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# AquaCrop on the ground

## Model applications for sustainable agricultural water management

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By

**Maher Salman**
Food and Agriculture Organization of the United Nations, Rome

**Margarita García Vila**
Institute for Sustainable Agriculture, Cordoba, Spain

**Elias Fereres**
University of Cordoba, Spain

**Dirk Raes**
KU Leuven, Belgium

**Pasquale Steduto**
Formerly Food and Agriculture Organization of the United Nations, Rome

**Lee Heng**
Formerly Joint FAO/International Atomic Energy Agency, IAEA Centre, Vienna

**Gabrielle De Lannoy**
KU Leuven, Belgium

**Joost Wellens**
University of Liege, Belgium

**Timothy Foster**
University of Manchester, United Kingdom of Great Britain and Northern Ireland

**Louise Busschaert**
KU Leuven, Belgium

**Michel Bechtold**
KU Leuven, Belgium

**Shannon de Roos**
KU Leuven, Belgium

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# Contents

# FIGURES

# TABLES

# Foreword

In food production, the pursuit of efficient and sustainable water management is a paramount challenge. As the global population burgeons and climate change exacerbates water scarcity and variability, the imperative to optimize water use in agriculture has never been more pressing. To address this challenge effectively, crop models can play a crucial role by providing predictive analysis, optimizing irrigation scheduling, allocating resources efficiently, adapting to climate change, and ultimately, supporting decision-making processes. By leveraging these tools, policymakers, technicians and farmers can enhance water use efficiency, conserve natural resources, and sustainably intensify agricultural production to meet the growing demands for food security in a changing world.

In this context, the Food and Agriculture Organization of the United Nations (FAO) has made a determined commitment to the development of AquaCrop, a water productivity model tailored for managing water under limiting conditions. Since its launch in 2009, AquaCrop has evolved into a robust tool designed to assist researchers, agricultural practitioners and policymakers. Its widespread acclaim among these stakeholders underscores its effectiveness and usefulness in addressing water management challenges.

This report provides strong evidence of the transformative potential of the AquaCrop model in real-world settings, aligning with FAO's interest in ensuring that this tool transcends the realm of research. Through a collection of practical applications and case studies, readers will gain invaluable insights into the model's versatility and efficacy across diverse agroecological contexts. From arid regions grappling with water scarcity to humid climates facing excess moisture, AquaCrop emerges as a versatile ally in the quest for sustainable water management. Moreover, the report underscores the collaborative efforts of FAO, national agricultural agencies, research institutions and farming communities worldwide.

The authors, contributors and partners involved in the development and dissemination of AquaCrop have enriched this document with helpful insights and practical wisdom. By sharing experiences, best practices and lessons learned, the report fosters a collective understanding of AquaCrop's potential and refines its application for the benefit of farmers and ecosystems. This report has been conceived as a source of inspiration for promoting further collaboration, innovation and action towards sustainable water management in agriculture that contributes to food security, livelihoods and environmental sustainability worldwide.

Lifeng Li
Director, Land and Water Division
FAO, Rome

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The authors of this publication are Maher Salman (FAO NSL, Rome), Margarita García Vila (Institute for Sustainable Agriculture, Cordoba, Spain), Elias Fereres (University of Cordoba, Spain), Dirk Raes (KU Leuven, Belgium), Pasquale Steduto (former chief of Water Service, FAO), Lee Heng (former Joint FAO/International Atomic Energy Agency - IAEA Centre, Austria), Gabrielle De Lannoy (KU Leuven, Belgium), Joost Wellens (University of Liege, Belgium), Timothy Foster (University of Manchester, United Kingdom of Great Britain and Northern Ireland), Louise Busschaert (KU Leuven, Belgium), Michel Bechtold (KU Leuven, Belgium), and Shannon de Roos (KU Leuven, Belgium).

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This publication is dedicated to Professor Theodore "Ted" C. Hsiao, one of the four members that originally developed AquaCrop, who passed away on 16 October 2023. His contributions to model development and his commitment to its improvement and dissemination were truly exceptional and will always be remembered.

# Abbreviations

| | |
|---|---|
| **AIW** | applied irrigation water |
| **AWM** | agricultural water management |
| **B** | aboveground biomass |
| **CC** | green canopy cover |
| **CCact** | green canopy cover development under limited conditions |
| **CCpot** | green canopy cover development under non-limiting conditions |
| **CMIP** | coupled model intercomparison project |
| **DI** | deficit irrigation |
| **Dr** | root zone depletion |
| **dS** | deciSiemens |
| **E** | evaporation |
| **ECe** | electrical conductivity of the saturated soil-paste extract |
| **ECMWF** | European Centre for Medium-Range Weather Forecasts |
| **ECsw** | electrical conductivity of the soil water |
| **$ET_o$** | reference evapotranspiration |
| **ETc** | crop evapotranspiration |
| **FC** | field capacity |
| **FACE** | free air $CO_2$ enrichment experiments |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **GAPs** | good agricultural practices |
| **GCM** | global climate model |
| **GDD** | growing degree days |
| **GUI** | graphical user interface |
| **HI** | harvest index |
| **HPA** | high plains aquifer |
| **HWSD** | harmonized world soil database |
| **ICRISAT** | International Crops Research Institute for the Semi-Arid Tropics |
| **$I_{net}$** | net irrigation water requirement |
| **ISIMIP** | The Inter-Sectoral Impact Model Intercomparison Project |
| **ISRIC** | International Soil Reference and Information Centre |
| **KcTr** | crop transpiration coefficient |
| **Ksat** | hydraulic conductivity of the soil at saturation |

| | |
|---|---|
| **LIS** | land information system |
| **LF** | leaching fraction |
| **NENA** | Near East and North Africa |
| **NGOs** | non-governmental organizations |
| **Pc** | crop price received by the farmer |
| **POWER** | Prediction of Worldwide Energy Resources |
| **PTFs** | pedotransfer functions |
| **PWP** | permanent wilting point |
| **RAW** | readily available water |
| **RCM** | regional climate model |
| **RCP** | representative concentration pathway |
| **$RI_{net}$** | range in net irrigation requirements |
| **SA** | AquaCrop's stand-alone version |
| **SaltOut** | salts drained out of the soil profile |
| **SaltTot** | fluctuation of the amount of salts stored in the soil profile |
| **SSP** | shared socioeconomic pathways |
| **TAW** | total available soil water |
| **TGM** | total gross margin |
| **Tn** | minimum air temperature |
| **Tr** | crop transpiration |
| **Tx** | maximum air temperature |
| **URNRD** | Upper Republican Natural Resources District |
| **WP** | water productivity |
| **WP*** | normalized biomass water productivity |
| **$WP_{B/Tr}$** | conservative relation between biomass production and crop transpiration |
| **$WP_{ET}$** | water productivity of evapotranspiration |
| **$WP_{IRR}$** | water productivity of irrigation |
| **$WP_{Y/ET}$** | yield water productivity, defined as the ratio of crop yield to evapotranspiration |
| **Ya** | actual yield |
| **Yp** | potential yield |
| **Ywl** | crop yield limited by water |
| **Ywfl** | crop yield limited by water and fertility |


# 1. Introduction

## 1.1. AQUACROP RELEVANCE IN AGRICULTURAL WATER MANAGEMENT: FROM RESEARCH TO THE GROUND

As global water scarcity becomes an increasingly pressing issue, the efficient use of water in agriculture is vital for food security, economic stability and environmental sustainability. Efficient agricultural water management (AWM) can optimize food production, ensuring that water is allocated efficiently and allowing farmers to produce higher yields per drop. Proper AWM also helps to mitigate the risks associated with drought, floods and other water-related uncertainties, enhancing farmers' resilience to climate variability and ensuring consistent food production. By integrating climate-smart practices into AWM strategies, adaptive capacities can be enhanced and the adverse effects of climate variability on agriculture mitigated. This promotes economic stability and attracts investment, boosting rural economies.

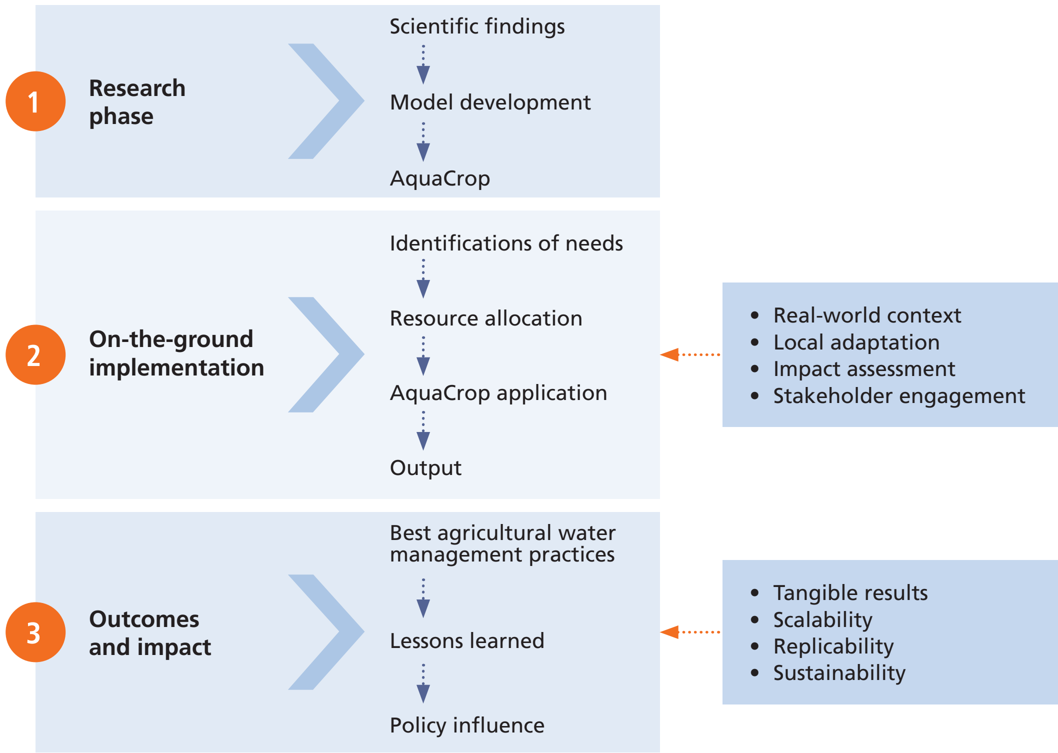
It is crucial to recognize that AWM plays a pivotal role in balancing the interconnected challenges of water, energy and food security, often referred to as the Water–Energy–Food Nexus. By optimizing water allocation, reducing energy consumption and enhancing agricultural productivity, AWM contributes to a more sustainable and integrated approach to managing water, energy and food systems. It is imperative to prioritize environmental sustainability as an integral facet of this strategy. Conserving water resources, preserving aquatic ecosystems and maintaining water quality should be ensured through proper AWM. The relevance of AWM extends beyond the boundaries of individual farms – it influences global food security, economic stability and environmental sustainability.

In light of this, FAO serves a crucial role in promoting sustainable AWM worldwide. FAO has spearheaded numerous initiatives, projects and partnerships to optimize water use in agriculture. It employs a multifaceted approach encompassing policy advocacy, capacity building, training and innovative research endeavours. FAO's crop–water productivity model, the AquaCrop model, can be considered a pioneer in innovative research (Steduto *et al.,* 2012). The model was designed to assess the impact of water management practices on crop yield and water productivity. Unlike traditional crop models that require extensive data input and complex computations, AquaCrop uses a simplified approach that balances accuracy with user-friendliness. By considering factors such as weather conditions, soil properties, crop characteristics and irrigation strategies, AquaCrop provides tailored recommendations to enhance water-use efficiency and maximize crop yields. It serves as a bridge between scientific research and practical application, offering valuable insights for optimizing water use in various agroecological settings. It is especially well suited for situations where water significantly limits crop production.

Since its initial launch in 2009, AquaCrop has undergone various versions with new developments. The model's credibility stems from rigorous scientific research and validation studies conducted across diverse agroclimatic regions (Salman *et al.,* 2021). The continuous refining of the model based on empirical data and field observations ensures its reliability and applicability in real-world scenarios The predictive capability, analytical rigour and user-friendly interface of AquaCrop allow it to transcend theoretical research and transform scientific insights into a practical tool that offers actionable solutions for farmers, policymakers and other stakeholders. This was always the spirit behind the model's development, moving beyond research and ensuring its relevance, effectiveness and scalability in real-world settings.

On the ground, AquaCrop implementation can generate relevant data that inform evidence-based decision-making processes. The model allows the assessment of the scalability and replicability of interventions in AWM across different contexts and regions. By analysing the model's output in conjunction with other tools and incorporating stakeholder feedback, strategies can be refined to optimize resources and achieve the desired outcomes more effectively. It is crucial to enhance stakeholder engagement and collaboration in the implementation of AquaCrop on the ground. This will ensure that interventions align with local needs, priorities and aspirations, and that collective expertise, resources and networks can be leveraged to address complex challenges collaboratively. By piloting and scaling successful initiatives, the impact can be amplified, reaching broader audiences and contributing to changes at regional and global levels. On-the-ground implementation generates tangible results, success stories and lessons learned that influence policy development, advocacy efforts, and institutional reforms to improve AWM. Figure 1 shows the pathway of the AquaCrop model on the ground.

**FIGURE 1**
**Pathway of the AquaCrop model implementation on the ground**




*Source*: Authors' own elaboration.

## 1.2. OVERVIEW OF AQUACROP APPLICATIONS

Since its launch in 2009, the AquaCrop model has been tested and widely applied in various environments and scenarios by a broad range of users that includes farmers, extension specialists, field engineers, water planners, policy analysts and scientists. It has been implemented in numerous countries across the world's five continents, under different agroecological zones (Salman *et al.*, 2021). The applications of AquaCrop can be classified broadly under these categories: agronomic management, environmental change assessment and policy. The model's versatility stems from its ability to simulate crop yield under both optimal and constrained conditions, which include having stress factors such as temperature, water, nutrition and salinity.

The AquaCrop model predicts the attainable yield of a crop based on the available water supply in a field, farm or region, enabling comparison with the actual yield. The model is also useful for developing irrigation schedules for maximum production and providing decisions and strategies under water-deficit conditions, such as deficit irrigation, to best utilize available irrigation water (García Vila *et al.*, 2009; Geerts *et al.*, 2010). AquaCrop is therefore suitable for determining water productivity gaps as it allows the identification of factors that may enhance water use efficiency. It has also been used in crop management decisions, such as optimizing planting dates (Tsegay *et al.*, 2015), fertilizer (Akumaga *et al.*, 2017), and salinity management (Hassanli *et al.*, 2016), as well as evaluating mulching use.

With rainfall patterns and climate becoming more erratic and unpredictable, there is an urgent need to better understand crop responses to environmental changes, including the impact of climate change. Equally important is to identify constraints to crop production and water productivity, especially in arid, semi-arid, and drought-prone environments. AquaCrop is particularly suitable for forecasting the effects of global climate change. It has been used to perform drought severity evaluation (Martins *et al.,* 2018) and to assess the impacts of water quality deterioration and soil salinization, which are exacerbated by climate change, while helping to identify optimal management strategies. Other applications of AquaCrop include studying the future trends of crop production. This can be achieved by running AquaCrop using past or historical records and forecasting long-term climate scenarios.

Similarly, the AquaCrop model has been used to analyse scenarios for water administrators and managers, economists, policy analysts and scientists for planning purposes. This aids in water allocations and other water policy decision-making; in planning cropping patterns; and in enhancing crop productivity while protecting natural resources.

## 1.3. OBJECTIVES, TARGET AUDIENCE AND STRUCTURE OF THE REPORT

In building on the insights from the publication, *The AquaCrop model – Enhancing crop water productivity: Ten years of development, dissemination and implementation 2009–2019* (Salman *et al.,* 2021), which evaluated the model's impact during its initial decade, it is imperative to present the diverse applications of AquaCrop beyond research. Even though crop models are made in research and academic environments, AquaCrop was developed so that a model could be used to assist in implementing effective water management strategies and practices. The aim was to develop a tool beneficial to planners, water managers, extension services, consulting engineers, governmental bodies, non-governmental organizations (NGOs) and farmers' groups. Numerous instances showcase the use of AquaCrop for on-farm decision-making in projects worldwide. Concurrently, there is a growing demand from governmental agencies for tools centred on best water management practices, propelling the practical application of AquaCrop through different types of projects as highlighted in the AquaCrop publication by Salman *et al.* (2021). Still, there is a need to delve deeper into the potential applications of the model on the ground, with clear examples through case studies.

Based on these considerations, the objective of this publication is to furnish pertinent examples of AquaCrop applications on the ground for sustainable AWM. The aim is to drive the transition of the model from research to practice, presenting its instrumental role in addressing on-the-ground challenges.

Chapter 2 of the report offers guidance on AquaCrop implementation. It examines the model's capabilities, primary limitations, required data and sources, and the synergies achieved when the model is integrated with other tools. The subsequent five chapters detail the applications of AquaCrop across various domains: water resources allocation and irrigation planning (Chapter 3); operation and management decisions, i.e. irrigation scheduling under limiting and non-limiting conditions (Chapter 4); agronomic management applications for enhancing crop water productivity (Chapter 5); benchmarking of yield gaps through the prism of water management (Chapter 6); assessment of climate change effects on crop production and water use; and identification of adaptive strategies (Chapter 7).


# 2. Guidelines for AquaCrop implementation

## 2.1. WHAT CAN BE SIMULATED BY THE MODEL

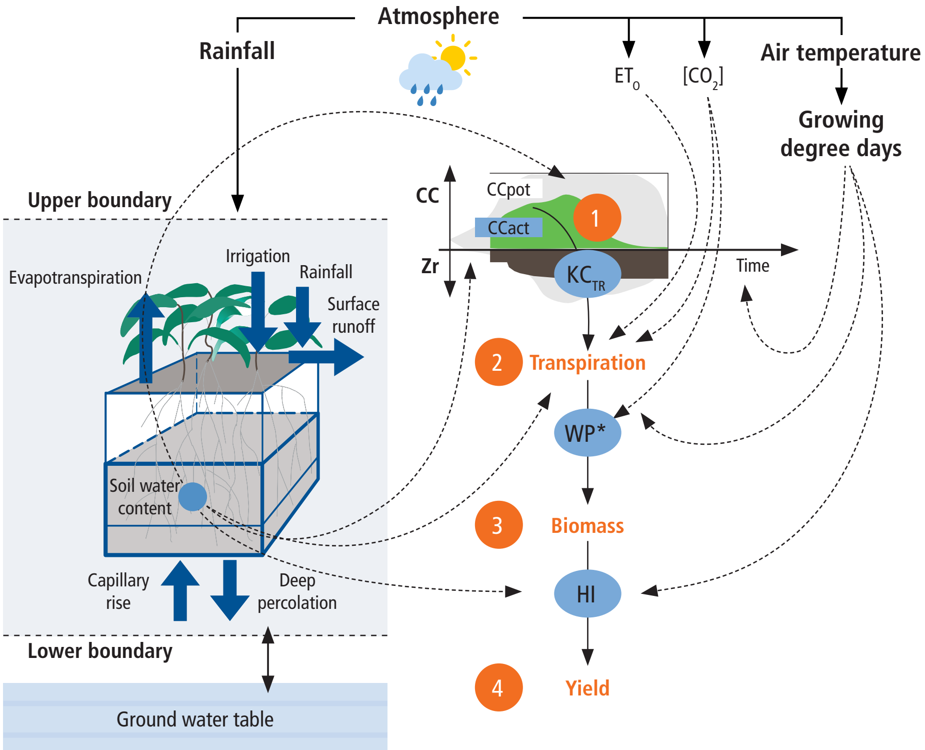
Building on the concept of a direct connection between crop water use and yield, the AquaCrop model evolved from the approach of Doorenbos and Kassam (1979). It distinguishes between non-productive soil evaporation and productive crop transpiration and estimates biomass production directly from actual crop transpiration through a water productivity parameter. Details of AquaCrop simulation processes are provided in the succeeding sections.

### 2.1.1. Calculation scheme

For each day of the growing cycle, AquaCrop simulates the green canopy cover, crop transpiration, biomass production and crop yield, as described by Steduto *et al.* (2009) and Raes *et al.* (2009).

