainees will be highly desirable to capitalize efforts. This could be done by creating a community of users who are willing to exchange experiences and to participate in future training sessions.

There is a need to demonstrate the value of water-limited yield predictions to policy makers that must be operational under water supply constraints, aggravated in the event of a drought. AquaCrop is essential for determining water productivity gaps thus allowing the identification of factors that may contribute to enhancing the efficiency of water use.

This publication has benchmarked the results achieved in the use of the AquaCrop model and has described some of the advances made in the first ten years of the model life. If further efforts and commitments are devoted to AquaCrop, there is no doubt that this crop model will be even more valuable that it has been so far in facing the challenges that water limited agriculture will confront in the near future.

References

Acevedo, E., Fereres, E. 1993. Resistance to abiotic stress. In: *Plant Breeding: Principles and prospects.* Hayward, M.D., Bosemark, N. O., and Romagosa, I. (Eds.). Springer Netherlands, pp 406-421.

Akumaga, U., Tarhule, A., Yusuf, A.A. 2017. Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rainfed maize in Nigeria, West Africa. *Agricultural and Forest Meteorology*, 232:225-234.

Albrizio, R., Steduto, P. 2003. Photosynthesis, respiration and conservative carbon use efficiency of four field grown crops. *Agric. For. Meteorol.*, 116:19-36.

Albrizio, R., Steduto, P. 2005. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea: I. Radiation use efficiency. *Agric. For. Meteorol.*, 130:254-268.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. *Crop evapotranspiration: guidelines for computing crop water requirements.* Irrigation and Drainage Paper n. 56. FAO, Rome, Italy, 300 pp.

Alocilja, E.C., Ritchie, J.T. 1988. *Upland rice simulation and its use in multicriteria optimization*. Research Report Series No. 1, IBSNAT project, University of Hawaii, Honolulu.

Araus, J.L., Bort, J., Steduto, P., Villegas, D., Royo, C. 2003. Breeding cereals for Mediterranean conditions: ecophysiological clues for biotechnology application. *Ann. Appl. Biol.*, 142: 129-141.

Araya, A., Kisekka, I., Holman, J. 2016.Evaluating deficit irrigation management strategies for grain sorghum using AquaCrop. *Irrig. Sci.* 34:465–481.

Ardakanian, R. Walter, T. 2011. *Capacity Development for Farm Management Strategies to Improve Crop-Water Productivity using AquaCrop: Lessons Learned. Knowledge No. 7*. UNW-DPC Publication Series, UNW-DPC, Bonn.

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., Kimball, B. A., Ottman, M. J., Wall, G. W., White, J. W., Reynolds, M. P., Alderman, P. D., Prasad, P. V., Aggarwal, P. K., Anothai, J., Basso, B., Biernath, C., Challinor, A. J., de Sanctis, G., Doltra, J., Fereres, E., García-Vila, M., Gayler, S., Hoogenboom, D., Hunt, L. A., Izaurralde, R. C., Jabloun, M., Jones, C. D., Kersebaum, K. C., Koehler, A.-K., Müller, C., Naresh Kumar, S., Nendel, C., O"Leary, G., Olesen, J. E., Palosuo, T., Priesack, E., Eyshi Rezaei, E., Ruane, A. C., Semenov, M. A., Shcherbak, I., Steduto, P., Stöckle, C., Stratonovich, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wang, E., Wallach, D., Wolf, J., Zhao, Z., Zhu, Y. 2015. Rising temperatures reduce global wheat production. *Nature Climate Change,* 5(2):143-147.

Basso, B., Liu, L., Ritchie, J.T. 2016. A Comprehensive Review of the CERES-Wheat, -Maize and -Rice Models' Performances. *Advances in Agronomy*, 136: 27-132.

Bastiaanssen, W., Steduto P. 2017. The water productivity score (WPs) at global and regional level: methodology and first results from remote sensing measurements of wheat, rice and maize. *Science of the Total Environment,* 575: 595–611.

Boote, K.J., Jones, J.W., Hoogenboom, G. 1998. Simulation of crop growth: CROPGRO model. In: Peart RM, Curry RB (Eds.), *Agricultural Systems Modeling and Simulation.* Marcel Dekker Inc. New York, pp. 651-692.

Boote, K.J., Minguez, M.I., Sau, F. 2002. Adapting the CRPGRO-legume model to simulate growth of faba bean. *Agronomy J.*, 94:743-756.

Boote, K.J., Porter, C.H., Hargreaves, J., Hoogenboom, G., Thorburn, P., Mutter, C. 2015. AgMIP training in multiple crop models and tools. In: *HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments. Part 2.* C. Rosenzweig and D. Hillel (Eds.), World Scientific, pp. 393-410.

Bormann, H., Steinbrecher, J., Althoff, I., Roth, H., Baez, J., Frank, C., Gonzalez, M., Huenchuleo, C., Lugo, L., Mata, R., Portela, M.M., Reichert, J.M., Rodrigues, M.F., Sanchez, I. 2016. Recommendations for Capacity Development in Water Resources Engineering and Environmental Management in Latin America. *Water Resour. Manage.* 30:3409–3426.