The green canopy cover (CC) is the fraction of the soil surface covered by the canopy. In the absence of stress, the canopy development is driven by thermal time and increases from a minimum value at emergence to the maximum canopy cover. Without stress, crop transpiration (Tr) is proportional to the simulated CC, and biomass production (B) is proportional to Tr. In the final step, crop yield is obtained from B by considering the Harvest Index (HI), a fraction of B which is the harvestable product. Figure 2 shows the schematic presentation of the four successive daily time steps of the AquaCrop simulation process of crop yield, where Zr is the rooting depth, CC is the green canopy cover, KcTr is the crop transpiration coefficient, WP* is the biomass water productivity normalized for climate and carbon dioxide ($CO_2$) concentration, HI is the Harvest Index, $ET_o$ is the reference evapotranspiration, and GDD is the growing degree days. The distinction is made between CC development in the absence of water stress (CCpot) and with the effect of water stress (CCact).

**FIGURE 2**
**Schematic presentation of the four successive daily time steps of the AquaCrop simulation process of crop yield**




*Source:* **Raes, D., Steduto, P., Hsiao, T.C. & Fereres, E.** 2023a. Chapter 1. FAO crop-water productivity model to simulate yield response to water. In: Raes, D., Steduto, P., Hsiao, T. C. and Fereres, E., eds. *AquaCrop version 7.1. reference manual.*

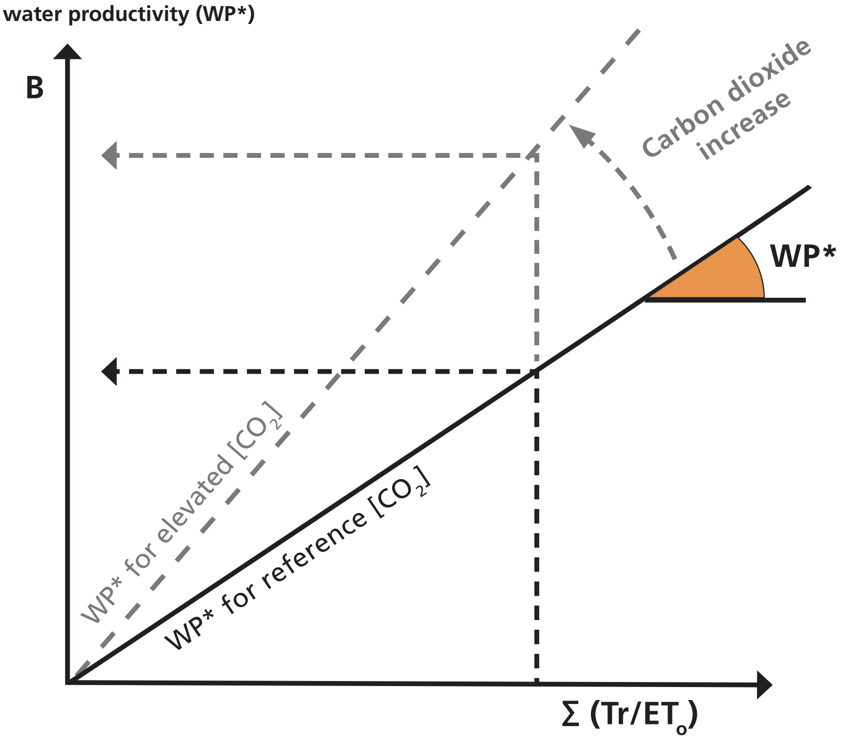
Water, temperature, soil fertility and soil salinity stresses, and weed infestation might affect one or more of the above processes as detailed in the AquaCrop reference manual (Raes *et al.,* 2023c).

### 2.1.2. Biomass water productivity

***Biomass water productivity normalized for climate and reference carbon dioxide concentration***

AquaCrop distinguishes itself from the other crop models by using a water-driven instead of a solar-driven growth engine. To simulate biomass production, it uses the conservative relation between cumulative crop transpiration (water) and aboveground biomass production. Figure 3 shows the biomass water productivity (WP*), which is the proportional factor between dry aboveground biomass (B) and cumulative crop transpiration normalized for climate ($\sum(Tr/ET_o)$ and for the reference (369.41 ppm, the average atmospheric $CO_2$ concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii) and elevated $CO_2$ concentration.

FIGURE 3
**Biomass water productivity (WP*)**




*Source:* **Raes, D., Steduto, P., Hsiao, T.C. & Fereres, E.** 2023a. Chapter 1. FAO crop-water productivity model to simulate yield response to water. In: Raes, D., Steduto, P., Hsiao, T. C. and Fereres, E., eds. *AquaCrop version 7.1. reference manual.* FAO. pp. 1–167.

The normalized biomass water productivity (WP*) has shown a remarkable conservative behaviour when standardized for the atmospheric evaporative demand ($ET_o$) and for a particular $CO_2$ concentration of the atmosphere. WP* is proven to be nearly constant for a given crop when mineral nutrients are not limiting, regardless of water stress, except for extremely severe cases (Steduto *et al.,* 2012). A single value of WP* is used for the entire crop cycle. When running a simulation, AquaCrop adjusts WP* when the yearly atmospheric $CO_2$ concentration differs from its reference value (369.41 ppm).

### *Biomass water productivity for elevated $CO_2$ concentration*

The increase of biomass water productivity (WP*) to elevated $CO_2$ concentrations was theoretically derived by Steduto *et al.* (2007) and extended with a sink term by Vanuytrecht *et al.* (2011, 2012) through a meta-analysis on C3 crops in free air $CO_2$ enrichment (FACE) experiments. To avoid an unrealistic simulation of biomass production at $CO_2$ concentrations above 550 ppm, the correction coefficient for WP* was adjusted in version 7 of the AquaCrop model.

The so-called "$CO_2$ fertilization" is the result of the strong increase of WP* under elevated $CO_2$, as schematically depicted in Figure 2. This means that with the same amount of crop transpiration, more biomass can be produced in future climates. However, producing more biomass also requires more nutrients. Without adapting soil fertility management, crops cannot fully benefit from the fertilization effect of increased atmospheric $CO_2$ concentration. Only if soil fertility is improved will it be possible for crops to benefit from $CO_2$ fertilization and for the negative impacts of other climatic changes to be counterbalanced (Raes *et al.,* 2021).

## 2.1.3. Simulation unit and fluxes exchange

As with most other crop growth models, AquaCrop runs on a simulation unit characterized by homogeneous weather, soil, crop and management practices. The crop is assumed to grow and develop in a uniform large field in which water and energy exchanges are controlled by one-dimensional vertical fluxes. Through the upper boundary, the system is linked to the atmosphere which determines the evaporative demand ($ET_o$) and supplies $CO_2$ and energy to grow. Water drains from the system through the lower boundary to the subsoil and groundwater table. If the groundwater table is shallow, water can move upward in the system by capillary rise. Since the aquifer does not belong to the simulated system, its depth and water quality need to be specified as input.

Apart from surface runoff of the excess rainfall that cannot infiltrate in time, horizontal water and/or energy fluxes are not considered in the simulations.

## 2.1.4. Crop types

### *Calibrated crops in the database of AquaCrop*

AquaCrop has been developed to predict yield response to water of herbaceous crops. In the database of AquaCrop, calibrated and validated values of the conservative crop parameters are provided for 14 major annual herbaceous crops, two less common crops (teff and quinoa), and one perennial forage crop (alfalfa):

- **fruit/grain-producing crops:** barley, cotton, dry beans, maize, quinoa, rice, sorghum, soybean, sunflower, tef, tomato and wheat.
- **root and tuber crops:** cassava, potato and sugar beet.
- **leafy vegetable crops:** sugar cane.
- **perennial forage crops:** alfalfa.

When running a simulation for a specific cultivar or in a climate or management different from the environment in which the crop was calibrated and validated, the cultivar-specific and less conservative crop parameters might require an adjustment.

### *Crops not yet available in the AquaCrop database*

The widespread use of Aquacrop has resulted in applications for a broad variety of crops. A literature review in 2019 revealed that the model has already been implemented for 46 different crops (Salman *et al.,* 2021). Although not clear in all publications, detailed data are needed for the validation and parameterization of the model for a particular crop. A guide for the parameterization, calibration and validation of AquaCrop is available in Steduto *et al.* (2012). Maize calibration has been worked out by Hsiao *et al.* (2009) and Heng *et al.* (2009) and serves as a good example.

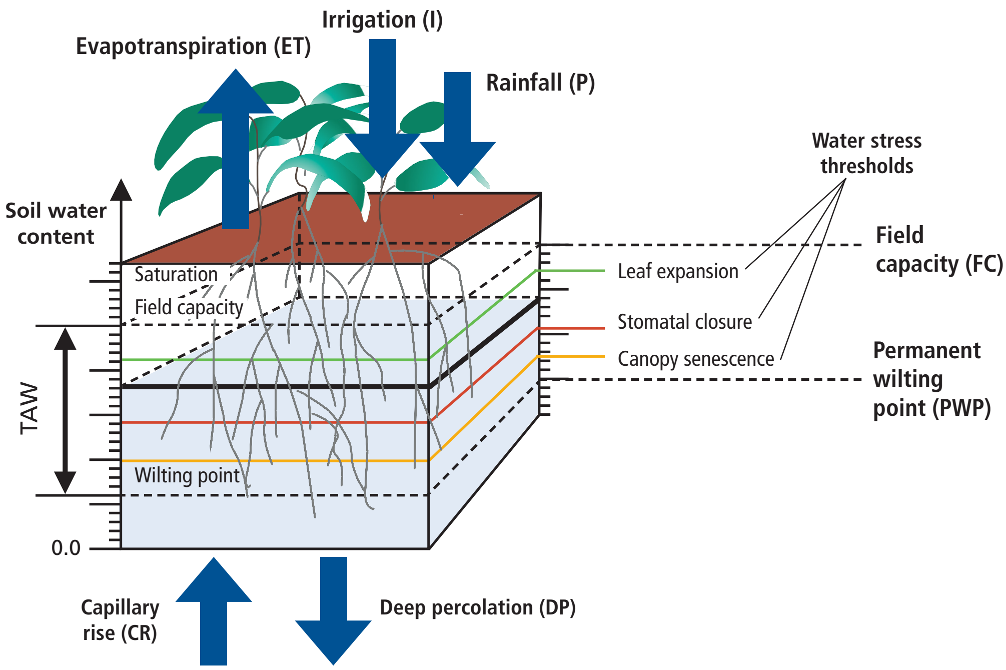
### *Limitations*

Although a few applications of AquaCrop to fruit trees have been attempted, the model has only been designed for herbaceous crops. The complex behaviour of fruit trees may make it difficult to simulate the yield response of tree crops with the calculation procedures described in Figure 2. In addition, mixed cropping (intercropping) cannot be simulated as uniform large fields are assumed.

## 2.1.5. Soil water stress

By keeping track of the incoming and outgoing water fluxes, AquaCrop calculates daily the soil water content in the root zone and the degree of water stress. To accurately simulate the crop response to water stress, AquaCrop considers three soil water stress levels instead of one as in most crop growth models (Figure 4). The lowest stress level is valid for canopy expansion since it is substantially more sensitive than stomatal conductance, and early canopy senescence will be triggered at a third stress level (Hsiao, 1973; Bradford and Hsiao, 1982). Transpiration will be also affected when the root zone becomes waterlogged (except for paddy rice). Further on, water stress may alter HI either positively or negatively depending on the timing, strength and duration of the stress.

**FIGURE 4**
**Water stress threshold for leaf expansion (green line), stomatal closure (red), and early canopy senescence (yellow) expressed as a fraction of total available soil water (TAW)**




*Source:* Authors' own elaboration.

The water stress thresholds are expressed as a fraction of the total available soil water (TAW), which is the difference between the water content at field capacity (FC) and permanent wilting point (PWP). The global sensitivity analysis of the water productivity model AquaCrop revealed that for the soil parameters, FC and PWP have one of the highest individual and total sensitivity indices (Vanuytrecht *et al.*, 2014).

### 2.1.6. Air temperature stress

#### *Cold and heat stresses*

Growing degree days (GDDs) are calculated by subtracting the crop base temperature from the average air temperature. When running simulations in thermal time, the time required to reach a particular growth stage is expressed in GDDs. Consequently, the canopy development and root development are adjusted to the thermal regime of the year.

AquaCrop considers the reduction in stomatal closure at low temperatures and heat and cold stresses during pollination. The global sensitivity analysis of the AquaCrop model revealed that the base temperature and cold stress affecting crop transpiration are most influential in temperate climates (Vanuytrecht *et al.,* 2012).

#### *Limitations*

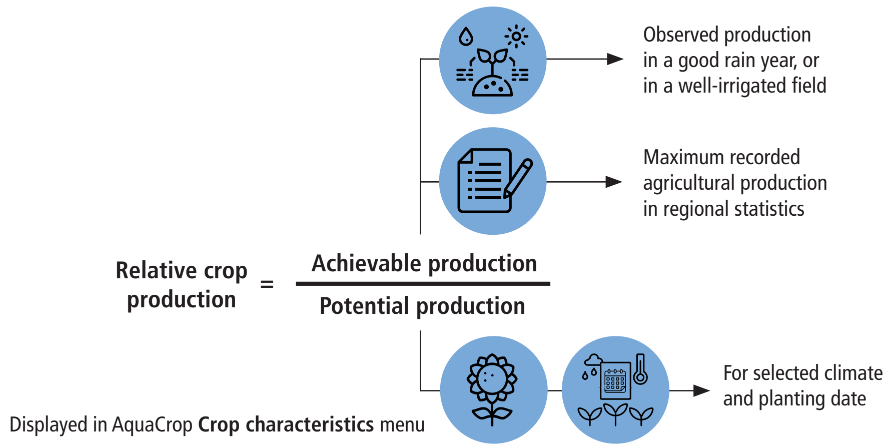
AquaCrop considers only the effect of heat stress during pollination. Responses to heat stress after pollination (from anthesis to maturity) are not considered in AquaCrop.

### 2.1.7. Soil fertility stress

#### *Calculation procedure*

Most crop models make use of a nutrient balance approach for modelling crop response to soil fertility. To counter the vast input data requirement that is typical for these models, AquaCrop adopts a semi-quantitative approach. Instead of requiring details of nutrient levels, AquaCrop uses the soil fertility level as model input. This level is expressed by the relative crop production (with reference to the potential production) that can be achieved with the specified soil fertility level in the absence of water stress or any other stressors. (Figure 5).

**FIGURE 5**
**Required input for soil fertility, expressed as relative crop production**




*Source:* Authors' own elaboration.

For the selected climate and planting date, AquaCrop displays the potential crop production in the crop characteristics menu. The achievable crop production for the current soil fertility level, in the absence of water stress, is the observed production in a good rainy year or a well-irrigated field. The maximum recorded agricultural production in regional statistics is often a good first indication of the production that can be achieved with the current soil fertility level in the absence of water stress or any other stressors (Figure 5).

When running a simulation, AquaCrop mimics the effects of soil fertility stress (expressed by the specified relative crop production) by limiting the canopy growth and gradually decreasing WP* as more and more biomass is produced. Following case-specific calibration for teff in Ethiopia, maize and wheat in Nepal, and quinoa in the Plurinational State of Bolivia, AquaCrop was able to accurately simulate the soil water balance, crop development, biomass production, and yield for several soil fertility levels in different environments (Van Gaelen *et al.,* 2015).

### *Limitations*

The lack of a nutrient balance in AquaCrop makes it impossible to simulate the transference effect of soil fertility management in one season to the next season or crop in a sequence.

### 2.1.8. Soil salinity stress

### *Salt balance*

By keeping track of incoming and outgoing salt fluxes, AquaCrop simulates daily the salt content in the root zone (tonne/ha). The corresponding average electrical conductivity of the saturated soil-paste extract (ECe) is used as the indicator for soil salinity stress. In AquaCrop, soil salinity stress limits the canopy development and reduces the conductivity of the stomata, resulting in a decline in crop transpiration, biomass production and crop yield.

### *Limitations*

The use of average ECe as an indicator of soil salinity stress might work well in well-watered soils. However, the indicator cannot describe the effects of the increase of the salt concentration in drying soil. Therefore, a calculation procedure is available in AquaCrop that further reduces the conductivity of the stomata in drying soil by considering the increase of EC of the soil water (ECsw). Since this procedure is largely untested and yield reduction due to toxicity is not considered, AquaCrop should still be used with caution under these situations.

## 2.2. DATA REQUIREMENTS, SOURCES AND MANAGEMENT

The effectiveness of crop model applications in real-world scenarios is largely determined by their data requirements. Therefore, it is crucial to carefully consider data needs and identify potential data sources. AquaCrop employs a concise set of parameters and easily understandable input variables, typically established through commonly used or straightforward methods. This simplicity enhances its usability and implementation, making it one of the most widely utilized models today (Salman *et al.,* 2021). Input encompasses climate data, soil properties and crop characteristics for the specific cultivar. These are tuned to the environment and management practices that delineate the environment in which the crop will thrive (Raes *et al.,* 2023b). Comprehensive details regarding the necessary data for AquaCrop implementation are available in Steduto *et al.* (2012) and in the reference manuals of the model (https://www.fao.org/aquacrop/resources/referencemanuals/en/).

### 2.2.1. Climate data

For each day of the simulation period, AquaCrop requires minimum (Tn) and maximum (Tx) air temperature; reference evapotranspiration ($ET_o$) as a measure of the atmospheric evaporative demand; and rainfall (Raes *et al.,* 2023b). $ET_o$ should be calculated from weather station data using the FAO Penman-Monteith equation, as outlined in Allen *et al.* (1998). AquaCrop incorporates an $ET_o$ calculator specifically designed for this task, which allows the use of climatic data in different units and provides methods to estimate any absent climatic data.

Obtaining daily climate data is a difficult task in various regions worldwide. Many areas lack meteorological monitoring systems or face logistical and infrastructural barriers that make consistent data collection almost impossible. Gaps in daily climate records arise, making it challenging to generate accurate and reliable datasets for these locations. Nevertheless, in recent years, the emergence of low-cost weather stations in the market has ushered in a new era of opportunities, revolutionizing how meteorological data can be gathered, analysed and utilized. These affordable and accessible devices have made it easy for people, communities and organizations to monitor local weather conditions with unprecedented ease and accuracy, democratizing access to crucial weather information. The devices can measure a wide range of meteorological parameters, including temperature, humidity, rainfall, wind speed and solar radiation, among others, providing all the data needed to compute $ET_o$. Moreover, the data collected from these weather stations can be shared and analysed using cloud-based platforms, open-source software, and collaborative networks, fostering data exchange, collaboration and innovation.

In case local climate monitoring systems are unavailable or setting up a low-cost weather station is not yet feasible, several global climate databases offer a resourceful alternative for obtaining the necessary climate data input. These repositories provide a wealth of opportunities for the potential applications of AquaCrop. One of the primary advantages of global climate databases is their extensive coverage, providing access to historical, current and projected climate data from diverse geographical regions worldwide. These databases centralize climate data from multiple sources, making them easily accessible through user-friendly platforms and tools. Some examples of these global climate databases that provide the data required for AquaCrop are in Table 1.

**TABLE 1**
**Examples of global climate databases that provide data required for AquaCrop**

| Name | Institution | Period | Data access |
|---|---|---|---|
| Prediction of Worldwide Energy Resource (POWER) | National Aeronautics and Space Administration (NASA) | 1981 - present | https://power.larc.nasa.gov/ |
| ERA5 | European Centre for Medium-Range Weather Forecasts (ECMWF)Copernicus Climate Change Service (C3S) | 1960 - present | https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form |
| Global Daily Downscaled Projections (NEX-GDDP-CMIP6) | NASA Earth Exchange | 1950 - 2100 | https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6 |
| ISIMIP3b data set | The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) | 1850 - 2100 | https://www.isimip.org/ |

*Source:* Authors' compilation.

In addition to the daily parameters needed, it is essential to know the average annual atmospheric $CO_2$ concentration. AquaCrop includes a historical time series of average annual atmospheric $CO_2$ concentrations measured at the Mauna Loa Observatory in Hawaii, along with projected concentrations for the near future.

### 2.2.2. Soil properties

Data on soil properties play a pivotal role in crop modelling, serving as fundamental input that significantly influence the accuracy, reliability and applicability of model predictions. One of the primary reasons for their importance lies in their impact on water dynamics. Soil properties such as texture, structure, porosity and organic matter content influence water infiltration, retention and availability within the root zone, as well as water uptake. Accurate characterization of these properties enables models to simulate soil–water–plant interactions more effectively.