Bos, M.G., Nugteren, J. 1974. On irrigation efficiencies. *ILRI Publication 19,* Wageningen.

Bouman, B.A.M., van Keulen, H., van Laar, H.H., Rabbinge, R. 1996. The "school of de Wit" crop growth simulation models: a pedigree and historical overview. *Agricultural Systems*, 52:171- 198.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Mraux, F., Seguin, B., Sinoquet, H. 2003. An overview of the crop model STICS. *Europ. J. Agronomy,* 18:309-332.

Camargo Rodriguez, A.V., Ober, E.S. 2019. AquaCropR: Crop Growth Model for R. *Agronomy*, 9, 378.

Chen, K. Z., Flaherty, K., Zhang, Y. 2012. *China: Recent developments in public agricultural research.* ASTI Country Note. International Food Policy Research Institute (IFPRI), Washington, D.C.

Condon, A.G., Richards, R.A., Rebetzke, G.J., Farquhar, G.D. 2004. Breeding for high water-use efficiency. *J. Exp. Bot.*, 55:2447-2460.

Cowan, I.R. 1977. Stomatal behavior and environment. *Adv. Bot. Res.*, 4:117-228.

Cowan, I.R. 1982. Regulation of water use in relation to carbon gain in higher plants. In: Lange OL, Nobel PS, Osmond CB, Zigler H (Eds.), *Physiological Plant Ecology II. Encyclopedia of Plant Physiology (NS),* vol. 12B, Springer-Verlag, Berlin, pp. 589-613.

de Roos, S., de Lannoy, G.J.M., Raes, D. 2021. A regional version of the AquaCrop model evaluated with satellite retrievals and backscatter data. *Proceedings of IEEE International Geoscience and Remote Sensing Symposium*, Brussels, July 11-16.

de Wit, C.T. 1958. *Transpiration and crop yields.* Versl. Landbouwk. Onderz. 64.6 Institute of Biological Chemistry Research On Field Crops and Herbage, Wageningen, The Netherlands.

de Wit, C.T. 1992. Resource use efficiency in agriculture. *Agric. Syst.*, 40:125-151.

Delgoda, D., Malano, H., Saleem, S.K., Halgamuge, M.N. 2016. Irrigation control based on model predictive control (MPC): Formulation of theory and validation using weather forecast data and AQUACROP model. *Environ. Model. Softw*., 78:40–53.

Doorenbos, J., Kasssam, A.H. 1979. *Yield response to Water.* FAO Irrigation and Drainage Paper No. 33. FAO, Rome.

Duvick, D.N. 2005. The contribution of breeding to yield advances in maize (Zea mays L.). *Adv. in Agron*., 86:83-145.

Eitzinger, J., Thaler, S., Schmid, E., Strauss, F., Ferrise, R., Moriondo, M., Bindi, M., Palosuo, T., Rötter, R., Kersebaum, K. C., Olesen, J. E., Patil, R. H., Şaylan, L., ÇaldaŞ B. 2013. Sensitivities of crop models to extreme weather conditions during flowering period demonstrated for maize and winter wheat in Austria. *The Journal of Agricultural Science*, 151(6):813-835.

FAO, 2012. *FAO approaches to capacity development in programming: processes and tools.* Learning module 2. FAO Capacity Development, FAO, Rome.

FAO, 2017. The future of food and agriculture – Trends and challenges. FAO, Rome.

FAO, 2019. *Our priorities – The Strategic Objectives of FAO.* FAO, Rome.

Farahani, H.J., Izzi, G., Oweis, T.Y. 2009. Parameterization and Evaluation of the AquaCrop Model for Full and Deficit Irrigated Cotton. *Agronomy Journal 101* (3): 469-476.

Fischer, R.A., Connor, D.J. 2018. Issues for cropping and agricultural science in the next 20 years. *Field Crops Res*., 222:121-142.

Foster, T., BrozoviŞ N., Butler, A.P., Neale, C.M.U., Raes, D., Steduto, P., Fereres, E., Hsiao, T.C. 2017. AquaCrop-OS: An open source version of FAO's crop water productivity model. *Agricultural Water Management,* 181:18-22.

Gaffney, J., Schussler, J., Löffler, C., Cai, W., Paszkiewicz, S., Messina, C., Groeteke, J., Keaschall, J., Cooper, M., 2015. Industry scale evaluation of maize hybrids selected for increased yield in drought stress conditions of the US corn belt. *Crop Sci*., 55:1608-1618.

Gallagher, J.N., Biscoe, P.V. 1978. Radiation absorption, growth and yield of cereals. *J. Agric. Sci*. Cambridge, 91:47-60.

GarcíaŞVila, M., Fereres, E., Mateos, L., Orgaz, F., Steduto, P. 2009. Deficit Irrigation Optimization of Cotton with AquaCrop. Agronomy Journal 101 (3): 477-487.

García-Vila, M., Fereres, E. 2012. Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. *European Journal of Agronomy,* 36:21-31.

Garcia-Vila, M., Morillo-Velarde, R., Fereres, E. 2019. Modeling Sugar Beet Responses to Irrigation with AquaCrop for Optimizing Water Allocation. *Water*, 11, 1918.

Geerts, S., Raes, D., Garcia, M., Miranda, R., Cusicanqui, J.A., Taboada, C., Mendoza, J., Huanca, R., Mamani, A., Condori, O., Mamani, J., Morales, B., Osco, V., Steduto, P. 2009. Simulating Yield Response of Quinoa to Water Availability with AquaCrop. *Agronomy Journal 101* (3): 499-508.

Geerts, S., Raes, D., Garcia, M. 2010. Using AquaCrop to derive deficit irrigation schedules. *Agricultural Water Management,* 98:213-216.

Gobin, A., Kersebaum, K.C., Eitzinger, J., Trnka, M., Hlavinka, P., TakáŞ J., Kroes, J., Ventrella, D., Marta, A.D., Deelstra, J., LaliŞ B., Nejedlik, P., Orlandini, S., Peltonen-Sainio, P., Rajala, A., Saue, T., Şaylan, L., StriŞevic, R., VuŞetiŞ V., Zoumides, C. 2017. Variability in the Water Footprint of Arable Crop Production across European Regions. *Water*, 9:93.

Goosheh, M., Pazira, E., Gholami, A., Andarzian, B., Panahpour, E. 2018. Improving Irrigation Scheduling of Wheat to Increase Water Productivity in Shallow Groundwater Conditions Using Aquacrop. *Irrig. and Drain*., 67:738– 754.

Gosse, G., Varlet-Grancher, C., Bonhomme, R., Chartier, M., Allirand, J.M., Lemaire, G. 1986. Maximum dry matter production and solar radiation intercepted by a canopy. *Agronomie*, 6:47-56.

Hanks, R.J. 1983. Yield and water-use relationships. In: Taylor HM, Jordan WR, Sinclair TR (Eds), *Limitations to Efficient Water Use in Crop Production*. ASA, CSSA, SSSA, Madison, Wisconsin, USA, pp. 393-411.

Hassanli, M., Ebrahimian, H., Mohammadi, E., Rahimi, A., Shokouhi, A. 2016. Simulating maize yields when irrigating with saline water using the AquaCrop, SALTMED, and SWAP models. *Agric. Water Manage*., 176:91-99.

Heng, L.K., Hsiao, T.C., Evett, S., Howell, T., Steduto, P. 2009. Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize. *Agronomy Journal 101* (3): 488-498.

Hsiao, T.C. 1993. Effect of drought and elevated CO2 on plant water use efficiency and productivity. In: Jackson MB and Black CR (Eds.), *Global Environment Change. Interacting Stresses on Plants in a Changing Climate*. NATO ASI Series I, Springer Verlag, Berlin, pp. 435-465.

Hsiao, T.C., Bradford, J.K. 1983. Physiological consequences of cellular water deficits. In: Taylor HM, Jordan WR, Sinclair TR (Eds.), *Limitations to Efficient Water Use in Crop Production*. ASA, CSSA, SSSA, Madison, Wisconsin, USA, pp. 227-265.

Hsiao, T.C., Steduto, P., Fereres, E. 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. *Irrigation Scienc*e, 25:209-231.

Hsiao, T.C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agronomy Journal,* 101:448-459.

Hsiao, T.C., Fereres, E., Steduto, P., Raes, D. 2012. AquaCrop parameterization, calibration, and validation guide. In *Crop Yield Response to Water*; Steduto, P., Fereres, E., Raes, D., (Eds.). FAO, Rome, Italy. pp. 70–87.

Huang, X., Yu, C., Fang, J., Huang, G., Ni, S., Hall, J., Zorn, C., Huang, X., Zhang, W. 2018. A dynamic agricultural prediction system for large-scale drought assessment on the Sunway TaihuLight supercomputer. *Computers and Electronics in Agriculture*, 154:400-410.

Israelsen, O.W. 1950. *Irrigation principles and practices.* John Wiley, New York.

Jin, X., Yang, G., Li, Z., Xu, X., Wang, J., Lan, Y. 2018. Estimation of water productivity in winter wheat using the AquaCrop model with field hyperspectral data. *Precision Agric.*, 19:1–17

Jones, C.A., Kiniry, J.R. 1986. *CERES-Maize: A Simulation Model of Maize Growth and Development.* Texas A&M Univ. Press, College Station, Texas.

Jones, C.A., Dyke, P.T., Williams, J.R., Kiniry, J.R., Benson, C.A., Griggs, R.H. 1991. EPIC: an operational model for evaluation of agricultural sustainability. *Agricultural Systems,* 37:341-350.

Jones, J., Antle, J.M., Basso, B., Boote, K., Conant, R., Foster, I., Godfray, H., Herrero, M., Howitt, R., Janssen, S., Keating, B., Munoz-Carpena, R., Porter, C., Rosenzweig, C., Wheeler, T. 2016. Brief history of agricultural systems modeling. *Agric. Syst.,* 155:240-254.