The soil characteristics required by AquaCrop are the water retention in the fine soil fraction at saturation (θsat), field capacity (θFC), and at permanent wilting point (θPWP), and the hydraulic conductivity of the soil at saturation (Ksat) (Raes *et al.,* 2023b). Users have the option to utilize the reference values provided by AquaCrop for different soil texture classes or incorporate locally obtained or derived soil texture data using pedo-transfer functions (PTFs). Estimating soil hydraulic properties using PTFs offers a practical and efficient approach to characterize soil water dynamics, particularly when direct measurements are limited or unavailable. These functions relate easily measurable soil properties, such as texture, bulk density and organic matter content to more complex hydraulic parameters. Several software tools and models have been developed to relate measured soil properties to the desired hydraulic parameters using PTFs. Some examples of these tools are in Table 2.

**TABLE 2**
**Examples of tools for the estimation of soil hydraulic properties using pedo-transfer functions**

| Name | Institution | Available at |
|---|---|---|
| ROSETTA | U.S. Department of Agriculture (USDA) | https://www.ars.usda.gov/pacific-west-area/riverside-ca/agricultural-water-efficiency-and-salinity-research-unit/docs/model/rosetta-model/ |
| Soil water characteristics | U.S. Department of Agriculture (USDA) | https://www.ars.usda.gov/research/software/download/?softwareid=492 |
| SOILPAR | University of Naples/CRA | https://soilpar2.software.informer.com/ |

*Source:* Authors' compilation.

Similar to climate data, some global soil databases can provide the required information when locally obtained data are not available or when large-scale AquaCrop applications are desired. These databases ensure consistent and standardized soil information across different regions, facilitating comparative analyses, regional assessments, and global-scale modelling efforts. Some examples of global soil databases are in Table 3.

**TABLE 3**
**Examples of global soil databases that provide data required for AquaCrop**

| Name | Institution | Data access |
|---|---|---|
| Harmonized World Soil Database (HWSD) | FAO | https://gaez.fao.org/pages/hwsd |
| SoilGrids | International Soil Reference and Information Centre (ISRIC) | https://www.isric.org/explore/soilgrids |
| European Soil Data Centre | European Commission | https://esdac.jrc.ec.europa.eu/ |

*Source:* Authors' compilation.

## 2.3. AQUACROP ASSETS AND COMBINATION WITH OTHER TOOLS

AquaCrop can be combined with a range of other tools to meet specific user applications. Since the release of AquaCrop version 7 (and higher versions), the official distribution of FAO AquaCrop has consisted of an open-source version-controlled Fortran90 code on GitHub, and standalone programs for Windows, macOS and Linux operating systems, along with the well-known standard program with user interface. These assets aim to serve the broader user community to efficiently exploit the capability of AquaCrop for scientific field-scale applications, global applications, practical web-based applications or targeted user applications.

### 2.3.1. Official AquaCrop assets

The three main AquaCrop assets distributed by FAO (https://www.fao.org/aquacrop/en/) are shown in Figure 6. These are (i) the standard program with a graphical user interface (GUI); (ii) the open-source Fortran90 code on GitHub; and (iii) the standalone programs for Windows, macOS and Linux platforms. A fourth asset is AquaCrop embedded into NASA's Land Information System (LIS), which is being evaluated for public dissemination. The standard GUI has not been changed in recent versions of AquaCrop.

**FIGURE 6**
**AquaCrop assets available from AquaCrop v7 onwards**


*Source:* Adapted from FAO AquaCrop webpage (https://www.fao.org/aquacrop/en/).

#### *Open-source Fortran90 code*

The original (up to version 6) AquaCrop source code was written in Delphi/Pascal, whereas the v7 open-source release on GitHub was done in Fortran90 after a line-by-line conversion. Fortran is an easy-to-use, high-level language that is widely used in the climate sciences community. It allows for efficient interfacing with other Fortran-based modelling frameworks, such as NASA's LIS. Furthermore, C (++) and Python interfaces can be generated automatically. The open-source code is free to use, study, improve and share for non-commercial applications.

#### *Standalone programs*

The Fortran90 code was used to compile the executables on the three most commonly used operating systems: Windows, macOS and Linux. The resulting standalone or plugin programs are provided as official assets online but can also be compiled from the open-source code following the instructions on the GitHub page. The standalone program can be plugged into any applications, including geographical information systems, data assimilation tools, calibration tools, visualization tools, and web applications.

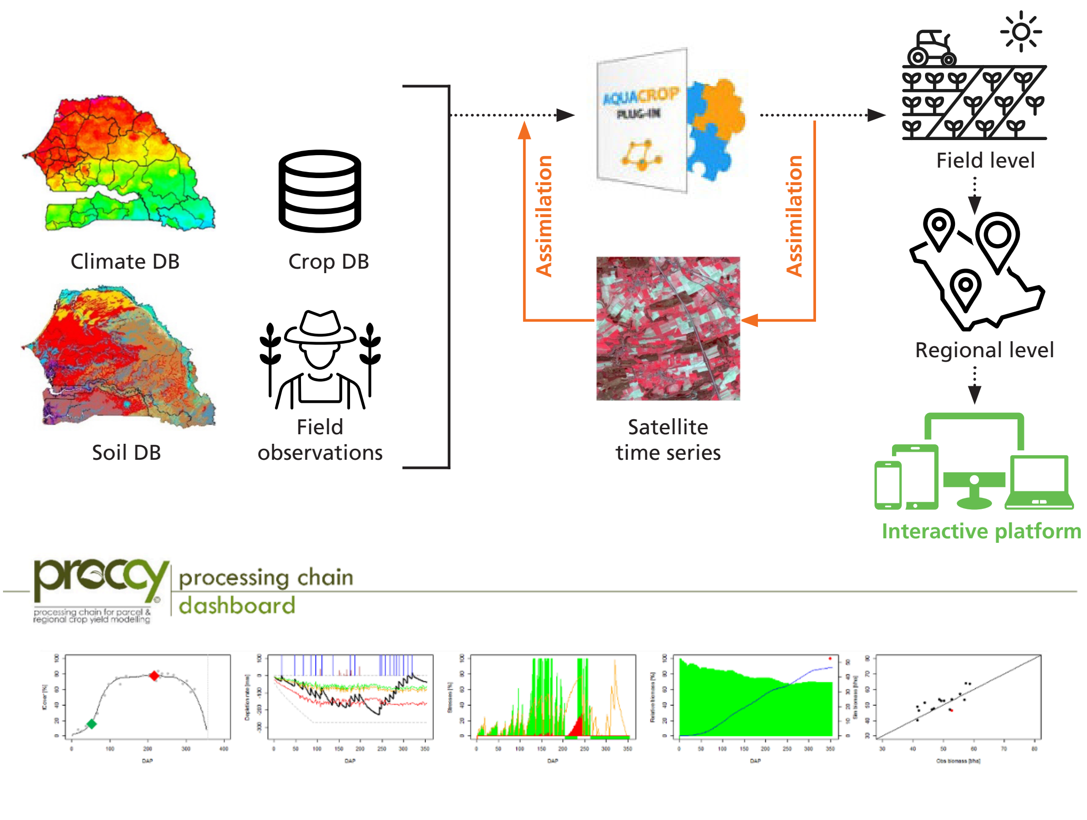
### 2.3.2. Combinations with other tools

There is a range of possibilities to combine AquaCrop with other tools. This includes preparing input files or visualizing output efficiently; running the model in a spatially distributed way; plugging the model into web applications; calibrating the model parameters; or more generally, interfacing the model with *in situ* or satellite-based observations.

#### *AquaCrop Processing Chain for Regional & Parcel Crop Yield modelling*

AquaCrop's standalone version has been used to help, among others, the Compagnie Sucrière Sénégalaise (Wellens *et al.,* 2021a) and Belgian farmers (Wellens *et al.,* 2017a; Picard *et al.,* 2017; Mohamed Sallah *et al.,* 2019) monitor and manage their ensembles of sugar cane (Senegal), maize, potato and winter wheat fields (Belgium). To facilitate the processing of thousands of fields, the AquaCrop standalone version has been integrated into an R environment (Figure 7) named PROCCY or Processing Chain for Regional & Parcel Crop Yield modelling (Wellens *et al.,* 2017b). This environment typically contains authoritative soil and climate data, calibrated crop files, and field management information. Maximum canopy cover and time of emergence are updated using assimilation. R-scripts ingest the required data, launch the AquaCrop standalone, and read out the simulation results. With a single run, a multitude of fields can be assessed through a dashboard, aggregated or individually.

**FIGURE 7**
**Processing chain for parcel and regional crop yield monitoring (PROCCY) workflow and dashboard with typical AquaCrop outputs**

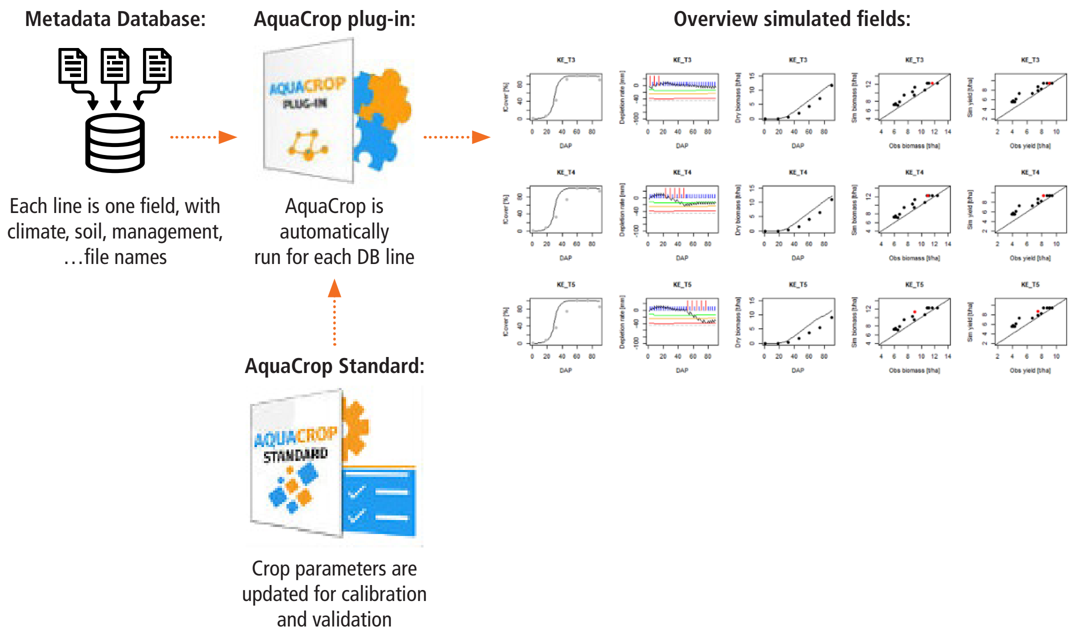



*Source:* Authors' own elaboration.

### *AquaCrop calibration support*

Although AquaCrop requires relatively few parameters, calibrating and validating new crops remains a tedious trial-and-error work, especially when large datasets are available. A beta version of the AquaCrop batch processor (Figure 8) was successfully implemented recently to calibrate cassava (Wellens *et al.,* 2021b) and alfalfa (Raes *et al.,* 2023a). A metadata database containing all the specific field information was established. Embedded in an R-environment, the AquaCrop standalone version retrieves all the required information from this database, runs all the fields, and visualizes simulation results and statistics. Crop parameters are updated in the AquaCrop GUI version to respect phenological constraints imposed by the model. Instead of running trials field-per-field, the batch processor allows the simulation and assessment of parameter changes for the ensemble of fields with one click.

**FIGURE 8**
**AquaCrop batch processor workflow for calibration**




*Source:* Authors' own elaboration.

### *Spatially distributed simulations*

For regional spatially distributed simulations at any spatial resolution of the user's choice, an open-source Python wrapper is made available (de Roos *et al.,* 2021, Busschaert *et al.,* 2022, https://ees.kuleuven.be/project/shui-regionalaquacrop/data/) to call the AquaCrop standalone program in parallel for multiple pixels. The input and output consist of the standard ASCII AquaCrop input and output files for each pixel, which can be combined into spatial maps through postprocessing.

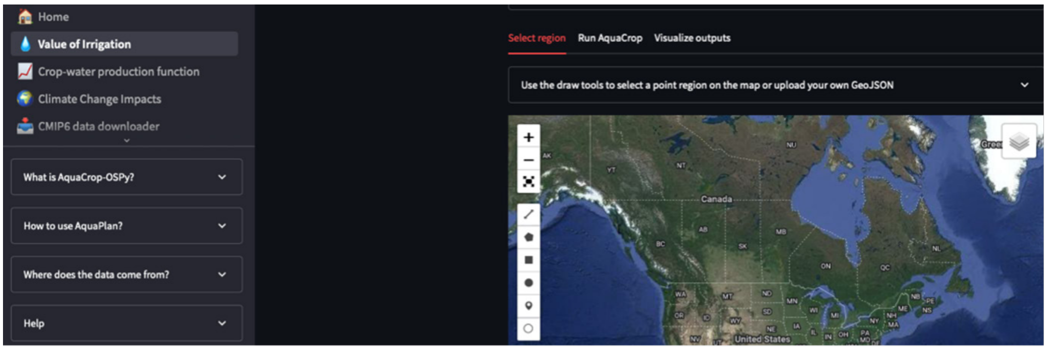
To facilitate modelling with any historical or future climate forcing dataset, texture information, or other input datasets, and to allow interaction with a wide range of satellite data, AquaCrop v7 is the first crop model that is plugged into NASA's Land Information System (LIS). LIS offers a range of plugins to access various physically based land surface models; meteorological and parameter input datasets at the spatial resolution of the user's choice; and tools for ensemble generation and satellite data assimilation (Kumar *et al.,* 2008, 2015; Modanesi *et al.,* 2022; Heyvaert *et al.,* 2023; de Roos *et al.,* 2024, https://lis.gsfc.nasa.gov/). This system currently only runs on HPC Linux platforms.

### *AquaCrop-OSPy and AquaPlan*

Next to the official FAO assets, an additional version of the AquaCrop model was developed in Python (AquaCrop-OSPy) (Kelly and Foster, 2021). AquaCrop-OSPy has a modular design incorporating key elements of AquaCrop's water-limited growth engine, with additional functionality to link with routines for agricultural water management decision-making from farm to catchment scales. Examples of AquaCrop-OSPy application include field-level optimization of irrigation scheduling (Kelly *et al.,* 2021; Kelly *et al.,* 2023), regional scale assessments of crop water footprints (Mialyk *et al.,* 2022), and hydro-climatological risks (Richter *et al.,* 2023; Variani *et al.,* 2023).

To break down barriers to the uptake of the model by policymakers and practitioners, an interactive web application, AquaPlan (https://www.tinyurl.com/aquaplan), has been developed for AquaCrop-OSPy. AquaPlan provides a no-code interface (Figure 9) that allows users to interactively set up, design and run simulations anywhere in the world based on regional and global gridded soil, crop and meteorological datasets. Its key features include tools to quantify the improvements in crop yields that can be obtained through the use of irrigation; optimize water use and scheduling for different weather and economic conditions; and assess the impacts of climate change on crop yields and water requirements. All these can be done interactively within a web browser, without the need for any programming expertise or computational infrastructure.

**FIGURE 9**
**AquaPlan interface**




*Source:* https://www.tinyurl.com/aquaplan


# 3. Water resources allocation and irrigation planning

## 3.1. OVERVIEW OF SPECIFIC POTENTIAL APPLICATIONS

As water scarcity pressures increase, there is growing emphasis in many parts of the world on how to allocate water to meet the demands of agriculture while also meeting the requirements for other human activities and the environment. Water allocation considers the sharing of water between agriculture and other sectoral users, as well as the allotment of water within the agricultural sector.

Within the agricultural sector, water allocation occurs across two dimensions: the spatial and the temporal (addressed either independently or simultaneously). Spatial allocation of water resources within agriculture considers water sharing between farms within a given basin or catchment; between different crops over a given farm; and within individual fields for irrigation. On the other hand, temporal allocation of water considers decisions around the distribution of available water between years or seasons (e.g. when to extract water stored in aquifers or reservoirs) as well as within seasons through irrigation schedules during the crop growing season to meet variable crop water requirements.

At the farm scale, the allocation of irrigation water implies a decision-making process made by the farmer at two levels: (i) the selection of the most suitable crops to cultivate in available land, considering effective cropping rotations and constraints to growing periods; and (ii) an optimal – both spatial and temporal – allocation of water among the selected crops. This decision-making process involves both agronomic and economic considerations. A farmer must consider the agronomic suitability of crops vis-a-vis the land and climatic conditions of the area, the response of yield to quantity and quality of irrigation water, the irrigation methods that could be adopted, the management capacity of farmers, and the available technologies. Economically, decision-making is affected by the market demand and prices of the various crops; the cost of cultivating each crop including irrigation water supply; and other factors relevant to satisfying the criteria for economic sustainability, including regulatory and policy contexts for farm operations.

At the regional or catchment scale, allocation of water involves choices about how to (i) distribute water within the agricultural sector such as between different farms or fields and (ii) manage trade-offs between water use in agriculture versus other sectors (e.g. domestic supply or industry) and environmental water needs. At this scale, decisions are typically made by water managers or regulators who must make choices about the allocation of rights to limited available freshwater resources considering the social, economic and political values attached to different uses of water (e.g. economic returns or importance to food security of different crops). Allocation at these levels is influenced by pre-existing water rights systems and regulations that determine which farms or sectors get priority over water and must also consider temporal dimensions (e.g. how to allocate stored or non-renewable water resources over time).

The FAO AquaCrop model can provide important input to help solve and inform the optimization of water allocation at both farm and regional scales, and in terms of spatial and temporal allocations (Steduto *et al.,* 2009). The optimal allocation of water for irrigation – and considerations of trade-offs between agricultural and non-agricultural uses of water – assumes more relevance when water is scarce (water is a major limiting factor to crop production). However, the use of AquaCrop for water allocation planning is also relevant when water is not a dominant limiting factor as it will provide the opportunity to increase the overall economic efficiency of water use, which in turn supports the preservation of water resources for other human and environmental uses.

As with any other optimization problem, assessing the optimal allocation of water for irrigation requires (i) an objective function aiming at a specific purpose and (ii) the boundary conditions, specifically representing the constraints to the objective function. The setup of the objective function differs depending on the entity in charge of managing water and its goals. For instance, a water resources department may have the purpose of minimizing the consumption of water, considered scarce by an environmental agency. A groundwater agency may have the purpose of minimizing the discrepancy between water consumption and water recharge and thus achieve sustainable groundwater management. Alternatively, a food security agency may have the purpose of maximizing the output of proteins from a local territory where villages suffer from undernutrition. On the other hand, commercial farmers have the purpose of maximizing the total net revenue of cultivated areas with the selected crops. Similarly, the boundary conditions or constraints of each objective function are different, depending on the entity, and therefore the scale of the optimization problem. There may be a link between the various entities and scales, so that some of the objective functions at a higher scale may become a constraint for the objective function at a lower scale. This is the case when, for example, the water resources department and/or the groundwater agency may set a cap on water consumption by the commercial farmers, or when the food security agency limits the selection of crops.

By providing a means of quantifying crop-yield response to water, AquaCrop can provide critical information to support each of these different types of optimization scenarios. For example, AquaCrop can be used to generate crop-water production functions – a mathematical expression of the continuous relationship between crop yields and irrigation water inputs for a given set of climate conditions and farm management practices (García Vila and Fereres, 2012; Smilovic *et al.,* 2016; Foster and Brozović, 2018). Typically, these crop-yield response functions are represented by non-linear regressions (like the one of Mistscherlich), having two or three parameters (e.g. in Hexem *et al.,* 1976), which are generally derived empirically through local experiments. These equations have limited representativeness when applied outside the local conditions where experiments were conducted, but crop models such as AquaCrop can describe more complex crop-yield response to water use that can be extrapolated more readily to different environments.

Production functions derived from AquaCrop are a critical input to the various objective function types, enabling a farmer, water manager or other entity to assess how crop productivity will be influenced by different quantities, timings or distribution of water supply, either due to hydrologic, technological or regulatory constraints to supply. When combined with economic information (e.g. crop and water prices, costs of production), information about crop-yield response to water generated by AquaCrop can be used to help farmers understand how best to allocate available land resources between crops to maximize total revenue; how to allocate water during the growing season for a given crop to maximize crop water productivity or economic returns to water; or how much added value will be generated by investing in new on-farm management practices or technologies that improve water use efficiency.

At the regional or catchment scale, information on crop-yield response to water given by AquaCrop provides critical input to water resource management and policy analyses, as well as to modelling studies. By enabling the quantification of the value of water between different farms or fields, production functions can help assess the distributional impacts of water scarcity on agriculture. They can also serve as an input to support the design of policies (e.g. water quotas, pricing systems, water markets) to manage the competing demands for limited freshwater resources and ensure the most efficient and valuable uses of these resources. Similarly, production functions can be used to enable the assessment of water allocation over time, for example when considering the allocation of non-renewable groundwater resources or assessing the changing value of water over time due to climate or socioeconomic changes.

Different real cases of optimal allocation of irrigation water resources are presented in this chapter.


## 3.2. CASE STUDIES

### *Design and assessment of groundwater allocation quotas for agriculture supported by AquaCrop*

Groundwater enables agriculture to smooth out the risks posed by variability in rainfall and surface water flows. However, high levels of groundwater abstractions by agriculture are also a major driver of unsustainable groundwater use in many regions (Mieno *et al.,* 2024). Resulting aquifer depletion has many important societal and environmental consequences, including land subsidence, drying up of streams and wetlands, and seawater intrusion (Bierkens and Wada, 2019). For agriculture, aquifer depletion creates risks through reduced future water availability and increased risks of regulatory restrictions on abstractions (Foster *et al.,* 2017; Deines *et al.,* 2020; Mieno *et al.,* 2024).

To address the impact of unsustainable groundwater irrigation and ensure the future prosperity of rural farming economies, governments and water management agencies increasingly recognize the need for policy interventions to limit or control agricultural groundwater abstractions. One of the most common policy interventions is the introduction of groundwater abstraction restrictions or quotas, which seek to influence the allocation of water between farmers and between agriculture and other sectors. Quota design may also consider how groundwater abstraction rights should be given over multiple periods, particularly if the goal is managing long-term storage dynamics within an aquifer (Young *et al.,* 2020).

The case study describes an application of the AquaCrop model to support the design and evaluation of groundwater quota systems as part of regional aquifer sustainability efforts (Young *et al.,* 2020). It utilizes the AquaCrop-OS model, developed in Matlab (Foster *et al.,* 2017) and Python (Kelly and Foster, 2021). The case study focuses on the High Plains Aquifer (HPA) in the central United States of America. Irrigated agriculture primarily depends on groundwater in this region, which is also the main area of grain production in the United States, contributing billions of dollars annually to the US economy and playing a critical role in global food security (Fenichel *et al.,* 2016).

One of the key policy issues linked to groundwater pumping for irrigation in the HPA and other regions globally is streamflow depletion. Streamflow depletion is the process through which stream discharge rates are impacted due to the lowering of groundwater levels in an aquifer, which reduces the natural rate of groundwater discharge to streams (Barlow and Leake, 2012). Streamflow depletion has negative consequences for freshwater-dependent ecosystems and species, and also for downstream water users whose rights to extract river flows may be impeded. Streamflow depletion is an important issue in the northern High Plains (Palazzo and Brozović, 2014), where recharge rates are often sufficient to limit aquifer drawdown but not to avoid the impacts of pumping on streamflow.

The analysis focuses specifically on the Upper Republican Natural Resources District (URNRD) in the southwest of the state of Nebraska. URNRD is part of the Republican River Basin, which has experienced significant reductions in baseflow over recent decades linked to intensive groundwater-fed irrigation (Zipper *et al.,* 2021). Streamflow depletion has led to interstate disputes and litigation over the infringement of downstream surface water rights and impacts on freshwater ecosystems. In response, the URNRD and other groundwater management agencies within the basin have introduced restrictions on groundwater pumping by farmers. However, there have been large variations in how these quotas were designed. In particular, some management agencies restrict farmers to an average level of pumping over multiple years while others impose fixed single-year allocations and have varying rules on the carryover of unused water between allocation periods.

AquaCrop-OS is used to simulate the response of maize yields – the main irrigated crop in the region – to different levels of seasonal irrigation water allocation and how this relationship varies across different potential scenarios of growing season weather conditions drawn from 30 years of historical observed weather data. These simulated crop-water production functions were embedded in a farm-scale agroeconomic model and an empirical hydrologic model of streamflow depletion to assess the economic and environmental outcomes of different groundwater quota allocation systems. Specifically, the effects on farm profits and streamflow depletion rates were assessed by (i) the size of the groundwater quota per year, ranging from 0 ML/year to 450 ML/year and (ii) the number of years over which the quota was averaged, ranging from 1 year to 30 years.

The findings demonstrated important trade-offs between the objectives of farmers and water managers in the design of groundwater allocation quotas. More flexible quotas, i.e. those that allow farmers to average abstraction rates over multiple years, increased agricultural productivity and profitability as they enabled farmers to increase water usage to fully meet crop water needs during drought years while lowering water usage in wetter years. However, this flexibility comes at the cost of increasing both peak and cumulative rates of streamflow depletion. Streamflow depletion depends on the specific rate of pumping in individual growing seasons or periods, and therefore the flexibility to increase pumping in drought years leads to higher acute streamflow depletion events which are the most damaging for freshwater ecosystems and species.

The trade-offs identified through the case study show how AquaCrop can be an important tool to help guide water managers in the design of regulatory policies such as water allocation quotas. It shows that flexibility in abstraction rules can be crucial where irrigation is used to supplement rainfall and water demands and, therefore, vary significantly across years or seasons. However, in groundwater irrigation systems, levels of flexibility may need to be reduced to avoid acute pumping externalities such as streamflow depletion. In particular, AquaCrop showed that varying flexibility of quotas according to different farmers' streamflow depletion risks (e.g. proximity to streams) can help the regulator to optimize economic benefits to agriculture while also minimizing cumulative and acute impacts on stream ecosystems and surface water rights.

### *Assessing the impact of variation in water allocation dates*

Many regions in the Mediterranean face structural water scarcity due to periodic drought and increasing water demands from agriculture and other sectors. Consequently, irrigated agriculture is often the first to experience water allocation cuts, making water scarcity an important issue for the future of irrigated agriculture. In years marked by drought, having early information about the available water for irrigation becomes crucial for effective farm planning and management. The sooner the farmers know the water availability, the more options they have to adapt to the limited resources. In contrast, water authorities often defer making allocation decisions, hoping for additional rainfall and attempting to balance water demands across various sectors. This tendency to delay decisions exacerbates uncertainty, making it challenging for farmers to optimize their use of limited water resources.

In this study, a pre-season economic optimization model based on AquaCrop was employed to quantify the impact of the delays in communicating water allocation levels on farm income (García Vila and Fereres, 2012).

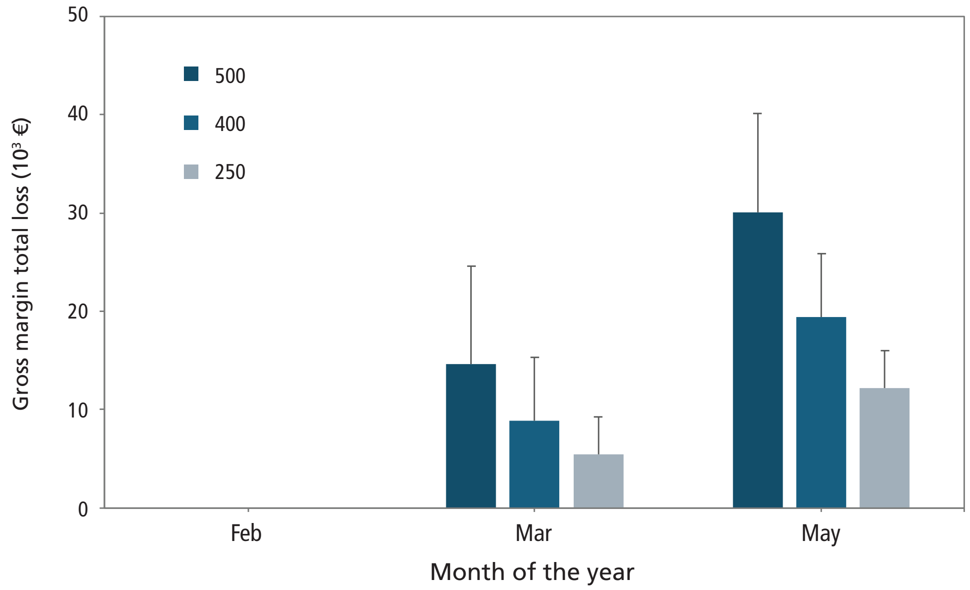
The study was conducted in the Genil–Cabra irrigation scheme (García Vila *et al.,* 2008), which currently encompasses 37 000 ha located in the Guadalquivir Valley, Southern Spain. The climate in the region is typically Mediterranean with an annual average precipitation of around 600 mm (mainly between October and April), and an average annual $ET_o$ of around 1300 mm. The area has a modern pressurized on-demand delivery irrigation system (García Vila *et al.,* 2008).

An ideal farm was conceptualized as a reference, incorporating a maximum of four crops: cotton, maize and sunflower – being major crops in the region – and potato, a horticultural crop with low irrigation requirements during winter planting. Following the calibration and validation of AquaCrop in the area, the model was employed to simulate yield based on applied irrigation water (AIW) and to formulate crop-water production functions. Yield response functions to AIW for each crop were derived from 26-year simulations using regression techniques. From these functions, the 20th and 80th percentile yield values for each AIW were selected to develop two crop-water production functions, representing unfavourable and favourable climatic conditions. Leveraging these yield response functions, a non-linear programming model was developed using the General Algebraic Modeling System or GAMS (Rosenthal, 2007). This model optimizes an objective function – the total gross margin or TGM – by selecting the optimal crop pattern and the optimal amount of AIW for each crop, with the variables subject to a series of linear restrictions. The model in this instance was specifically utilized to simulate the farmer's behaviour, aiming to maximize the farm's TGM. This involved determining the crop area and AIW under various scenarios, including the amount of water allocation, date of communication, and crop price (Pc) received by the farmer, all within three different climatic scenarios.

A database spanning 19 irrigation seasons (1990/1991–2008/2009) within the study area was used to build different scenarios for water allocation levels and communication dates through frequency distribution analysis, incorporating the 20th, 50th, and 80th percentiles from both distributions. The resulting water allocation levels were set at 250 mm, 400 mm and 500 mm, each corresponding to approximate communication dates in mid-February, mid-March and mid-May, respectively. Recognizing the significant impact of market dynamics and farmers' perceptions of the climate on their decisions, three scenarios for Pc were introduced: the 20th, 50th and 80th percentiles of Pc, representing low, medium and high Pc scenarios, respectively. Three climate scenarios (favourable, average and unfavourable) were also considered to account for varying climatic conditions.

The analysis of farmer's behaviour detailed in García Vila *et al.* (2008) laid the ground for formulating a series of optimization strategies (various approaches to utilizing the optimization model). These strategies were employed to simulate farmer's behaviour under diverse scenarios, as elaborated in García Vila (2010) and García Vila and Fereres (2012). In drought years, the date on which farmers know the level of water restrictions is critical for their seasonal planning. Figure 10 shows the TGM losses for the ideal farm of 100 ha that would occur when the decision is delayed until three different dates and for three different water allocation amounts. The bars depict the variability in profit losses attributed to diverse scenarios, encompassing variations in crop prices and seasonal weather conditions. As expected, economic losses increased as the decision on water allocation is delayed by the water authority, reaching EUR 30 000 in May (16 percent of TGM). If the level of water allocation turns out to be high, the opportunities for growing crops of high profitability (e.g. maize) are greater, and the losses relatively increase in a situation where substantial water constraints materialize. As decisions are postponed, farmers tend to adopt a conservative approach, reacting to uncertainty by planting crops with low irrigation requirements and lower profitability (e.g. sunflower). For the prevalent scenario in the Genil-Cabra irrigation scheme (communication in mid-March with a 400 mm water allocation), the model projects a potential loss of approximately EUR 9 000 (5 percent of TGM). This is relative to knowing the same water allocation level before February, emphasizing the economic repercussions of delayed decision-making in the face of water scarcity.

**FIGURE 10**
**Total gross margin losses in a 100 ha farm depending on communication date and amount of water allocation, under different crop price and climatic year scenarios**




*Source:* **García Vila, M. & Fereres, E.** 2012. Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at the farm level. *European Journal of Agronomy* 36(1): 21-31

While the extraction of decision rules is inherently intricate, the optimization model created using AquaCrop, coupled with a set of farmer's decision criteria, serves as a valuable tool for assessing the economic impacts of delaying information to farmers regarding water allocation levels by the water authority (with maximum losses reaching EUR 300 ha–1). These findings underscore the imperative to enhance the decision-making process by water authorities, aiming to achieve the desired objectives of effective water scarcity management without jeopardizing the sustainability of farming practices.


# 4. Operation and management decisions: irrigation scheduling under limiting and non-limiting conditions

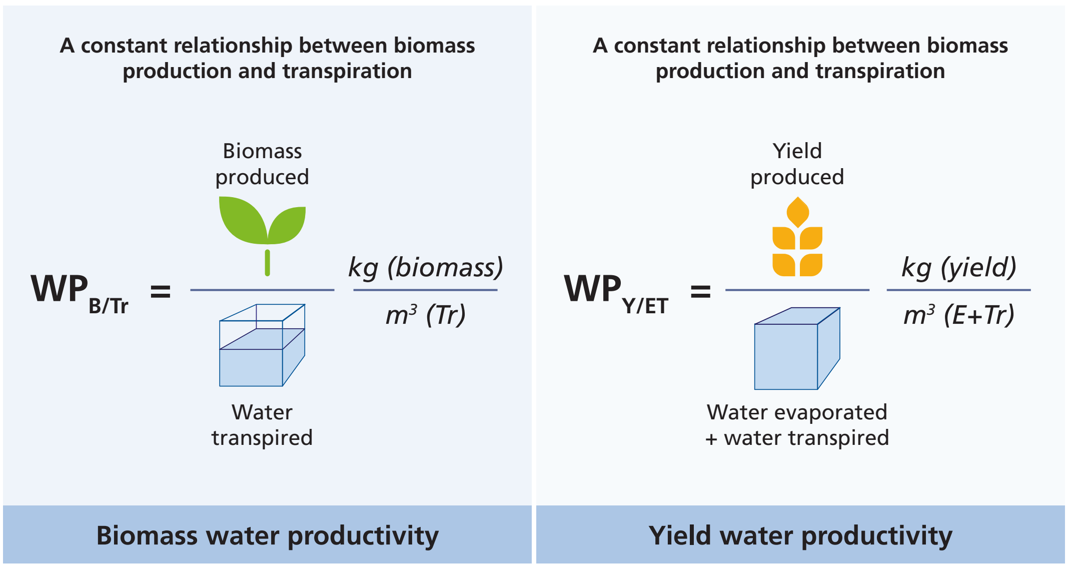
## 4.1. OVERVIEW OF SPECIFIC POTENTIAL APPLICATIONS

AquaCrop is very suitable for tackling problems of water scarcity and for assessing and developing irrigation strategies. Rather than using a solar-driven growth engine, AquaCrop differs from other crop models by using a water-driven growth engine that simulates crop production by means of the conservative relation ($WP_{B/TR}$) between biomass production and crop transpiration (water) (Steduto *et al.,* 2007). While most crop models have only one soil water stress level, AquaCrop uses three levels to consider the difference in sensitivity to water stress between canopy expansion, stomatal conductance, and the triggering of early senescence (Hsiao, 1973; Bradford and Hsiao, 1982). Additionally, the occurrence of water stress may alter the reference Harvest Index either positively or negatively depending on the timing, strength and duration of the simulated water stress (Steduto *et al.,* 2009; Raes *et al.,* 2009). These calculation procedures allow AquaCrop to simulate adequately the response of a crop to different water stress levels (Hsiao *et al.,* 2009; Heng *et al.,* 2009).

### 4.1.1. Biomass water productivity and yield water productivity

Water productivity (WP) expresses the trade-off between carbon assimilation (or subsequent carbon storage) and water release (Fatichi *et al.,* 2023). In AquaCrop, the distinction is made between biomass water productivity ($WP_{B/TR}$), which is the conservative ratio between dry above-ground biomass and the water lost by the plant through transpiration, and yield water productivity ($WP_{Y/ET}$) which is the ratio between crop yield and the water lost in the field by evapotranspiration (ET), as seen in Figure 11.

**FIGURE 11**
**Biomass water productivity ($WP_{B/Tr}$) versus yield water productivity ($WP_{Y/ET}$)**




*Source:* Authors' own elaboration.

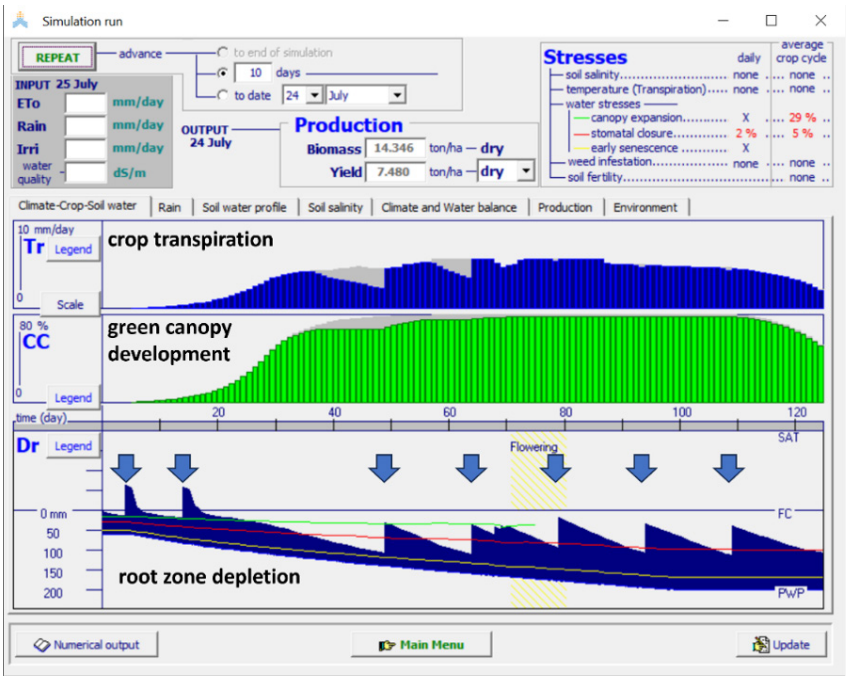
While for a particular crop, $WP_{B/TR}$ (normalized for climate) does not change materially with time and management practices, the value of $WP_{Y/ET}$ for the same crop is strongly affected by climate, irrigation and field management.

In a worldwide meta-analysis, Mbava *et al.* (2020) studied the main factors affecting the yield water productivity ($WP_{Y/ET}$) of main field crops, using data from 514 experiments around the world. The $WP_{Y/ET}$ differed significantly between crops, but climate and soil texture also had a significant impact on $WP_{Y/ET}$. Expressed in kg (yield)/m³ (ET), the $WP_{Y/ET}$, is a good performance indicator of a system. In an environment not quite suitable for crop production, it will be smaller than 0.5 kg/m³, which means that for every 1 000 litres of water consumed through crop evapotranspiration (ETc) process on the field, less than 0.5 kg of crop yield is produced. Typical ranges for $WP_{Y/ET}$ reported in the literature are 0.6–1.7 kg/m³ (wheat), 0.6–1.6 kg/m³ (rice), and 1.1–2.7 kg/m³ for maize (Zwart and Bastiaanssen, 2004).

### 4.1.2. Assessment of an existing irrigation schedule

Simulation results of AquaCrop are recorded in output files and can be retrieved in spreadsheet programs for processing and data analysis. In the graphical user interface of AquaCrop, the results are plotted in several graphs which are updated at the end of each daily time step (Figure 12). As such, the user can follow throughout the simulation run the effects of water stress on crop development and production. The user can switch between several displays presented in different folders. The opportunity to simulate in short time steps and switch between several folders is very practical if one wants to study the effect of a particular event on a specific parameter (Raes *et al.,* 2009).

**FIGURE 12**
**Display of simulation results in the AquaCrop simulation run menu with an indication of irrigation events (blue arrows)**




*Source:* https://www.fao.org/aquacrop/en/

The quality of an irrigation schedule and the corresponding crop response can be assessed by examining the results in the simulation run menu (Figure 12). The user can study the simulated and plotted root zone depletion (Dr), canopy development (CC), and crop transpiration (Tr). The simulated biomass, crop yield, and yield water productivity ($WP_{Y/ET}$) might also give valuable information about the quality of the schedule and ways it can be improved.