Jones, J.W. 1993. Decision support systems for agricultural development. In: Penning de Vries F., Teng P., Metselaar K. (eds) *Systems approaches for agricultural development. Systems Approaches for Sustainable Agricultural Development, vol 2.* Springer, Dordrecht. pp 459-471.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T. 2003. The DSSAT cropping system model. *Europ. J. Agronomy,* 18:235-265.

Karandish, F., Hoekstra, A.Y. 2017. Informing National Food and Water Security Policy through Water Footprint Assessment: the Case of Iran. *Water*, 9, 831.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agronomy*, 18:267-288.

Kiesselbach, T.A. 1916. *Transpiration as a factor in crop production.* Bulletin of the Agricultural Experiment Station of Nebraska No. 6.

Kijne, J.W., Barker, R., Molden, D. 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement. *Comprehensive Assessment of Water Management in Agriculture Series, No. 1*. Wallingford, UK: CABI; Colombo, Sri Lanka: International Water Management Institute (IWMI).

Kim, D., Kaluarachchi, J.J. 2015. Validating FAO AquaCrop using Landsat images and regional crop information. *Agricultural Water Management,* 149: 143-155

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cableguenne, M., Spanel, D.A. 1989. Radiation-use efficiency in biomass accumulation prior grain-filling for five grain-crops species. *Field Crops Res*., 20: 51-64.

Kumar, P., Sarangi, A., Singh, D.K. and Parihar, S.S. 2014. Evaluation of AquaCrop model in predicting wheat yield and water productivity under irrigated saline regimes. *Irrig. and Drain*., 63:474– 487.

Li, J., Song, J., Li, M., Shang, S., Mao, X., Yang, J., Adeloye, A.J. 2018. Optimization of irrigation scheduling for spring wheat based on simulation-optimization model under uncertainty. *Agric. Water Manag*., 208:245-260.

Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, D.B., Martre, P., Ruane, A.C., Wallach, D., Jones, J.W., Rosenzweig, C., Aggarwal, P.K., Alderman, P.D., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A., Deryng, D., De Sanctis, G., Doltra, J., Fereres, E., Folberth, C., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Kimball, B.A., Koehler, A.-K., Kumar, S.N., Nendel, C., O'Leary, G.J., Olesen, Jø.E., Ottman, M.J., Palosuo, T., Prasad, P.V.V., Priesack, E., Pugh, T.A.M., Reynolds, M., Rezaei, E.E., Rötter, R.P., Schmid, E., Semenov, M.A., Shcherbak, I., Stehfest, E., Stöckle, C.O., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wall, G.W., Wang, E., White, J.W., Wolf, J., Zhao, Z., Zhu, Y. 2016. Similar estimates of temperature impacts on global wheat yield by three independent methods. *Nature Climate Change*, 6:1130-1136.

Loomis, R.S., Rabbinge, R., Ng, E. 1979. Explanatory models in crop physiology. *Ann. Rev. Plant Physiol.*, 30:339-367.

Lorite, I.J., García-Vila, M., Santos, C., Ruiz-Ramos, M., Fereres, E. 2013. AquaData and AquaGIS: Two computer utilities for temporal and spatial simulations of water-limited yield with AquaCrop. *Computers and Electronics in Agriculture*, 96:227-237.

Martins, M.A., Tomasella, J., Rodriguez, D.A., Alvalá, R.C.S., Giarolla, A., Garofolo, L.L., Lázaro Siqueira Júnior, J., Paolicchi, L.T.L.C., Pinto, G.L.N. 2018. Improving drought management in the Brazilian semiarid through crop forecasting. *Agricultural Systems,* 160:21-30.

Mbabu, A.N., Hall, A. 2012. *Capacity Building for Agricultural Research for Development: Lessons from Practice in Papua New Guinea.* United Nations University-Maastricht Economic and Social Research Institute on Innovation and Technology (UNU-MERIT), Maastricht, The Netherlands.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D., Huth, N.I. 1995. APSIM: an agricultural production system simulation model for operational research.*Math. Comput. Simul.*, 39 (3–4):225-231.

McCown, R.L., Keating, B., Carberry, P.S., Hochman, Z., Hargreaves, D. 2002. The Co-Evolution of the Agricultural Production Systems Simulator (APSIM) and Its Use in Australian dryland Cropping Research and Farm Management Intervention. *Agricultural System Models in Field Research and Technology Transfer.* Boca Raton, FL United States: CRC Press.1-27

Mohammadi, M., Ghahraman, B., Davary, K., Ansari, H., Shahidi, A., Bannayan, M. 2016 Nested Validation of Aquacrop Model for Simulation of Winter Wheat Grain Yield, Soil Moisture and Salinity Profiles under Simultaneous Salinity and Water Stresss. *Irrig. and Drain.,* 65:112– 128.

Mondal, M.S., Saleh, A.F.M., Razzaque Akanda, M.A., Biswas, S.K., Moslehuddin, A. Z. Md., Zaman, S., Lázár, A.N., Clarke, D. 2015. Simulating yield response of rice to salinity stress with the AquaCrop model.*Environ. Sci. Process. Impacts*, 17(6):1118-1126.