### 4.1.3. Determination of irrigation water requirement

By running simulations for several successive years, an option in AquaCrop allows the determination of the daily net irrigation water requirement in different years. With the help of frequency analysis, 10-day and seasonal net irrigation requirements can be obtained for different probabilities of exceedance. The results, once corrected for field application and conveyance efficiencies, are useful for designing irrigation systems and estimating irrigation water requirements in a given region. Table 4 gives an example of a 10-day gross irrigation requirement in the spring at the field inlet (80 percent application efficiency), and a seasonal requirement (60 percent efficiency above farm gate) for dry, normal and humid weather conditions in 21 years (1980–2000) for winter wheat sown in December in the region of Tunis (Tunisia) on sandy loam soil. The 20 percent, 50 percent and 80 percent probability of exceedance of water requirements are considered representative of dry, normal and humid weather conditions, respectively.

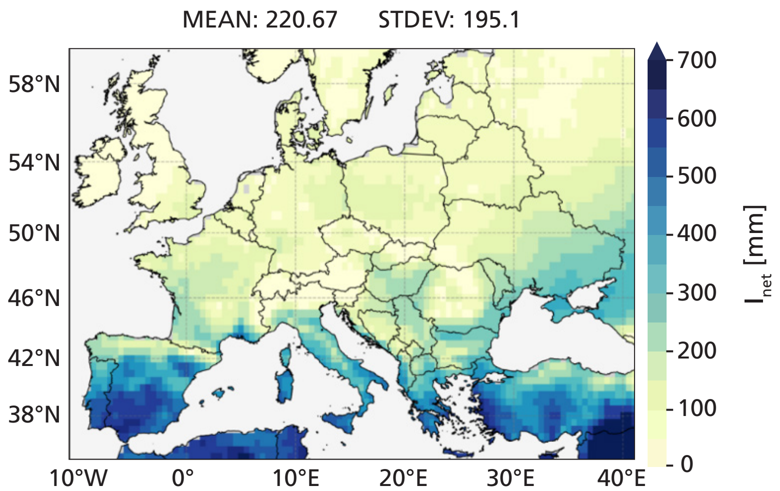
**TABLE 4**
**Example of irrigation water requirement determination in Tunisia**

| Month | March | | April | | | May | | Season |
|---|---|---|---|---|---|---|---|---|
| 10-day | 2 | 3 | 1 | 2 | 3 | 1 | 2 | Dec–May |
| **Gross irrigation requirement for various weather conditions** | | | | | | | | |
| Weather | $m^3$/10-day.ha | | | | | | | $m^3$/season.ha |
| Dry | 300 | 450 | 438 | 400 | 475 | 500 | 475 | 4 967 |
| Normal | 150 | 288 | 313 | 288 | 338 | 300 | 263 | 3 550 |
| Humid | 0 | 0 | 200 | 175 | 213 | 150 | 25 | 2 383 |

*Source:* Authors' own elaboration.

Using the spatial version of AquaCrop (de Roos *et al.*, 2021), Busschaert *et al.* (2022) determined the net irrigation requirement ($I_{net}$) in the 3-month summer period of June–August in the mainland of Europe by considering the crop water requirement of a well-developed generic crop, near-optimal field management, soil type and climate (Figure 13).

**FIGURE 13**
**Average 3-monthly net irrigation requirement ($I_{net}$) in summer for 30 years (1985–2014) in mainland Europe, determined by the spatial version of AquaCrop**




Notes: STDEV = standard deviation.
Refer to the disclaimer on page ii for the names and boundaries used in this map.

*Source:* **Busschaert, L., de Roos, S., Thiery, W., Raes, D. & De Lannoy, G. J. M.** 2022. Net irrigation requirement under different climate scenarios using AquaCrop over Europe, Hydrol. Earth Syst. Sci., 26, 3731–3752.

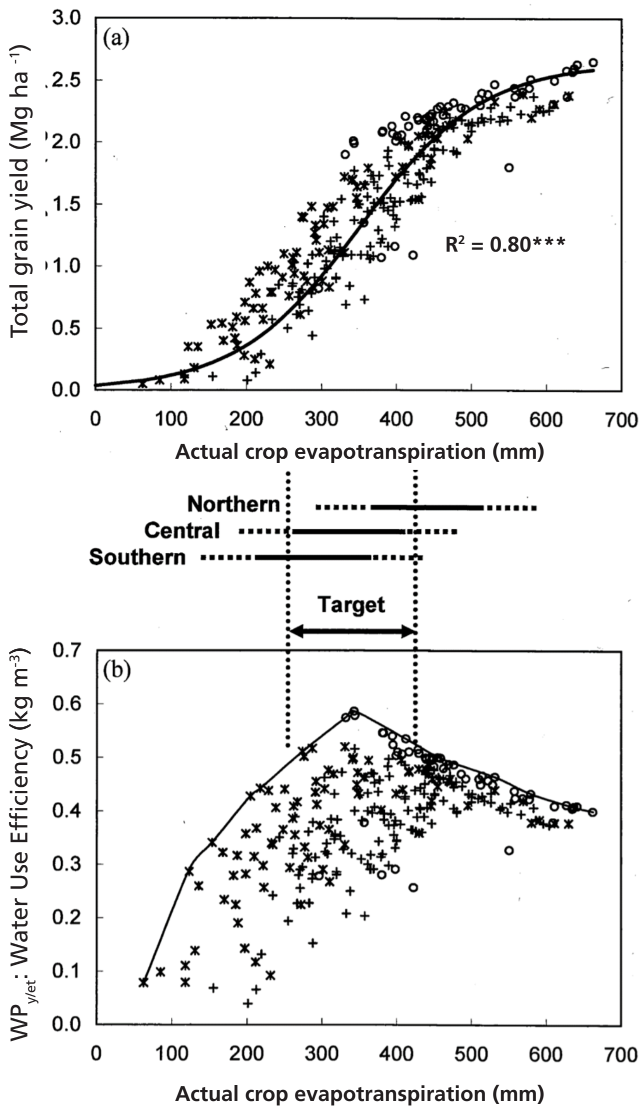
To assess changes in the mean and interannual variability of the irrigation demand, they compared in their study also the net irrigation requirement ($I_{net}$) for a near and far future climate period to the baseline period by using an ensemble of five general climate models (GCMs) and three different emission scenarios.

### 4.1.4. Irrigation scheduling under water limiting conditions

If water and other stresses do not limit crop development and growth, the maximum production can be reached when crop water requirements are completely met by rain and/or irrigation. Although the maximum production does not correspond with the maximum yield water productivity (Figure 14), achieving maximum production is most often the goal of irrigation applications when water is not limited.

**FIGURE 14**

**AquaCrop simulations of (a) grain yield and (b) yield water productivity ($WP_{Y/ET}$) for rainfed, fully irrigated and deficit irrigated quinoa in the northern (circle), central (plus sign), and southern Bolivian Altiplano**




*Source:* Adapted from **Geerts, S.** 2008. Deficit irrigation strategies via crop water productivity modeling: Field research of quinoa in the Bolivian Altiplano. Leuven, Belgium. KU Leuven University. Dissertationes de Agricultura (research) No. 814.

When water is restricted, limiting the irrigation applications to drought-sensitive growth stages (i.e. deficit irrigation) is often practiced as a valuable and sustainable production strategy. Deficit irrigation (DI) aims to maximize yield water productivity and to stabilize – rather than maximize – yields. By reviewing selected research from around the world, Geerts and Raes (2009) confirmed that for various crops, DI is successful in increasing yield water productivity ($WP_{Y/ET}$) without causing severe yield reductions. Geerts *et al.* (2008) derived from field experiments a promising DI strategy for quinoa in the central Bolivian Altiplano. This strategy consisted of mitigating drought only during plant establishment and during the reproductive stage (flowering and early grain filling).

Yield water productivity ($WP_{Y/ET}$) is typically used as an indicator to assess the performance of an irrigation strategy. Under conditions of water scarcity, the performance indicator is useful to identify the best strategy to maximize the yield per unit of water consumed on the field. Many irrigation strategies were assessed and/or developed with AquaCrop for various crops in different regions (see for example: García Vila and Fereres, 2012; Afshar and Neshat, 2013; Khoshravesh *et al.,* 2013; Xiangxiang *et al.,* 2013; Linker *et al.,* 2016; Nie *et al.,* 2021).

In addition to restrictions on total water use over a season, irrigation scheduling may also be influenced by intraseasonal restrictions on when or how much water can be applied. These could include regulatory and policy restrictions on timing or hydrologic conditions for which water abstractions for irrigation are legally permitted (Rio *et al.,* 2018). Alternatively, technological or hydrologic limitations may also influence abstraction rates and irrigation scheduling during the growing season. An example is presented in the case study of irrigated maize production in Bushland, Texas in the United States, in which AquaCrop has been used to assess the impacts of reductions in groundwater well yields due to aquifer depletion (Foster *et al.,* 2014; Foster *et al.,* 2015; Foster and Brozović, 2018), which influence farmers irrigation scheduling options and hence, their ability to meet crop water requirements and avoid yield losses in drought years.

### 4.1.5. Design of an irrigation schedule

Irrigation systems and schedules are mostly designed to cover the irrigation requirement during the peak period, when ETc is high and rainfall is scarce or absent. Outside this peak period, irrigation scheduling needs to be adjusted to the prevailing weather conditions and crop development. Because guidelines for scheduling are rarely available at their level, small farmers often follow a rather fixed irrigation calendar without adjustments to weather, crop development or environmental constraints, and are likely to over-irrigate during part of the season.

To provide farmers with some guidelines, Irrigation schedule charts can be developed with AquaCrop. The charts provide guidance for adjusting the irrigation interval to the actual weather conditions and water shortage. Irrigation charts should be developed in close cooperation with the extension service for a specific crop, planting date, climate, soil type, field management and irrigation method. An example of irrigation schedule charts is given in the case study of irrigated potatoes in Zimbabwe. The development consists of collecting:

- daily historical minimum–maximum air temperature and $ET_o$ data for 20–30 years (NASA, through its POWER project, makes worldwide meteorological data sets available);
- soil physical characteristics;
- crop parameters of the local cultivar and the crop planting date (for crops not yet calibrated for AquaCrop, indicative values of crop parameters of annual and perennial crops are available in FAO Irrigation and Drainage Paper No. 56 by Allen *et al.,* 1998); and
- field management (soil fertility management, presence of mulches, etc.)

The development should also study and discuss the ongoing irrigation practices (irrigation method, application dose and irrigation timing) with farmers, extension staff and irrigation managers.

### 4.1.6. Crop production and irrigation management under saline conditions

#### *Simulation of soil salinity stress in AquaCrop*

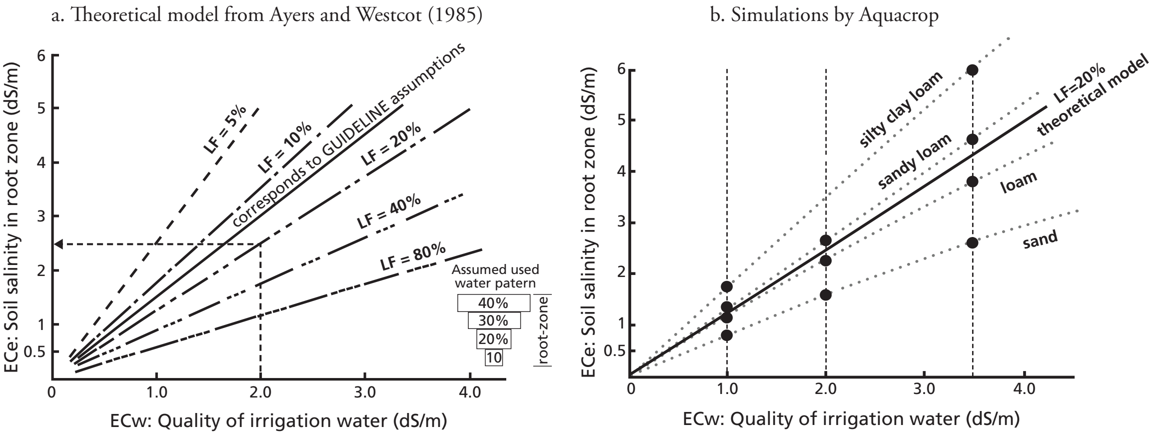
Salts enter the soil profile as solutes with the irrigation water or through capillary rise from a shallow saline groundwater table (often the result of poor irrigation management). The extent to which salts accumulate in the soil depends on the quality and quantity of irrigation water that infiltrate into the soil; the frequency of wetting; the adequacy of leaching by rainfall and/or overirrigation; the importance 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 leached out of the soil profile when the water content in the root zone exceeds field capacity due to excessive rainfall (often in the off-season) and/or overirrigation applications.

By keeping track of incoming and outgoing salt fluxes, AquaCrop simulates daily the salt content in the root zone (tonne/ha). The corresponding electrical conductivity of the saturated soil-paste extract (ECe) is used as the indicator for soil salinity stress. In AquaCrop, soil salinity stress decreases the canopy development and the conductivity of the stomata, resulting in a decline in crop transpiration, biomass production and crop yield. The salinity stress is crop-specific and is specified by two ECe thresholds (Ayers and Westcot, 1985; Allen *et al.,* 1998). Under optimum management conditions, crop yields remain at potential levels until a lower ECe threshold is reached. The more ECe in the root zone exceeds the lower ECe threshold, the stronger the drop in production. Once ECe exceeds the upper threshold, the stress becomes so severe that biomass production ceases.

#### *Leaching salts out of the root zone*

To prevent yield decline, salts must be leached from the root zone. The leaching fraction (LF) is the fraction of the water applied at the surface, which passes through the entire root zone and takes along a portion of the accumulated salts. Ayers and Westcot (1985) calculated the theoretical buildup of salts for different leaching fractions assuming a 40–30–20–10 percent root extraction pattern (Figure 15a). To evaluate the salt balance of AquaCrop, long-term irrigations were simulated with AquaCrop with different LF and quality of irrigation water. The results for medium textured soils (loam, sandy loam) correspond well with the theoretical model of Ayers and Westcot (Figure 15b).

**FIGURE 15**
**Effect of salinity of irrigation water (ECw) on soil salinity (ECe) in the root zone for (a) different leaching fractions (LF) according to the theoretical model, and (b) a leaching fraction of 20 percent for different soil types as simulated by AquaCrop**




*Source:* Authors' elaboration concerning **Ayers, R.S. & Westcot, D.W.** 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29. Rome.

AquaCrop simulates that in fine-textured soils (silty clay loam) and finds that more salts remain in the soil profile than in coarse-textured soils (sand) because it contains more cells that can store salts (cells are used to describe the movement and retention of salt in the soil profile). Whether the leaching of salts by winter rains is sufficient to maintain high crop yields is explored in a case study in the region of Tunis (Tunisia). In the case study, simulations were done for an irrigated crop on uniform loamy soil. The crop was moderately sensitive to salinity stress (such as squash, peppers, lettuce, potato, maize, cabbage, spinach, radishes, cucumber, broccoli, tomato, alfalfa, cauliflower, berseem) with an upper ECe threshold of 2 dS/m (below which the crop yields remain at potential levels), and a lower threshold of 12 dS/m where biomass production ceases.

### *Crop production under saline conditions*

Several simulations of crop production under saline conditions are reported in the literature. AquaCrop was used to simulate, for example, crop response to salinity for winter wheat in the North China Plain (Zhai *et al.,* 2022), rice in Bangladesh (Mondal *et al.,* 2015), and wheat in the Islamic Republic of Iran (Mohammadi *et al.,* 2016) and India (Kumar *et al.,* 2014). The varying degrees of success might be due to the absence of proper calibration of the yield response to salinity in those studies (only available from v6 and higher). Since the simulation of the effects of soil salinity on canopy development and crop production is largely untested, AquaCrop should still be used with caution for these applications.

## 4.2. CASE STUDIES

### *Deficit irrigation of quinoa in the Bolivian Altiplano*

The case study describes how deficit irrigation guidelines for quinoa (Chenopodium quinoa Willd.) were developed for extension services and farmers in the Bolivian Altiplano with the help of AquaCrop, after a calibration of the model. Quinoa is a grain-producing crop that grows in The Plurinational State of Bolivia at high altitudes (4 000 masl) in harsh conditions (high radiation, large temperature variation) and on poor soils with low inputs. Under rainfed conditions, the grain yield is low and unstable. With irrigation, the yield can be stabilized and increased. However, given the water shortage in the region, full irrigation is not a sustainable option.

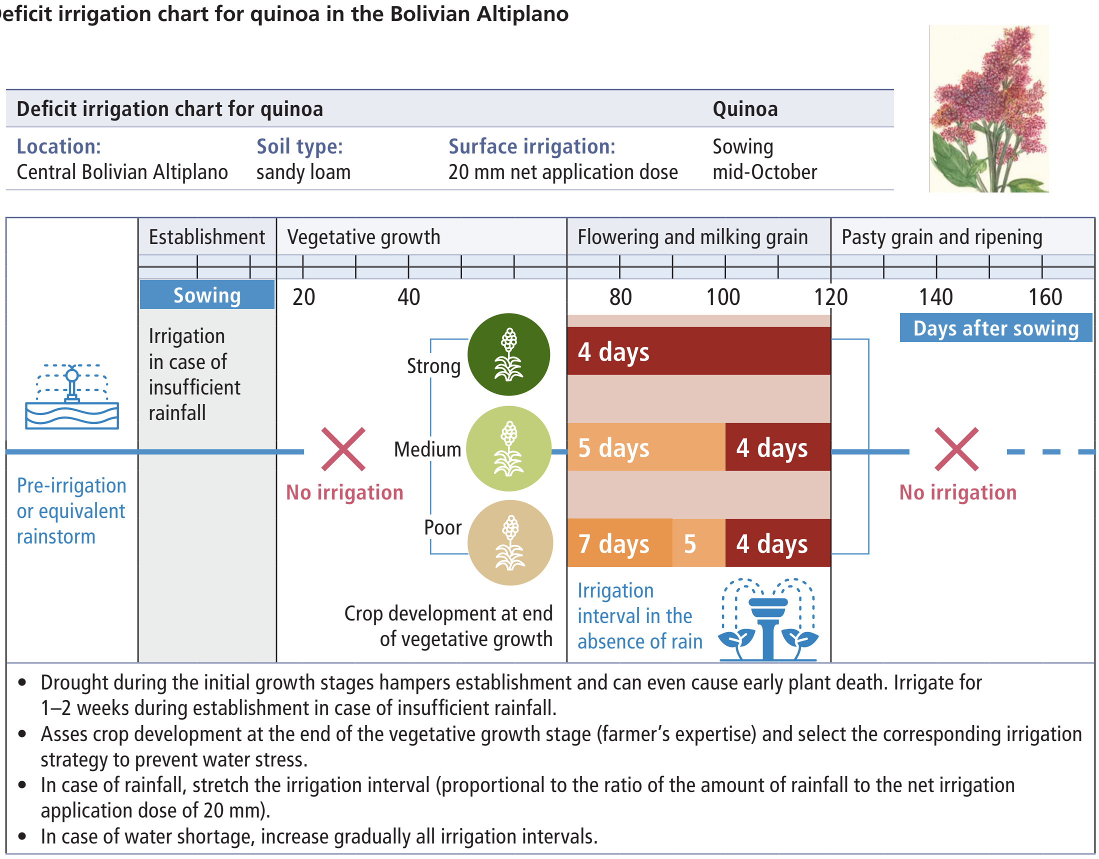
To calibrate AquaCrop for quinoa, field experiments were conducted for 3 years in the Bolivian Altiplano to assess the crop response to water stress under rainfed and irrigation conditions (Geerts *et al.,* 2009). Subsequently, the model was validated for different locations and cultivars using data from other experimental fields and farmers' fields.

A deficit irrigation strategy for quinoa was developed with the calibrated AquaCrop model by restricting irrigation to the sensitive growth stages: (i) establishment, (ii) flowering, and (iii) early grain-filling stage. The development consisted of the following steps (Geerts *et al.,* 2010):

1. Simulation of the dry-above-ground biomass (B) for a long series of historical data (20 years) in a rainfed scenario by considering local soil physical and management conditions and a typical sowing date (mid-October). To guarantee good germination and establishment of quinoa, a pre-irrigation of 20 mm was considered in the absence of sufficient rainfall.
2. Determination of a representative wet, normal, and dry year by evaluating for each year the simulated dry-above-ground biomass (B) at the end of the vegetative growth stage. B is considered a good indicator of the degree of crop development at that moment. The 20 percent, 50 percent and 80 percent probabilities of exceedance of B were determined with a frequency analysis, and representative years were then selected by considering 20 percent probability of exceedance as representative for a wet year, 50 percent for a normal year, and 80 percent for a dry year.

3. Generation of irrigation schedules for the three selected years by considering irrigation applications only during the sensitive stages to water stress (from flowering until the end of the milky grain stage). In the simulations, no rainfall was assumed during these stages, and a (net) irrigation application dose of 20 mm was applied each time the simulated soil water depletion in the root zone started to induce stomatal closure.
4. Simplification of the generated schedules with varying irrigation intervals during the sensitive growth stages and translating them into an easily readable irrigation chart (Figure 16).