Monteith, J.L. 1972. Solar radiation and productivity in tropical ecosystems. *J. Appl. Ecology,* 9:747-766.

Monteith, J.L. 1977. Climate and the efficiency of crop production in Britain. *Philos. Trans. R. Soc.* London, 281:277-294.

Monteith, J.L. 1990. Conservative behaviour in the responses of crops to water and light. In: *Simulation Monographs 34*. Pudoc, Wageningen, The Netherlands, pp. 3-15.

Moursi, H., Kim, D., Kaluarachchi, J.J. 2017. A probabilistic assessment of agricultural water scarcity in a semi-arid and snowmelt-dominated river basin under climate change. *Agricultural Water Management*, 193:142-152.

Nyakudya, I.W., Stroosnijder, L. 2014.Effect of rooting depth, plant density and planting date on maize (Zea mays L.) yield and water use efficiency in semi-arid Zimbabwe: *Modelling with AquaCrop. Agricultural Water Management,* 146: 280-296.

Oquist, P. 1978. The epistemology of action research. *Acta Sociol.*, 21:43-163.

Paola, A.D., Valentini, R., Santini M. 2016. An overview of available crop growth and yield models for studies and assessments in agriculture. *Journal of the Science of Food and Agriculture*, 96:709–714

Passioura, J.B. 2020. Translational research in agriculture. Can we do it better? *Crop & Pasture Science*, 71:517–528.

Perry, C., Steduto, P. 2017. *Does improved irrigation technology save water? A review of the evidence.* FAO, Cairo.

Qin, W., Heinen, M., Assinck, F.B.T., Oenema, O. 2016. Exploring optimal fertigation strategies for orange production, using soil-crop modelling. *Agriculture, Ecosystems and Environment,* 223:31-40.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal*, 101:438-447.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E. 2017. *AquaCrop on-line reference manual*. http://www.fao.org/nr/water/aquacrop.html

Raes, D., Steduto, P., Hsiao, C. T., Fereres, E. 2018. *Reference Manual, Annexes* – AquaCrop, Version 6.0 – 6.1. FAO, Rome.

Rallo, G., Agnese, C., Minacapilli, M., Provenzano, G. 2012b. Assessing Aquacrop water stress function to evaluate the transpiration reductions of olive mature tree. *Italian Journal of Agrometeorology*, 17(1): 21– 28.

Razzaghi, F., Zhou, Z., Andersen, M.N., Plauborg, F. 2017. Simulation of potato yield in temperate condition by the AquaCrop model. *Agricultural Water Management,* 191:113-123.

Reynolds, M., Kropff, M., Crossa, J., Koo, J., Kruseman, G., Molero Milan, A., Rutkoski, J., Schulthess, U., Balwinder-Singh, Sonder, K., Tonnang, H., Vadez, V. 2018. Role of Modelling in International Crop Research: Overview and Some Case Studies. *Agronomy*, 8:291.

Ritchie, J.T., Godwin, D.C., Otter-Nacke, S. 1985. *CERES-Wheat: A Simulation Model of Wheat Growth and Development.* Texas A&M Univ. Press, College Station, Texas.

Ritchie, J.T., Otter-Nacke, S. 1985. Description and performance of CERES-Wheat: use-oriented wheat yield model ARS Wheat Yield Project, ARS-38 *Natl. Tech. Inf. Serv.,* Springfield, VA, pp. 159-175.

Robertson, M., Carberry, P. 2010. The evolving role of crop modelling in agronomy research. *"Food Security from Sustainable Agriculture", Proceedings of the 15th Australian Agronomy Conference, 15 - 18 November 2010, Lincoln, New Zealand.* pp.7001 ref.5

Roseboom, J., Flaherty, K. 2016. The evolution of agricultural research in Africa: Key trends and institutional developments. In: *Agricultural research in Africa: Investing in future harvests.* Lynam, John; Beintema, Nienke M.; Roseboom, Johannes; and Badiane, Ousmane (Eds.). Chapter 2. Washington, D.C.: International Food Policy Research Institute (IFPRI). Pp. 31-58.

Salemi, H., Soom, M., Lee, T.S., Mousavi, S., Ganji, A., Yusoff, M. 2011. Application of AquaCrop model in deficit irrigation management of Winter wheat in arid region. *African Journal of Agricultural Research*, 6:2204-2215.

Sall, M.T., Diop, P., Wellens, J., Seck, M., Chopart, J.L. 2021. A framework for IWRM in the Water-Energy-Food Nexus for the Senegal River Delta. In: *Climate Change and Water Resources in Africa*, Diop, S., Scheren, P., Niang, A. (Eds.). Springer.

Salman, M., Pek, E., Fereres, E., García-Vila, M. 2020. **Field guide to improve crop water productivity in small-scale agriculture. The case of Burkina Faso, Morocco and Uganda.** FAO, Rome.