**FIGURE 16**
**Deficit irrigation chart for quinoa in the Bolivian Altiplano**




*Source:* Adapted from **Geerts, S., Raes, D. & Garcia, M.** 2010. Using AquaCrop to derive deficit irrigation schedules. *Agricultural Water Management* 98(1), 213-216.

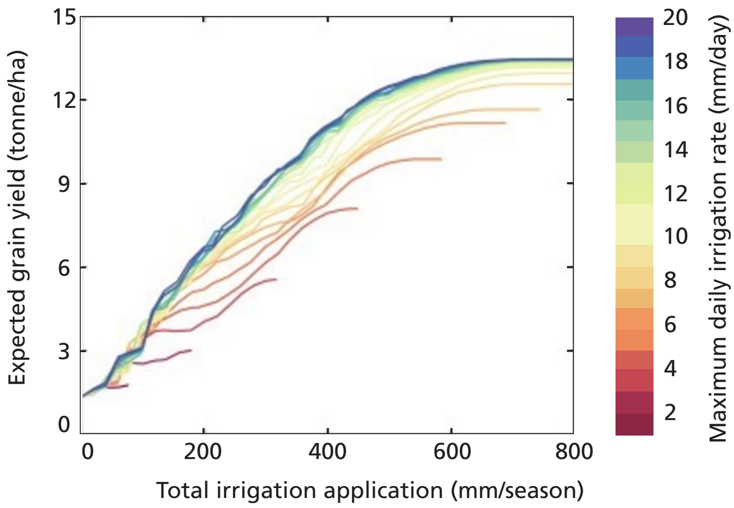
### *Impacts of declining groundwater pumping capacity on sustainable crop production*

The case study discusses the application of AquaCrop to assess the impacts of declining groundwater pumping capacity on crop production. Declining pumping capacity is a common consequence of aquifer depletion in regions with unsustainable levels of groundwater abstraction (Foster *et al.*, 2015). Pumping capacity affects farmers' irrigation scheduling by altering the maximum depth of water that can be applied per unit of irrigated area per day. As pumping capacity is lowered, it becomes increasingly difficult for a farmer to schedule irrigation to meet crop water requirements, especially at the peak of the growing season.

AquaCrop was set up for irrigated maize production in Bushland, Texas in the United States (Foster and Brozović, 2018) following a better calibration done on the model by Hsiao *et al.* (2009) and Heng *et al.* (2009). This area overlies the High Plains Aquifer, one of the world's most important areas of groundwater irrigation that has experienced significant depletion over the past 50–80 years due to overabstraction for irrigation. The soil type was assumed to be clay loam. The model was run for 30 years of historic weather data (1987–2016), assuming a planting date each year of 1 May consistent with local agronomic practices by farmers in the Texas High Plains. Simulations were repeated for different soil moisture triggers and irrigation application rates. Varying the irrigation application rate between 1 mm/day and 20 mm/day mimics the constraints imposed by different levels of groundwater pumping capacities, ranging from 500 m3/day to 10 000 m3/day, assuming a typical model irrigated field size of 50 ha in this region.

Figure 17 shows the simulated relationship between average total seasonal irrigation, assuming an optimized irrigation distribution between growth stages, and irrigated maize yields for different values of the maximum daily irrigation rate (Foster and Brozović, 2018). Two impacts of reducing groundwater pumping capacity are shown. First, the maximum attainable crop yield is reduced as the lower daily irrigation rates cap total seasonal irrigation to levels below crop water requirements particularly in drought years. Second, the crop yield achieved for a specific total seasonal depth of irrigation is reduced for lower daily application rates because this constraint limits farmers' ability to optimize irrigation scheduling according to crop water requirements. This second effect forces farmers to reduce or abandon irrigated areas in regions such as the southern High Plains where chronic aquifer depletion occurs, with significant negative impacts on rural economies and wider regional and global food supply chains (Foster *et al.,* 2017; Deines *et al.,* 2020; Jain *et al.,* 2021)

**FIGURE 17**
**Simulated relationship between average total seasonal irrigation and average crop yield over a 30-year historical period for maize grown in Bushland, Texas, United States of America**




*Source:* Adapted from **Foster, T. & Brozović, N.** 2018. Simulating crop-water production functions using crop growth models to support water policy assessments. *Ecological Economics*, 152, 9-21.

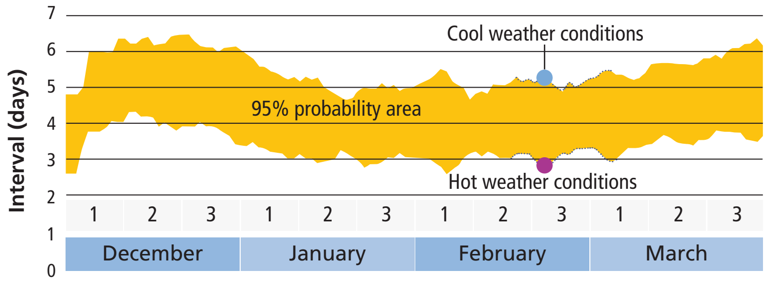
## *Irrigation schedule charts*

Irrigation systems and schedules are mostly designed to cover the irrigation requirement during the peak period, when ETc is high and rainfall is scarce or absent. Outside this peak period, irrigation scheduling needs to be adjusted to the prevailing weather conditions and crop development. Since at their level, guidelines for scheduling are rarely available, small farmers often follow a rather fixed irrigation calendar without adjustments to weather, crop development or environmental constraints and are likely to overirrigate during part of the season.

To assist farmers, irrigation schedule charts are created using AquaCrop. These charts offer guidance for adjusting irrigation intervals based on current weather conditions and water availability. The charts should be developed in collaboration with extension services, tailored to the specific (i) crop, (ii) planting date, (iii) climate, (iv) soil type, (v) field management practices, and (vi) irrigation method. For details on the development process, refer to Section 4.1.5.

By running AquaCrop without considering rainfall, irrigation intervals throughout the growing cycle are obtained for each year. In this example of Rusape in Zimbabwe, (i) a fixed irrigation application dose was selected based on local practices, soil and crop type, irrigation method and equipment, and (ii) irrigations were generated when 80 percent of the readily available water (RAW) was depleted from the root zone. The required variation of the irrigation interval throughout the growing cycle and for different weather conditions becomes evident by plotting the "average +/- k times the standard deviation" of the generated irrigation intervals (Figure 18). The magnitude of "k" determines the probability area.

**FIGURE 18**
**Irrigation intervals over the crop growth cycle in the absence of rainfall for the case of Rusape in Zimbabwe**




The 95 percent probability area (average +/- 1.96 standard deviation) of the generated 29-year irrigation intervals over the crop growth cycle, in the absence of rainfall

**Rusape (Zimbabwe)**

Potato planted on 1 December

**Simulation runs:** 29 years (1970–1999)

Clay loam soil

Optimal field management

**Sprinkler irrigation:**
- fixed net dose: 19 mm (gross application dose of 25 mm)
- timing: 80 percent RAW depletion

**Initial soil water content:** 50 percent TAW

*Source:* Authors' own elaboration.

The obtained indicative values for irrigation intervals are presented for each decade (10-day period) of the growing period in a table on a coloured irrigation chart for three weather conditions: normal, warm and cool, corresponding to the average and average +/- 1.96 standard deviation, covering 95 percent probability of occurrence (Figure 19).

**FIGURE 19**
**Irrigation guidelines for potatoes for the Rusape region in Zimbabwe**

**Irrigation guidelines for potatoes for the Rusape region (Zimbabwe)**

**Sprinkler irrigation** (75% field application efficiency)
**Gross irrigation application dose:** 25 mm
**Soil type:** Clay loam

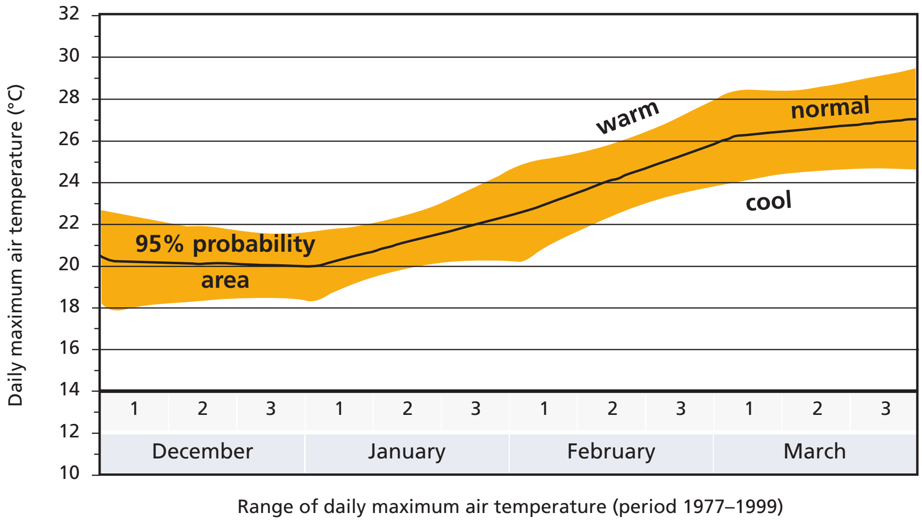
**Planting:** begins December
**Harvesting:** ends March

Irrigation interval given in days (in absence of rainfall)

| | December | | | January | | | February | | | March | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Warm | 3 | 4 | | | 3 days | | | | | | 4 | |
| Normal | 4 | 5 | | | 4 days | | | | | | 5 | |
| Cool | 5 | 6 | | | 5 days | | | | | | 6 | |
| Growing stage | Germination | Vegetative development | | | Yield formation | | | | | | Ripening | |
| Sensitivity to water stress | Very | Moderate sensitive | | | Very sensitive | | | | Sensitive | | Not | |

- The crop is extremely sensitive to water stress during establishment.
- During the early vegetative stage, the crop is moderately sensitive to water-stess and furthermore, root development is encouraged by a limited water supply.
- Water deficit during tuber initiation and yield formation have great adverse effect on yield.
- During ripening, less water is required.

By 19 mm (or more) rain, skip one irrigation event. In case of light rainfall, stretch the irrigation interval (proportional to the ratio of the amount of rainfall to the net application dose of 19 mm).




*Source:* Authors' own elaboration.

The irrigation interval that should be selected at a particular moment of the growing period is a function of the weather conditions at that moment. The 95 percent range of the daily maximum air temperatures, plotted on the irrigation chart, indicates the maximum air temperature that can be expected on a warm, normal and cool day, and helps the farmer select the correct irrigation interval for the current weather condition.
Information concerning the sensitivity of the crop to water stress is also presented. In case of water shortage, this information can help the farmer increase the irrigation interval during the periods when the crop is not sensitive to water stress. Information on the sensitivity of the crop to water stress is provided in FAO Irrigation and Drainage papers No. 33 and No. 66.

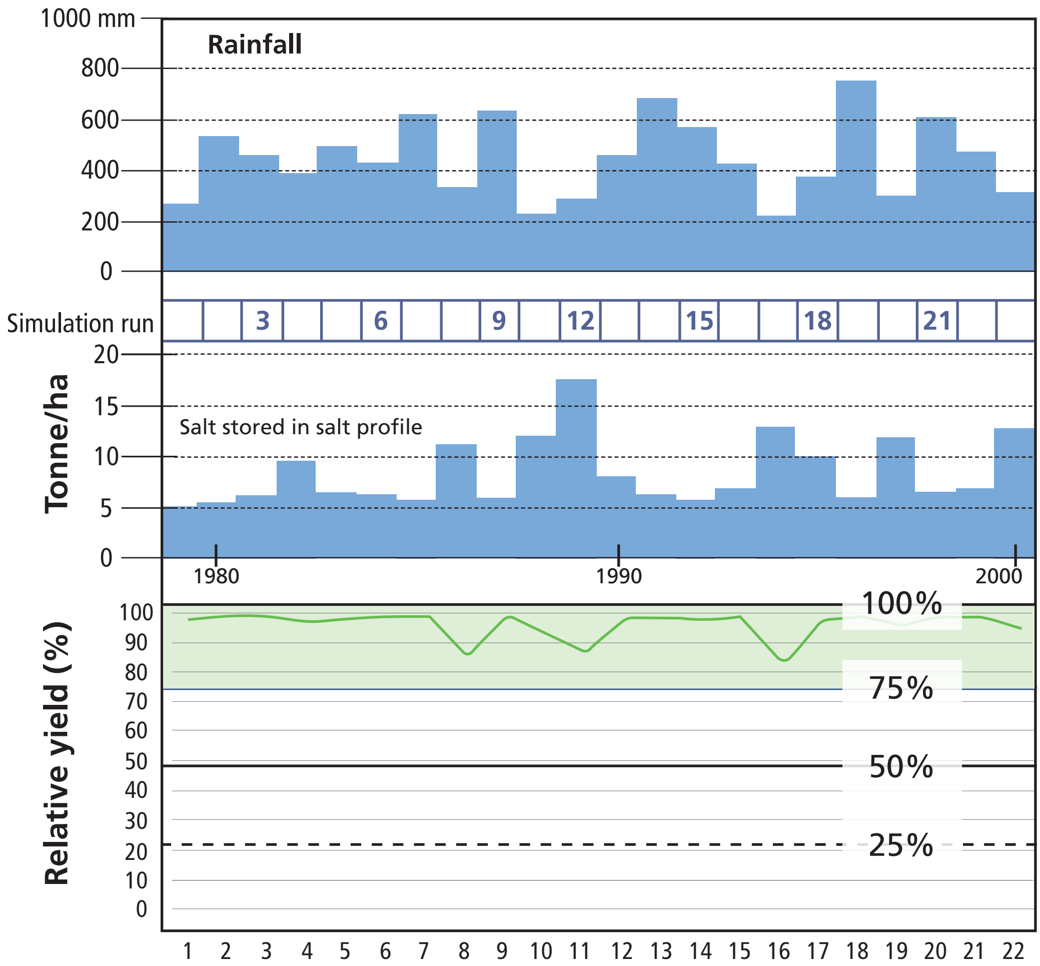
### *Is the leaching of salts by winter rains sufficient to maintain top crop yields?*

In this case study, simulations were run for an irrigated crop in the region of Tunis (Tunisia) on uniform loamy soil. The crop was moderately sensitive to salinity stress (such as squash, peppers, lettuce, potato, maize, cabbage, spinach, radishes, cucumber, broccoli, tomato, alfalfa, cauliflower, berseem) with an upper ECe threshold of 2 dS/m (below which the crop yields remain at potential levels), and a lower threshold of 12 dS/m where biomass production ceases.

The crop was planted on 1 May and was cultivated during the summer period with little to no rain (1 May – 31 August). The crop was irrigated with water of moderate quality (1.5 dS/m) without provoking leaching. A net irrigation application dose of 40 mm was applied, and each time 100 percent of the Readily Available soil Water (RAW) was depleted.

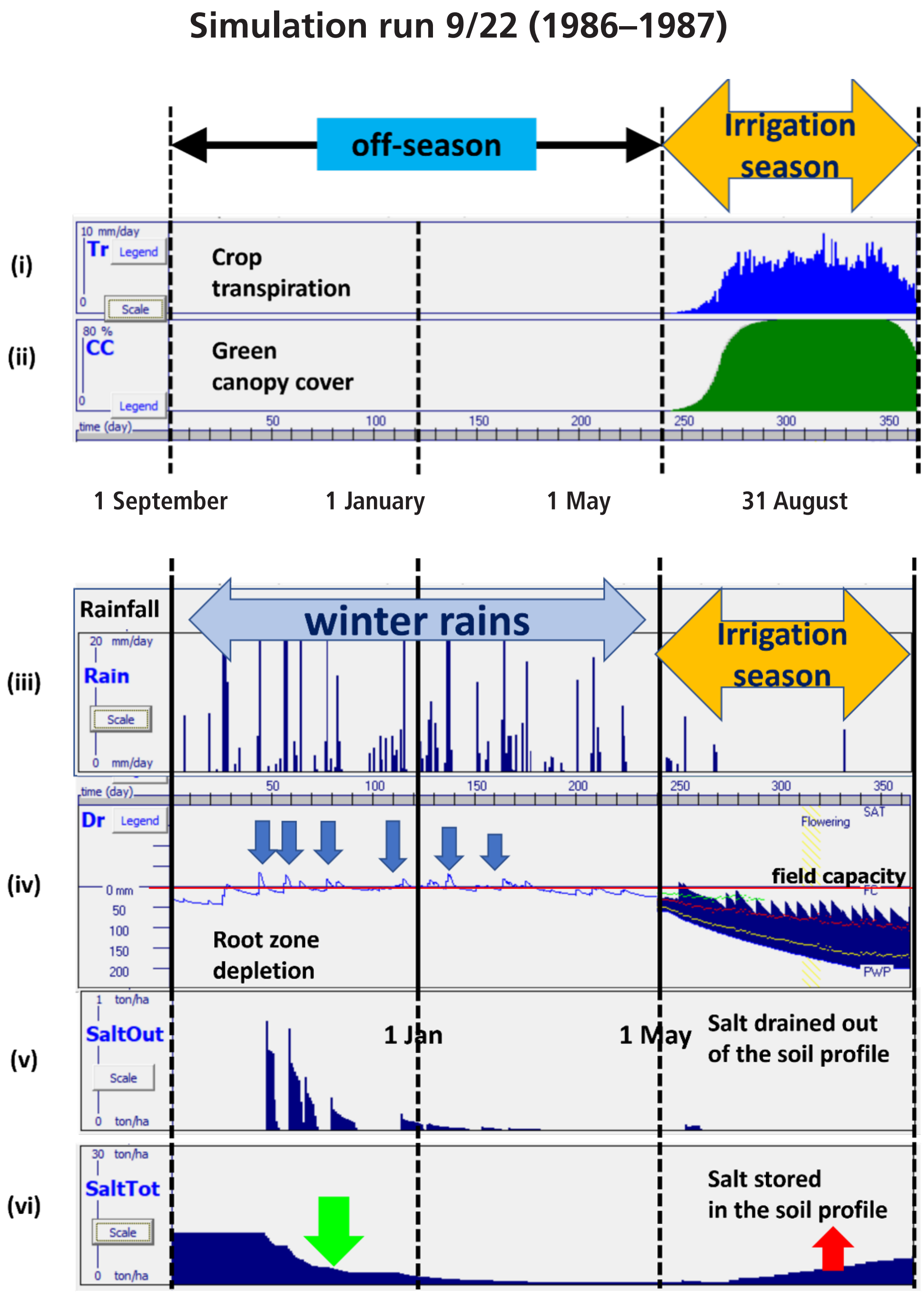
To study the building up of salts during the irrigation season and the leaching of salts by winter rains in the off-season, successive simulations were run for 22 years (1979–2000) with historical weather data. The soil water and salt content at the end of each run (31 August) were the initial conditions for the next run (1 September). The simulation results indicate that the winter rains are sufficient to keep the soil salinity in the root zone under control and that the drop in crop production remains below 25 percent.

**FIGURE 20**
**Total rainfall (mm), amount of salts (tonne/ha) stored in the root zone at the end of the irrigation season (31 August), and the relative yield of a crop moderately sensitive to salinity stress in 22 years (1979–2000) in the case study of Tunisia**




*Source:* Authors' own elaboration.

**FIGURE 21**
**Results of a simulation run 9 out of 22 (1 September 1986–31 August 1987) for the case study of Tunisia with an indication from top to bottom of the (i) simulated crop transpiration (Tr), (ii) development of the green canopy cover (CC), (iii) observed daily rainfall (Rain), (iv) root zone depletion (Dr), (v) amount of salts (tonne/ha) drained out of the soil profile (SaltOut), and (vi) fluctuation of the amount of salts (tonne/ha) stored in the soil profile (SaltTot) as displayed in the simulation run menu of AquaCrop.**




*Source:* Authors' own elaboration.


# 5. Agronomic management applications for enhancing crop water productivity

## 5.1. OVERVIEW OF SPECIFIC POTENTIAL APPLICATIONS

Different models have been used to assist in making agronomic decisions for some time. Their value consists in sparing farmers and decision-makers the lengthy and expensive field experimentation needed to explore diverse options and focus on a few alternatives that can then be considered to make a final decision. Decisions may be operational, such as setting the date of an irrigation application; tactical, such as determining the optimal planting date; or strategic, such as planning a multiyear crop sequence. AquaCrop, through simulation, is one of the models that can assist in making agronomic decisions.