Seligman, N.G. 1990. The crop model record: promise or poor show? In: Rabbinge, R., Goudriaan, J., van Keulen, H., Penning de Vries, F.W.T. and van Laar, H.H. (Eds). *Theoretical Production Ecology: Reflection and Prospects.* Simulation Monographs, Pudoc, Wageningen, pp. 249–263.

Shrestha, N., Raes, D., Vanuytrecht, E., Kumar Sah, S. 2013. Cereal yield stabilization in Terai (Nepal) by water and soil fertility management modelling. *Agricultural Water Management*, 122:53-62.

Silvestro, P.C., Pignatti, S., Yang, H., Yang, G., Pascucci, S., Castaldi, F., Casa, R. 2017. Sensitivity analysis of the Aquacrop and SAFYE crop models for the assessment of water limited winter wheat yield in regional scale applications. *PLoS ONE 12(11)*: e0187485.

Sinclair, T.R., Muchow, R.C. 1999. Radiation Use Efficiency. *Advances in Agronomy*, 65:215-265.

Steduto, P. 1996. Water Use Efficiency. In: Pereira L.S., Feddes R.A., Gilley J.R., Lessafre B. (Eds.). *Sustainability of Irrigated Agriculture,* Kluwer Academic Publishers, The Netherlands, pp. 193-209.

Steduto, P. 1997. Modeling for crop response to water: physiological aspects. In: Dupuy B. (Ed.). *Economic aspects of water management in the Mediterranean Area, Options Méditerranéennes, Serie A: Séminaires.* CIHEAM, pp. 289-312.

Steduto, P., Albrizio, R., Giorio, P., Sorrentino, G. 2000. Gas-exchange response and stomatal and non-stomatal limitations to carbon assimilation of sunflower under salinity. *Envir. Exper. Botany*, 44:243-255.

Steduto, P., Albrizio R. 2005. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea: II. Water use efficiency and comparison with radiation use efficiency. *Agric. For. Meteorol.*, 130:269-281.

Steduto, P., Hsiao, T.C., Fereres, E. 2007. On the conservative behaviour of biomass water productivity. *Irrigation Science*, 25:189-207.

Steduto, P., Hsiao, T.C., Raes, D., Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal,* 101:426-437.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D. 2012. *Crop yield response to water.* FAO Irrigation and Drainage Paper, No. 66. FAO, Rome, Italy.

Stöckle C.O., Kemanian A.R. 2020. Can Crop Models Identify Critical Gaps in Genetics, Environment, and Management Interactions? *Frontiers in Plant Science,* 11: 737.

Stöckle, C.O., Donatelli, M., Nelson, R. 2003. CropSyst, a cropping systems simulation model. *Europ. J. Agronomy,* 18:289-307.

Stricevic, R., Simic, A., Kusvuran, A., Cosic, M. 2017. Assessment of AquaCrop model in the simulation of seed yield and biomass of Italian ryegrass. *Archives of Agronomy and Soil Science*, 63(9):1301-1313.

Tanner, C.B., Sinclair, T.R. 1983. Efficient water use in crop production: research or re-search? In: Taylor H.M., Jordan W.R., Sinclair T.R. (Eds.), *Limitations to Efficient Water Use in Crop Production.* ASA, CSSA, SSSA, Madison, Wisconsin, USA, pp. 1-27.

Timsina, J., Humphreys, E. 2006. Applications of CERES-Rice and CERES-Wheat in Research, Policy and Climate Change Studies in Asia: A Review. *International Journal of Agricultural Research*, 1: 202-225.

Todorovic, M., Albrizio, R., Zivotic, L., Abi Saab, M.T., Stöckle, C., Steduto, P. 2009. Assessment of AquaCrop, CropSyst, and WOFOST Models in the Simulation of Sunflower Growth under Different Water Regimes. *Agronomy Journal 101* (3): 509-521.

Toumi, J., Er-Raki, S., Ezzahar, J., Khabba, S., Jarlan, L., Chehbouni, A. 2016. Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): Application to irrigation management. *Agricultural Water Management,* 163:219-235.

Travasso, M.J., Magrin, G.O. 1998. Utility of CERES-Barley under Argentine conditions. *Field Crops Res.*, 57:329-333.

Tsakmakis, I., Kokkos, N., Pisinaras, V., Papaevangelou, V., Hatzigiannakis, E., Arampatzis, G., Gikas, G.D., Linker, R., Zoras, S., Evagelopoulos, V., Tsihrintzis, V.A., Battilani, A., Sylaios, G. 2017. Operational Precise Irrigation for Cotton Cultivation through the Coupling of Meteorological and Crop Growth Models. *Water Resour. Manage*., 31:563–580.

Tsegay, A., Vanuytrecht, E., Abrha, B., Deckers, J., Gebrehiwot, K., Raes, D. 2015. Sowing and irrigation strategies for improving rainfed tef (Eragrostis tef (Zucc.) Trotter) production in the water scarce Tigray region, Ethiopia. *Agricultural Water Management*, 150:81-91.

Turner, N.C., Blum, A., Cakir, M., Steduto, Tuberosa, R., Young, N. 2014. Strategies to increase the yield and yield stability of crops under drought – are we making progress? *Functional Plant Biology,* 41:1199–1206.