### 5.1.1. Crop and cultivar choices for a changing climate

At the farm scale, decision-making starts with the selection of the crop(s) that would be planted. This decision is based on a myriad of factors, with economic and sociocultural dimensions having priority over technical and regulatory aspects related to crop choice. Models have limited scope in assisting decision-making at this point, but they can help in assessing the feasibility of new crops in an area and in exploring how to cope with a changing climate by comparing the performance of different crops in different future climate scenarios, an application that permits the assessment of climate change impacts on crop choices. For instance, in cold climates, crops that do not perform well at present due to cold damage may be viable in a future warming climate, and crop models can predict such viability by simulating a sequence of years for the future climate in a given location.

Once a decision is made on the crop selection, the cultivar(s) choice must follow. Models can assist in such selection which primarily focuses on season length. Early cultivars have generally less yield potential than late cultivars as crop growing season is also shorter. However, an early cultivar may fit better the planned crop sequence and give less opportunity to pests and accidents such as hail. In rainfed conditions, early cultivars may escape drought while late cultivars, which would have higher yields in good rainy years, will suffer more the impact of drought. By simulating a sequence of 20–30 years with cultivars of different season lengths, it is possible to develop yield probability curves that would help management decide the most appropriate cultivar for its set of conditions. To do this, the availability of reliable climatic data is essential, and the user must pay attention to the quality and representativeness of the data. For instance, it is desirable to use a dataset that covers the last 20–30 years rather than a historical series from decades earlier.

### 5.1.2. Planting date optimization

Planting date selection also has to do primarily with crop duration. In winter cereals, a compromise must be found between the risks of late spring frosts and terminal drought. If the crop is planted too early, frost damage at flowering may occur. But if it is planted late, grain-filling processes occur during the hot dry periods of early summer, and yields are greatly reduced. Thus, a simulation of a series of 20–30 years with the chosen cultivar at different planting dates would generate yield probability curves from which to select the optimal planting date over the years.

### 5.1.3. Planting density

Planting density determines the rate of canopy development and hence, the radiation interception and transpiration. Models such as AquaCrop delineate the trend in canopy development based on the initial planting density which, together with the canopy growth rate, determines the canopy size. A number of studies have determined the yield response to density and have shown that it is asymptotic, which is a response that is also simulated by AquaCrop. AquaCrop could also be used to assess the impact of changing planting density outside the recommended rate, but for most annual crops, optimal commercial densities have already been established and unless very low densities are proposed, the anticipated simulated response would be small.

### 5.1.4. Weed management

Weeds compete with crop plants for resources, primarily light above ground and water and nutrients below ground. While there is insufficient information to characterize all the interactions between weeds and crop plants, models have adopted simplified approaches to quantify the negative impact of a weed infestation on yield. AquaCrop apportions the growth of the canopy to both weeds and the crop. The severity of the weed infestation is thus assessed, and AquaCrop is used to calculate the impact on crop transpiration (Tr) due to weed water uptake. The T reduction is then computed to assess the impact on the final yield. The weed module has several options depending on the anticipated time trends of the weed infestation. The model is useful for a preliminary assessment of the impact of weed management at different times.

### 5.1.5. Soil–root interactions

Farmers have knowledge of soil properties related to fertility and water storage capacity but know less about what is going on below ground in terms of root system activity and exploration. AquaCrop requires inputs on soil water characteristics and rooting depth. Sensitivity analyses may be performed to evaluate the impact on yield of different soil water properties (field capacity, hydraulic conductivity) and of different rooting depths and speed of root penetration. In rainfed systems, such assessment is important to evaluate the need and potential impact of deep tillage.

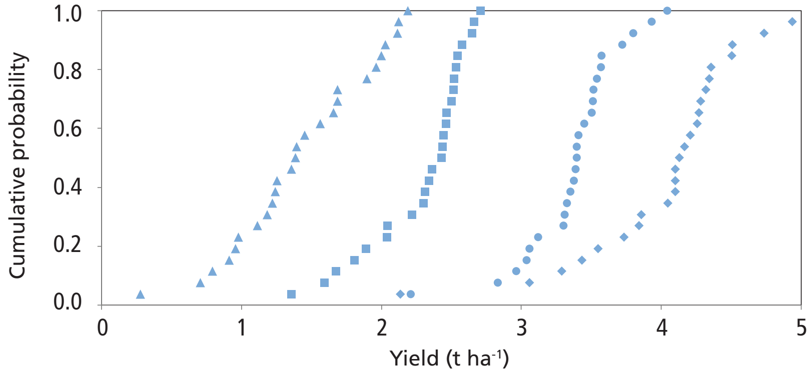
Another model application related to soil management is the assessment of the benefits of using mulches. Mulches delay and may reduce the rate of evaporation (E) from soil resulting in an improved crop water balance. AquaCrop simulates the change in soil evaporation (E) affected by the presence of a mulch and can predict the shift in the E/Tr balance and its impact on yield.

### 5.1.6. Fertility management

AquaCrop has a simplified procedure to simulate fertility levels. The normal simulations assume no nutrient limitations as the simulation target is the water-limited yield. When soil fertility limits yields, a fertility routine can be used to simulate the impact of less-than-optimal soil fertility. There are many situations in developing countries where the primary yield constraint is the availability of soil nutrient.

Figure 22 presents the results of simulating four rainfed sunflower production scenarios for 25 years (1980–2006) in Cordoba, Spain, a location of Mediterranean climate with 600 mm average annual rainfall. The cumulative probability of yield is shown first for sunflowers planted in spring (15 March, triangles), the conventional planting date, with limited soil fertility. In this case, the simulated yield of about 1.5 tonne/ha corresponds to a 50 percent probability. The squares represent the simulated yields of the same crop planted in winter (15 January) where yields are higher, about 2.4 tonnes/ha at 50 percent probability. The early plantings are combined in the simulation of a third scenario with genetic improvement – the ability to grow at low temperatures – and the results are shown as circles in Figure 22. By growing more at low temperatures and planting early, simulated yields are improved to about 3.3 tonnes/ha at 50 percent probability. All three scenarios have been simulated with low fertility levels, which is the characteristic of rainfed production in that area. However, if the simulations are conducted at optimal fertility (diamonds in Figure 22), yields increase to about 4.2 tonnes/ha at 50 percent probability. Thus, combining three agronomic measures – change in planting date, genetic improvement and soil fertility improvement – can lead to yield improvement (an increase of 280 percent over conventional agronomic management). While these advances are theoretical, the simulations paved the way for making rational recommendations that would facilitate better agronomic management.

**FIGURE 22**
**Cumulative probability of yield exceedance for sunflower simulated in Cordoba, Spain, under four different scenarios**

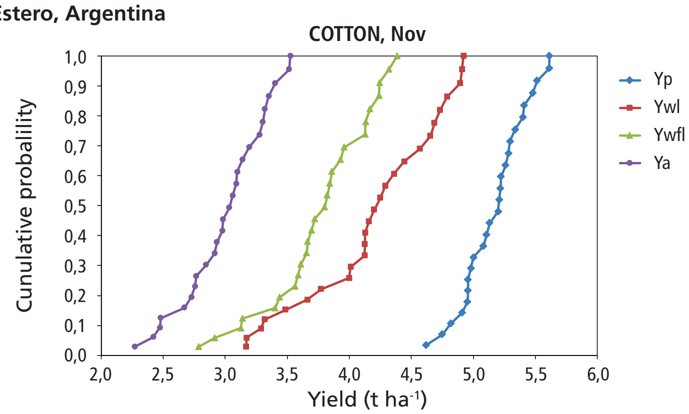



*Source:* Adapted from **Fereres, E., Orgaz, F., Gonzalez-Dugo, V., Testi, L. & Villalobos, F.J.** 2014. Balancing crop yield and water productivity tradeoffs in herbaceous and woody crops. *Functional Plant Biology.* 41, 1009–1018.

## 5.1.7. Irrigation management

The AquaCrop model can be used for multiple objectives related to on-farm irrigation management. Figure 23 shows the results of 30-year simulations of four scenarios on how the water delivery constraints in an irrigation system can affect cotton yield in Santiago del Estero, Argentina. The blue diamonds represent the simulation of yield potential (Yp) without any water or fertility limitations, giving about 5.2 tonnes/ha of yield at 50 percent probability. The irrigation district delivers water once a month, and farmers irrigate twice during the crop cycle, given the common summer precipitation. The purple circles represent the yields for the farmer's practices (Ya) with a yield of about 3.0 tonnes/ha at 50 percent probability. Given the edapho-climatic conditions, a maximum of three irrigation applications is possible (Angella *et al.,* 2016). This is simulated by the green triangles (Ywfl) that show an increase in yield, with about 3.7 tonnes/ha at 50 percent probability. Both scenarios were simulated with limited soil fertility while the third scenario (red squares; Ywl) has optimal soil fertility and gives an improved yield of about 4.3 tonnes/ha at 50 percent probability. The differences among the three scenarios, compared to that of optimal water and fertility supply, are caused by the rigidity of the delivery system that has a rotational delivery of once a month. To realize some of the simulated yield gains, farmers could be encouraged to create on-farm storage facilities to be able to schedule irrigations on demand.

**FIGURE 23**
**Cumulative probability of simulated yields of four different scenarios of irrigated cotton production in Santiago del Estero, Argentina**



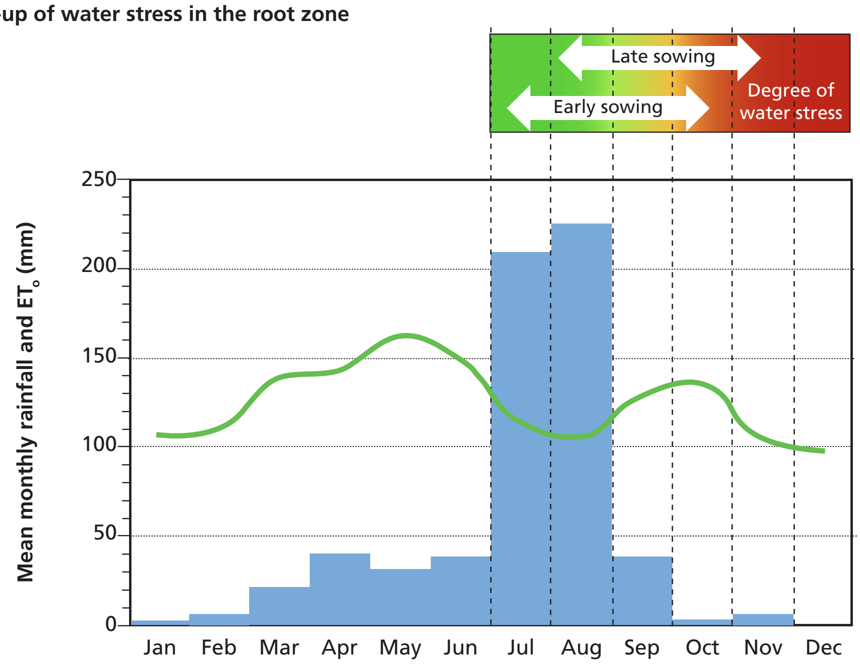

*Source:* Adapted from **Angella, G., García Vila, M.,López, J.M., Barraza, G., Salgado, R., Prieto Angueira, S., Tomsic, P. & Fereres, E.** 2016. Quantifying yield and water productivity gaps in an irrigation district under rotational delivery schedule. *Irrigation Science.* 34, 71–83.

## 5.2. CASE STUDIES

### *Improving water productivity of Teff in Tigray, Ethiopia*

The case study describes how the grain yield and water productivity of rainfed Teff (*Eragrostis tef* (Zucc.) Trotter) in the Tigray Highlands in Northern Ethiopia can be improved by early planting and an irrigation application during the reproductive growth stage (Tsegay *et al.*, 2015). Teff, an indigenous crop in the Horn of Africa, is one of the most important cereals in Ethiopia. It is an annual grass with very tiny seeds and a shallow but dense root system. At various locations in Tigray, Northern Ethiopia, field experiments were conducted from 2006 to 2009 to calibrate and validate AquaCrop for Teff (Tsegay *et al.*, 2012). The local cultivar, for which AquaCrop was calibrated, has a growing cycle of 100 days and a potential grain yield of about 2 tonnes per hectare.

**FIGURE 24**
**Mean monthly rainfall and reference evapotranspiration for Teff in Mekelle (Northern Ethiopia), with an indication of the growing period for late and early sowing, and a schematic representation of the building-up of water stress in the root zone**



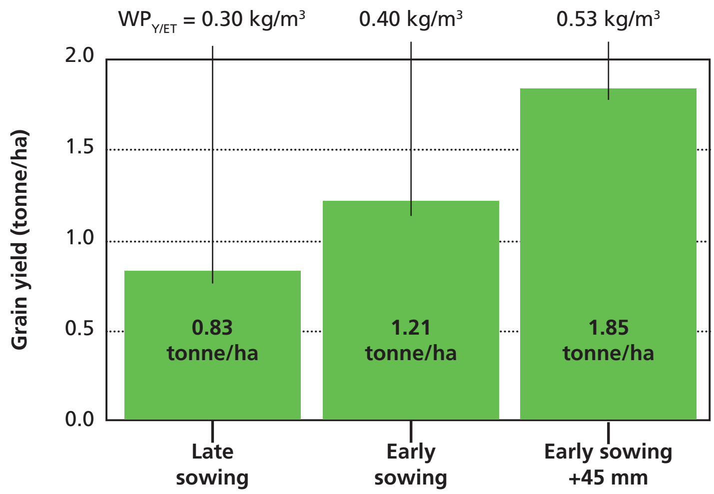

*Source:* Adapted from **Tsegay, A., Vanuytrecht, E., Abrha, B., Deckers, J., Gebrehiwot, K. & Raes, D.** 2015. Sowing and irrigation strategies for improving rainfed tef (Eragrostis tef (Zucc.) Trotter) production in the water-scarce Tigray region, Ethiopia. *Agricultural Water Management* 150, 81-91.

Although the annual rainfall in the Tigray Highlands in Northern Ethiopia is relatively important, rainfed agriculture is strongly affected by water stress due to the concentration of 65 percent of annual rainfall in two months (July and August). Notwithstanding the abundant rainfall in July, Teff is planted rather late, since farmers prefer to let weeds emerge from their seed banks and develop with the first rains in July. After the removal of the weeds by ploughing, Teff is sown in August.

Scenario analysis with AquaCrop showed that by sowing 2 to 3 weeks before 1 August, the mean yield could be increased by 50 percent and the mean ET water productivity ($WP_{ET}$) could be improved by one-third. In the simulations, the second occurrence of 40 mm rain in 4 successive days after 1 July was selected to generate appropriate sowing dates. The second occurrence of the rainfall criterion reduces the risk of a false start of the rainy season and ensures the germination and survival of the young seedlings. The rationale of early sowing is to reduce severe water stress during the second half of the growing cycle (reproductive growth stage). However, since weeds can no longer be removed by ploughing, early sowing requires manual weeding. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has formulated guidelines and provided support for sowing Teff in rows instead of the traditional broadcast method, as the row-sowing technique facilitates weed control.

Because rainfall is abundant in July and August, much water is lost from the fields as runoff during this period. Thanks to the support of the food for work programmes of the United Nations, many small field ponds have been constructed in the highlands to harvest rainwater in July and August. The stored amount of water is insufficient to fully irrigate crops when the rain ends but can be used to water Teff during the reproductive growth stage to reduce water stress. Simulations show that by applying a single irrigation event of 45 mm at the end of the main rainy season, the yield and ET water productivity ($WP_{ET}$) can drastically be improved in the region (Figure 25).

**FIGURE 25**
**Simulated grain yield and yield water productivity ($WP_{Y/ET}$) in the Tigray Highlands in Northern Ethiopia for rainfed Teff (i) sown late (1 August), (ii) sown early (early/mid-July), and (iii) with a one-time irrigation application of 45 mm during the reproductive growth stage**




*Source:* Elaborated from **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.

## *Enhancing water productivity of maize and onion in Uganda*

Improving irrigation practices in Uganda is vital for enhancing food security and the income of farmers. The imperative now is to shift the focus towards refining irrigation management, ensuring that the full spectrum of benefits it can offer to farmers and society at large is harnessed. A crucial metric in this context is water productivity (WP), which gauges the efficiency of water use by measuring the yield or benefits derived per unit of water utilized.

In Uganda, the untapped potential of irrigation remains substantial, presenting numerous opportunities to elevate on-farm water productivity. Many of these pathways for improvement are intricately linked to on-farm irrigation management. However, a comprehensive approach encompassing factors beyond water – such as fertilization, planting density, crop protection and more – exerts a significant influence on water productivity and, consequently, on the livelihoods of farmers. Therefore, a holistic strategy that addresses both water and non-water-related aspects of on-farm management is imperative to unlock the full potential of irrigation and amplify its positive impact on agriculture and the society in Uganda.

Under the framework of the FAO project "Strengthening Agricultural Water Efficiency and Productivity on the African and Global Level" funded by the Government of Switzerland, key management practices and practical actions were identified and implemented in the Mubuku irrigation scheme in order to enhance water productivity (Salman *et al.,* 2020).

Situated in Kasese, the Mubuku Irrigation scheme holds national significance as a high-priority area, primarily owing to its favourable climatic conditions for agriculture. Originally established as part of a government initiative to promote the efficient use of water resources, the scheme is crucial in addressing national food security concerns. With a substantial portion of the country's water potential remaining untapped, the creation of small-scale irrigation schemes emerges as a strategic pathway to mitigate food insecurity at a national scale. These initiatives also contribute to rural job creation and reduce dependence on imports. The Mubuku Irrigation scheme encompasses 540 hectares of agricultural land, jointly cultivated by 167 farmers. The investigated Phase II of the scheme covers a total area of 254 hectares, distributed among 56 farmers.

For the identification and implementation of the optimal farming practices, the following steps were adhered to:

1. Diagnosis and benchmarking of current agricultural productivity levels and farming practices at the farm level for major crops;
2. Evaluation of potential and attainable yields with AquaCrop;
3. Identification and delineation of optimal farming practices to improve crop water productivity;
4. Implementation of optimal farming practices to demonstrate their impact on crop water productivity.

The initial stages involved diagnosing existing agricultural productivity levels and pinpointing the factors limiting productivity, along with potential pathways to enhance water productivity. Comprehensive analyses of agricultural productivity and irrigation practices across the scheme were conducted, taking into account the diversity of farmers' practices that may lead to significant variations in productivity within the scheme. To achieve this, detailed interviews with farmers were conducted following a preliminary general data collection. These interviews aimed to gather specific information on agricultural productivity levels, individual management practices, and constraints faced by farmers. Upon completion of the data collection and analysis, the baseline for water productivity and a comprehensive understanding of current irrigation practices were established.

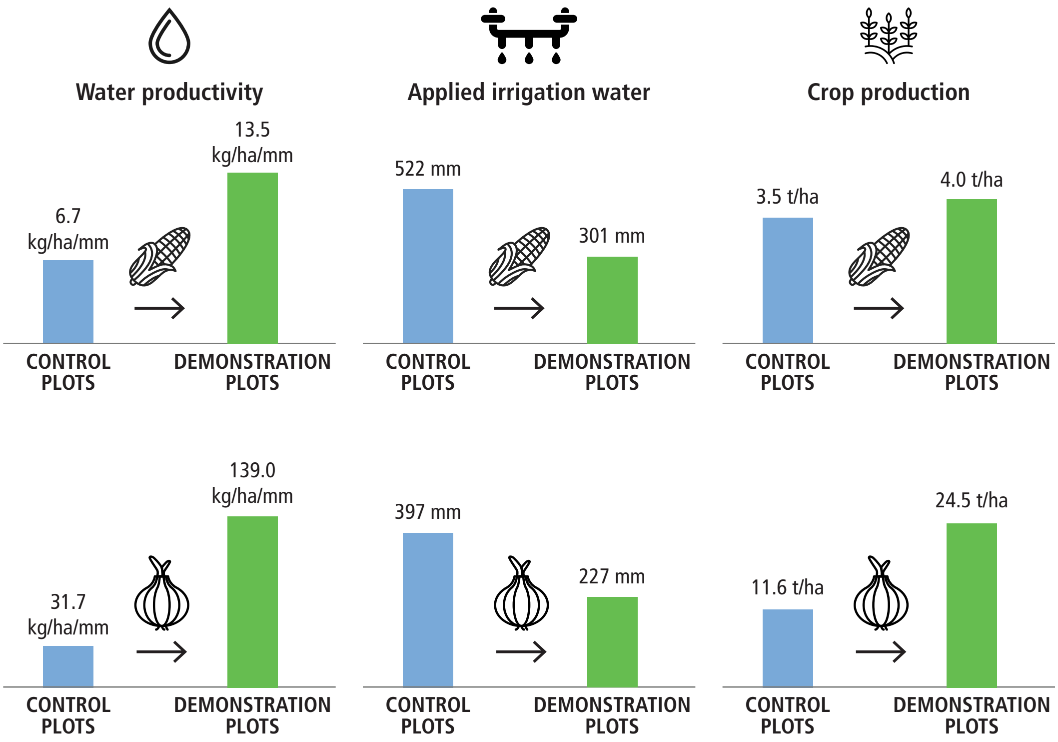
The subsequent step involved the utilization of the AquaCrop model to assess potential and achievable yields. This involved employing the model to i) independently estimate potential and attainable yields by utilizing extensive weather data; ii) pinpoint the factors contributing to the gaps between yield levels and propose management options to minimize these gaps where feasible; and iii) quantify the potential impact of implementing the proposed pathways to enhance water productivity. However, it is crucial to emphasize the significance of local model parametrization and validation. To address this, the model was parametrized and validated using data obtained from monitoring farms with diverse management practices.