Van Gaelen, H., Tsegay, A., Delbecque, N., Shrestha, N., Garcia, M., Fajardo, H., Miranda, R., Vanuytrecht, E., Abrha, B., Diels, J., Raes, D. 2015. A semi-quantitative approach for modelling crop response to soil fertility: evaluation of the AquaCrop procedure. *J. Agric. Sci.* 153, 1218–1233.

Van Gaelen, H., Delbecque, N., Abrha, B., Tsegay, A., Raes, D. 2016. Simulation of crop water productivity in weed-infested fields for data-scarce regions. *Journal of Agricultural Science,* 154 (6):1026–1039.

van Ittersum, M.K., Lefflaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudrian, J. 2003. *Europ. J. Agronomy,* 18:201-234.

Vanuytrecht, E., Raes, D., Willems, P. 2014a. Global sensitivity analysis of yield output from the water productivity model. *Environmental Modelling & Software,* 51:323-332.

Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., Heng, L.K., Garcia-Vila, M., Mejias Moreno, P. 2014b. AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling & Software,* 62:351-360.

Vergni, L., Todisco, F., Mannocchi, F. 2015. Analysis of agricultural drought characteristics through a two-dimensional copula. *Water Resour. Manage.* 29:2819–2835.

Villalobos, F. J., Fereres, E. 1990. Evaporation measurements beneath corn, cotton, and sunflower canopies. *Agron. J*., 82:1153-1159.

Vilvert, E., Lana, M., Zander, P., Sieber, S. 2018. Multi-model approach for assessing the sunflower food value chain in Tanzania. *Agricultural Systems,* 159:103-110.

Voloudakis, D. Karamanos, A., Economou,G., Kalivas, D., Vahamidis, P., Kotoulas, V., Kapsomenakis, J., Zerefos, C. 2015. Prediction of climate change impacts on cotton yields in Greece under eight climatic models using the AquaCrop crop simulation model and discriminant function analysis. *Agricultural Water Management,* 147:116-128.

Wang, E., Robertson, M.J., Hammer, G.L., Carberry, P.S., Holzworth, D., Meinke, H., Chapman, S.C., Hargreaves, J.N.G., Huth, N.I., McLean, G. 2002. Development of a generic crop template in the cropping system model APSIM. *Europ. J. Agronomy,* 18:121-140.

Wellens, J., Raes, D., Traore, F., Denis, A., Djaby, B., Tychon, B. 2013. Performance assessment of the FAO AquaCrop model for irrigated cabbage on farmer plots in a semi-arid environment. *Agricultural Water Management,* 127:40-47.

Wellens, J., Raes, D., Tychon, B. 2017. On the use of decision-support tools for improved irrigation management: AquaCrop-Based applications. *Current Perspective on Irrigation and Drainage,* Suren Kulshreshtha and Amin Elshorbagy, IntechOpen.

Wellens, J., Sall, M.T., Ville, A. 2020. Processing chain for parcel and regional crop monitoring (PROCCY): Open Data, Sentinel-2, AquaCrop and sugar cane. *iCROPM 2020 Symposium: Crop Modelling for the Future. 3-5 February 2020, Montpellier, France. Book of abstracts*, 165-166.

Williams, J.R., Renard, K.G., Dyke, P.T. 1983. EPIC – a new method for assessing erosions effect on soil productivity *J. Soil Water Conserv.*, 38 (5): 381-383.

Wolday, K., Hruy, G. 2015. A Review on: Performance Evaluation of Crop Simulation Model (APSIM) in Prediction Crop Growth, Development and Yield in Semi Arid Tropics. *Journal of Natural Sciences Research*, 5:34-39.

Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., Wada, Y. 2016. Inter- and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River basin (1961–2009). *Advances in Water Resources*, 87:29-41.

Zinyengere, N., Mhizha, T., Mashonjowa, E., Chipindu, B., Geerts, S., Raes, D. 2011. Using seasonal climate forecasts to improve maize production decision support in Zimbabwe. *Agricultural and Forest Meteorology,* 151:1792-1799.

FAO TECHNICAL PAPERS

FAO WATER REPORTS

1 Prevention of water pollution by agriculture and related activities, 1993 (E/S)
2 Irrigation water delivery models, 1994 (E)
3 Water harvesting for improved agricultural production, 1994 (E)
4 Use of remote sensing techniques in irrigation and drainage, 1995 (E)
5 Irrigation management transfer, 1995 (E)
6 Methodology for water policy review and reform, 1995 (E)
7 Irrigation in Africa in figures/L'irrigation en Afrique en chiffres, 1995 (E/F)
8 Irrigation scheduling: from theory to practice,1996 (E)
9 Irrigation in the Near East Region in figures, 1997 (E)
10 Quality control of wastewater for irrigated crop production, 1997 (E)
11 Seawater intrusion in coastal aquifers – Guide lines for study, monitoring and control, 1997 (E)
12 Modernization of irrigation schemes: past experiences and future options, 1997 (E)
13 Management of agricultural drainage water quality, 1997 (E)
14 Irrigation technology transfer in support of food security, 1997 (E)
15 Irrigation in the countries of the former Soviet Union in figures, 1997 (E) (also published as RAP Publication 1997/22)
16 Télédétection et ressources en eau/Remote sensing and water resources, 1997 (F/E)
17 Institutional and technical options in the development and management of small-scale irrigation, 1998 (E)
18 Irrigation in Asia in figures, 1999 (E)
19 Modern water control and management practices in irrigation – Impact on performance, 1999 (E)
20 El riego en América Latina y el Caribe en cifras/Irrigation in Latin America and the Caribbean in figures, 2000 (S/E)
21 Water quality management and control of water pollution, 2000 (E)
22 Deficit irrigation practices, 2002 (E)
23 Review of world water resources by country, 2003 (E)
24 Rethinking the approach to groundwater and food security, 2003 (E)
25 Groundwater management: the search for practical approaches, 2003 (E)
26 Capacity development in irrigation and drainage. Issues, challenges and the way ahead, 2004 (E)
27 Economic valuation of water resources: from the sectoral to a functional perspective of natural resources management, 2004 (E)
28 Water charging in irrigated agriculture – An analysis of international experience, 2004 (E) efforts and results, 2007 (E)
29 Irrigation in Africa in figures – AQUASTAT survey – 2005, 2005 (E/F)
30 Stakeholder-oriented valuation to support water resources management processes – Confronting concepts with local practice, 2006 (E)
31 Demand for products of irrigated agriculture in sub-Saharan Africa, 2006 (E)
32 Irrigation management transfer – Worldwide, 2008 (E/S)
33 Scoping agriculture–wetland interactions – Towards a sustainable multiple-response strategy, 2008 (E)
34 Irrigation in the Middle East region in figures – AQUASTAT Survey – 2008, 2009 (Ar/E)
35 The Wealth of Waste: The economics of wastewater use in agriculture, 2010 (E)
36 Climate change, water and food security (E)
37 Irrigation in Southern and Eastern Asia in figures – AQUASTAT Survey – 2011 (E)
38 Coping with water scarcity - An action framework for agriculture and food security (E/F)
39 Irrigation in Central Asia in figures (E)
40 Guidelines to control water pollution from agriculture in China Decoupling water pollution from agricultural production (E)
41 Yield gap analysis of field crops: Methods and case studies (E)
42 Drought characteristics and management in the Caribbean (E)
43 Water accounting and auditing: A sourcebook (E, F)
44 Drought characteristics and management in Central Asia and Turkey (E)
45 Drought characteristics and management in North Africa and the Near East (E)
46 Guidance on realizing real water savings with crop water productivity interventions (E)
47 The AquaCrop model: enhancing crop water productivity. Ten years of development, dissemination and implementation 2009-2019 (E)

Availability: February 2021

Ar	–	Arabic	Multil – Multilingual	
C	–	Chinese	*	Out of print
E	–	English	**	In preparation
F	–	French		
P	–	Portuguese		
S	–	Spanish		

The FAO Technical Papers are available through the authorized FAO Sales Agents or directly from Sales and Marketing Group, FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy.

47
FAO WATER REPORTS

The AquaCrop model: enhancing crop water productivity

Ten years of development, dissemination and implementation 2009-2019

Water resources are linked to the global challenges of food insecurity and poverty, as well as to climate change adaptation and mitigation. In line with the Sustainable Development Goals (SDGs), FAO works towards several dimensions of sustainable development, including the promotion of coherent approaches to efficient, productive and sustainable water management, from farm to river basin scales. Accordingly, FAO is enhancing well-informed on-the-ground decision-making processes on water management through projects, knowledge advancement, information-sharing and tools development, such as AquaCrop, the FAO crop-water productivity model. This model assists in assessing the effects of environment (including atmospheric CO_2 concentration) and management on crop production through the simulation of yield response to water of herbaceous crops. It is particularly suited to address conditions where water is a key limiting factor in crop production.

In 2009, FAO officially launched AquaCrop, being the result of several years of collaborative work among scientists, water and crop specialists and practitioners worldwide, bringing together previously fragmented information on crop yields in response to water use and water deficit. AquaCrop has evolved over the different versions released since its first launch, but it always balances accuracy, simplicity and robustness. This has enabled it to remain faithful to its goal, i.e., to be a dynamic tool accessible to several types of users, mainly practitioner-type end users, in different disciplines and for a wide range of applications. In addition, AquaCrop may be considered a valuable tool by research scientists for analysis and conceptualization.

After ten years of development, improvement, training and application of AquaCrop, a review and analysis of its performance and impact worldwide, including trends and challenges, have become relevant for FAO. Aware that several gaps and emerging issues remain, this assessment exercise is a first essential step towards the delineation of the future roadmap for the improvement, dissemination and proper application of AquaCrop. With that aim in mind, this report presents objective and comprehensive information and analyses on the current state, trends and impacts that the model has had on users, from a range of practitioners to the research community.

ISBN 978-92-5-135222-9 ISSN 1020-1203
9 789251 352229
CB7392EN/1/11.21