Following a phase of diagnostic and comparative analysis (benchmarking), the optimal management practices identified were subsequently put into action in demonstration plots. This approach not only facilitated the dissemination of effective means but also provided a practical demonstration of the recommended practices, enhancing their adoption and implementation within the agricultural community.

By utilizing this methodological approach, improvements were made to irrigation scheduling and fertilization programs for maize and onion in the demonstration plots, among other agricultural practices. In the Mubuku Irrigation Scheme, seasonal rainfall covers more than half of the crop water requirements of maize. Thus, the irrigation supply (i.e. irrigation turn, flow discharge and duration) is more than sufficient to meet the crop water requirements. Irrigation is particularly needed to ensure a good supply during the flowering and grain-filling stages of both crops. In the case of onion, however, it is necessary to increase the irrigation frequency over the existing practice, ensuring an irrigation event once a week. This is because onion is grown during the dry season and has a shallow root system. It is recommended that farmers concentrate irrigation water in the onion fields, especially during the bulb formation phase. Nutrient supply most often limits yields in the Mubuku scheme. The application of the correct nutrient source at the right time is a key issue for optimizing yields. Splitting nitrogen (N) applications during the growing season is highly recommended in the more coarse-textured soils to supply the crops with adequate nitrogen at all times while reducing the economic and environmental impact of nitrogen loss.

The implementation of the proposed practices led to an improvement in crop water productivity, as illustrated in Figure 26. The WP of maize witnessed a notable increase, surging from 6.7 to 13.5 kg/ha/mm, while the WP of onions rose from 31.7 to 139 kg/ha/mm. There was also a substantial reduction in applied irrigation water, with water savings reaching up to 221 mm in maize plots and up to 170 mm in onion plots. In terms of crop yield, the improvement strategy yielded a substantial increase in productivity for both maize and onions, translating to a gain of 0.5 tonne/ha for maize and 12.9 tonnes/ha for onions.

**FIGURE 26**
**Crop water productivity, applied irrigation water, and yield of maize and onion in control plots (farmers' practices) and demonstration plots (improved practices) in the Mubuku scheme in Uganda**




*Source:* Authors' own elaboration.

This enhancement strategy not only positively affected resource efficiency but also contributed to overall productivity. These outcomes align with both efficiency and socioeconomic objectives, supporting farmers' endeavours in advancing and transforming agriculture.

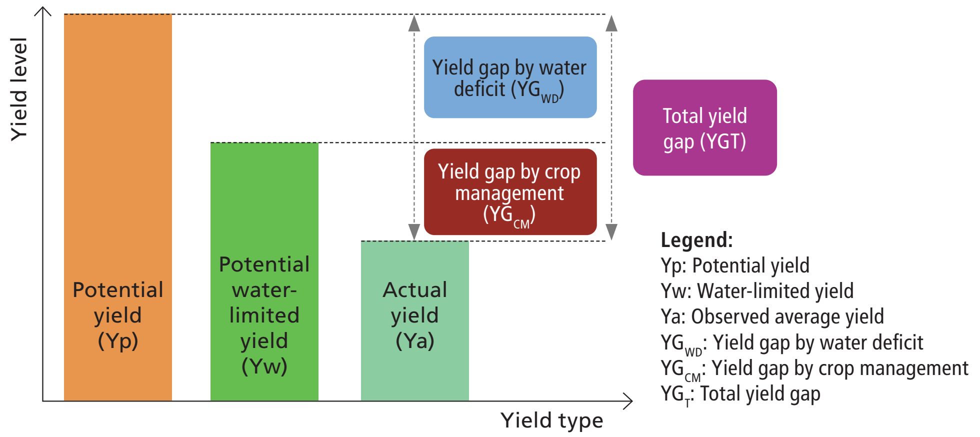

# 6. Benchmarking yield gaps through the prism of water management

## 6.1. OVERVIEW OF SPECIFIC POTENTIAL APPLICATIONS

In agronomy, the yield gap is hardly a new concept, but it has regained importance and attention as more people will need to be fed using lesser and more unstable land and water resources (Snyder *et al.,* 2017). As illustrated in Figure 27, a yield gap can be due to water deficit or crop management, (Ngcobo *et al.,* 2023). To assess these gaps, one needs to determine:

- Potential yield: the yield to be achieved under unlimited conditions, i.e. unconstrained access to water and nutrients, absence of pests and diseases, and optimum field management (land preparation, weed control, etc.);
- Potential water-limited yield: the yield to be obtained by crops not hindered by rainfall, irrigation and soil moisture; and
- Actual yield: the observed farmer-based yields.

**FIGURE 27**
**Conceptual framework describing yield gap analysis and its components**

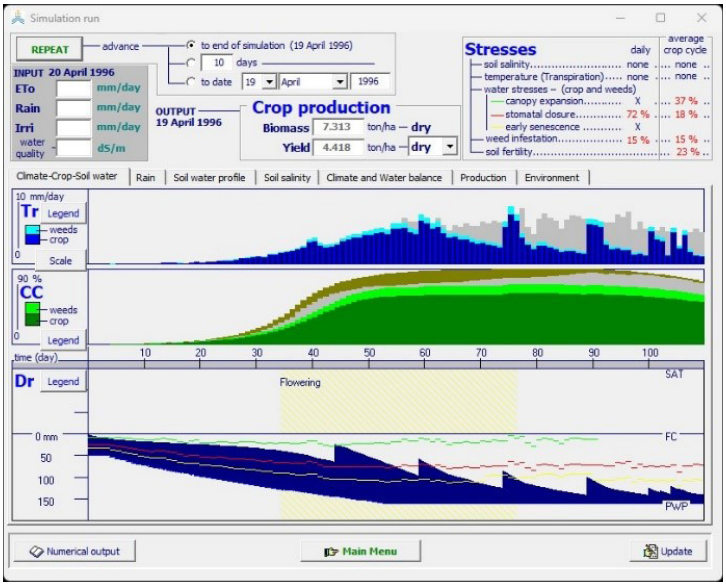



*Source:* **Ngcobo, S.I., Hill, T.R., Jewitt, G. & Archer, E.** 2023. A yield gap analysis to assess the vulnerability of commercial sugarcane to climatic extremes in southern Africa. *Journal of Agriculture and Food Research,* 14, 100734 https://doi.org/10.1016/j.jafr.2023.100734.

The difference between potential yield and potential water-limited yield results in the yield gap caused by water deficit, while the difference between the potential water-limited yield and actual yield is caused by crop management. Weed and nutrient management, pest and disease prevention, and good agricultural practices (GAPs) are considered the main drivers or causes of the crop management yield gap (Raes *et al.,* 2021; Senthilkumar, 2022; Ngcobo *et al.,* 2023; Winck *et al.,* 2023). Water availability, efficient irrigation calendars and reliable weather forecasts help diminish the water deficit yield gap (Kelly and Foster, 2021; Senbeta and Worky, 2023; Li *et al.,* 2024). To reduce yield gaps, it is important to break down those two types of gaps. Literature shows that both gaps are often equally important, and each gap has to be addressed appropriately. Winck *et al.* (2023) decomposed a yield gap for soybeans in Brazil into 22.4 percent explained by cultivars, 32.4 percent caused by cropping practices management, and 45.2 percent caused by water deficits. An extended literature review of rice yield gaps in Africa showed that water management, GAPs, and fertilizer application are responsible for 34 percent, 42 percent and 24 percent of the mean yield gaps, respectively (Senthilkumar, 2022). Similarly, Raes *et al.* (2021) pointed out that for future climatic conditions, tomato, sorghum, rice and maize crop yields in West Africa will not be able to benefit from supplementary irrigation if not accompanied by substantial field management improvements.

Crop modelling helps scale the efforts needed to close yield gaps (Winck *et al.,* 2023). AquaCrop, although a water-driver model, allows the simulation of these different yield reduction drivers and the assessment of their impact on final biomass and yield production. Figure 28 shows how these different yield gaps can be assessed in AquaCrop. The simulation shows a random tomato field characterized by underirrigation, fertility stress and imperfect weed management. Canopy cover development is reduced because of fertility stress (brown area), water deficits (grey area), and weeds' competition (light green area), each contributing to losses in biomass and yield. Since canopy cover is directly related to crop transpiration and transpiration is translated by AquaCrop into biomass, a reduced canopy cover will result in less biomass production. In this case, 33 percent of biomass loss occurs because of water deficits, and an additional 12 percent due to non-optimal fertilizer and weed management (Raes *et al.*, 2023c).

**FIGURE 28**
**AquaCrop simulation for a water-limited field, with fertilizer stress and imperfect weed management**




*Source:* Authors' own elaboration.

Yield gap closure generally requires higher inputs, investments in modern technologies, and supportive agricultural policies (Senbeta and Worku, 2023). In instances where yield gaps are driven by access to water resources, the continuous improvement of efficient irrigation techniques is imperative (Ngcobo *et al.*, 2023), but those techniques should increase yields and not water use. Geerts *et al.* (2009) managed to close spatial and timely quinoa yield gaps in the Plurinational State of Bolivia, and even economized water by developing a deficit irrigation approach in AquaCrop. Real-time irrigation monitoring, which integrated 5-day weather observations in AquaCrop, reduced maize and quinoa yield gaps by approximately 8 percent (Alvar-Betrán *et al.*, 2023). A set of climate-smart irrigation scenarios for wet, normal and dry years was also designed by Li *et al.* (2024). In-season switching between these different scenarios maximized water savings while sustaining stable crop yields. In wet years, a 50 percent deficit irrigation reduced yield by only 5 percent. Significant improvements in crop yield and water savings can also be achieved by precision irrigation. Precision irrigation is defined as "the process of accounting for the field-scale spatial variability in crop water needs and applying the right amount of water to match the spatial crop water need at the right time" (Adeyemi *et al.*, 2017, p.2). Precision irrigation attempts to close yield gaps by minimizing intrafield spatial and temporal heterogeneities. Fields can be monitored in real-time using low-cost weather-based, soil-based or plant-based sensors (Bwambale *et al.*, 2022). Closed-loop systems are created, which receive information from these sensors, make model-based decisions, and apply variable water rates.

Frequently overlooked yield gap closure interventions are technology transfers and agronomic management education. Much of the world's future food is expected to come from irrigated land and yield gap closure in developing countries. Where irrigation facilities are present, irrigation scheduling methods are often lacking. When the irrigation schedules are available, they tend to be more supply-based than knowledge-based (Senbeta and Worku, 2023). In North America, for example, over 80 percent of farmers rely on proxy approaches (seeing and feeling) of crop and soil conditions to trigger irrigation events. Not even a mere 5 percent turn to a simulation model approach to optimize irrigation events (USDA-NASS, 2018 as cited by Kelly *et al.,* 2021).

Despite these successful and promising scientific studies on yield gap closure, worldwide yield gaps remain, as shown on the Global Yield Gap Atlas (www.yieldgap.org). There is, however, a possibility that these yield gaps could simply be communication gaps.

## 6.2. CASE STUDIES

### *Yield forecast of maize in the Terai region of Nepal*

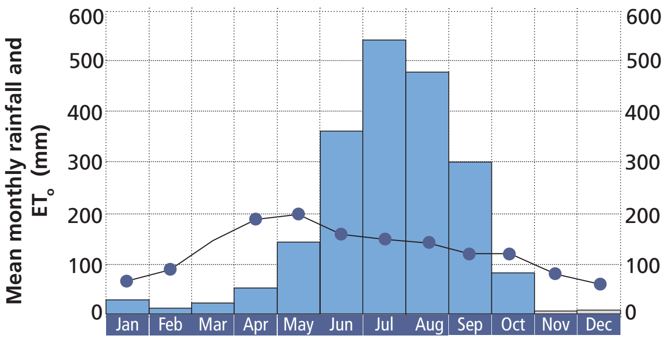
The case study describes the forecast of grain yield for rainfed maize in the upper hill area of Chitwan in the Terai region of Nepal (Shrestha, 2014), where maize is often cultivated before the planting of rice at the start of the monsoon season (June–September). The ability to accurately predict crop yield is crucial for:

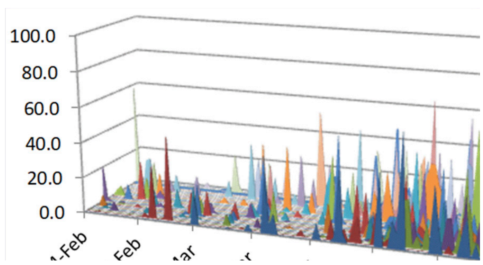
- making real-time crop management decisions throughout the growing season, such as whether to apply (additional) irrigation; and
- providing provide policymakers with information about impending crop failures or low yields, so they can take timely corrective actions to reduce the severity of the projected food shortage.

For this case study, the already calibrated AquaCrop for maize, rice and wheat (Shrestha *et al.,* 2013) was fine-tuned for maize cultivation in Rampur (Chitwan). The grain yield of a 95-day cultivar of maize, with the Nepalese Department of Agriculture's recommended fertilizer application, was forecasted for two distinct sowing dates: early sowing (14 February 2010) and late sowing (29 March 2011). Although late-sown maize benefits more from the rain during the growing cycle than early-sown maize, late sowing can cause severe water stress in the rice fields during the second half of the four-month growing cycle of rice due to delayed planting (mid-July).

Following a strategy proposed by Duchon (1986), the forecast of grain yield started by sequentially running AquaCrop with the historical daily climate data for each of the 29 previous years, 1981–2009 (Figure 29) to make a first, pre-seasonal, range-based forecast of the final yield. As the season advanced, the historical climate data were replaced by the observed weather conditions up to the time the yield prediction was made, while the remaining part of the season remained sequentially simulated with the climate data of the previous 29 years.

**FIGURE 29**
**Mean monthly rainfall and reference evapotranspiration at Rampur in Chitwan, Nepal and daily rainfall before the start of the monsoon for 29 years (1981–2009)**



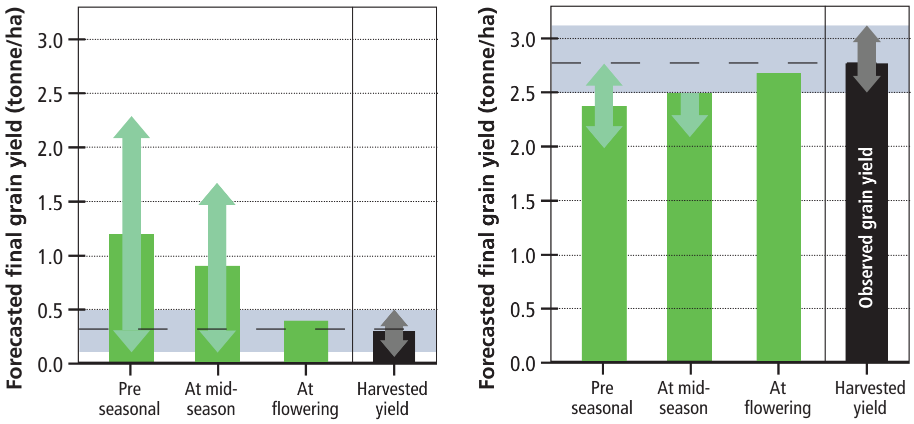




*Source:* Adapted from **Shrestha, N.** 2014. Improving cereal production in the Terai region of Nepal. Leuven, Belgium. KU Leuven Faculty of Bioscience Engineering, PhD dissertation 1176.

Yield predictions were made halfway through the growing cycle and in the middle of the flowering period. As the season progressed, the yield prediction range decreased towards zero. Figure 30 shows the evolution of yield prediction as the season progresses for rainfed maize for early and late sowing, with an indication of the mean (bars) and standard deviation (arrows) of the forecasted (green) and the observed final grain yield (black). The hatched area represents the average (dotted line) +/- standard deviation of the observed grain yield.

**FIGURE 30**

**Evolution of yield prediction as the season progresses for rainfed maize in the Terai region of Nepal**




*Source:* **Shrestha, N.** 2014. Improving cereal production in the Terai region of Nepal. Leuven, Belgium. KU Leuven University. PhD dissertation 1176.

The case study showed that the final yield's predictability was already evident by the middle of the season, which can be useful. At that moment, the tendency towards failure was already noticeable for maize sown early. The standard deviation showed that there still was an opportunity to save the crop by applying irrigation. For the two years covered in the case study, the final yield could already be predicted by flowering within the observed yield plus/minus the standard deviation.

If farmers can anticipate their crop's final output midway through the growing season, they can take the necessary steps to save their crop if it begins to fail. The capacity to foresee crop failures can also help policymakers and relief organizations prepare for them.

## *Yield and water productivity gaps in the Near East and North Africa region*

The expansion of irrigation over the last decades has contributed to a dramatic change in the availability of water supply for agriculture, going from an apparent abundance to increased water scarcity. Nowhere on the planet Earth is the scarcity of water more prevalent than in the Near East and North Africa (NENA) region, an area of arid or semi-arid climate where food production is heavily dependent on irrigation. The water limitation for agriculture is such that further irrigation expansion is not viable in most of the NENA countries, and efforts must be concentrated on attaining more output per unit of water used in food production.

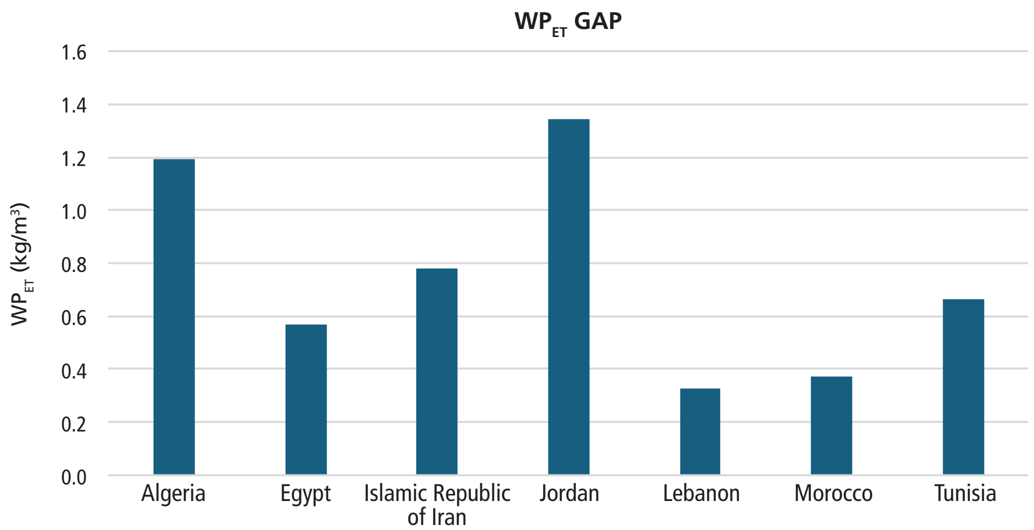
In 2017, the project "Implementing the 2030 Agenda for Water Efficiency/Productivity and Water Sustainability in NENA Countries" was launched in ten NENA countries. It was funded by the Swedish International Development Agency (SIDA) and implemented by FAO. The project aimed at enhancing technical, institutional and policy capacities in the NENA countries to advance water sustainability, food security, renewable energy and climate resilience, ultimately working towards achieving the water-related Sustainable Development Goals (SDGs) by 2030. Overall, the project was expected to improve food security in the NENA region through increased incomes and production; efficient and sustainable use of water resources; and mitigation of climate change effects, considering the reduction in the agriculture carbon footprint.

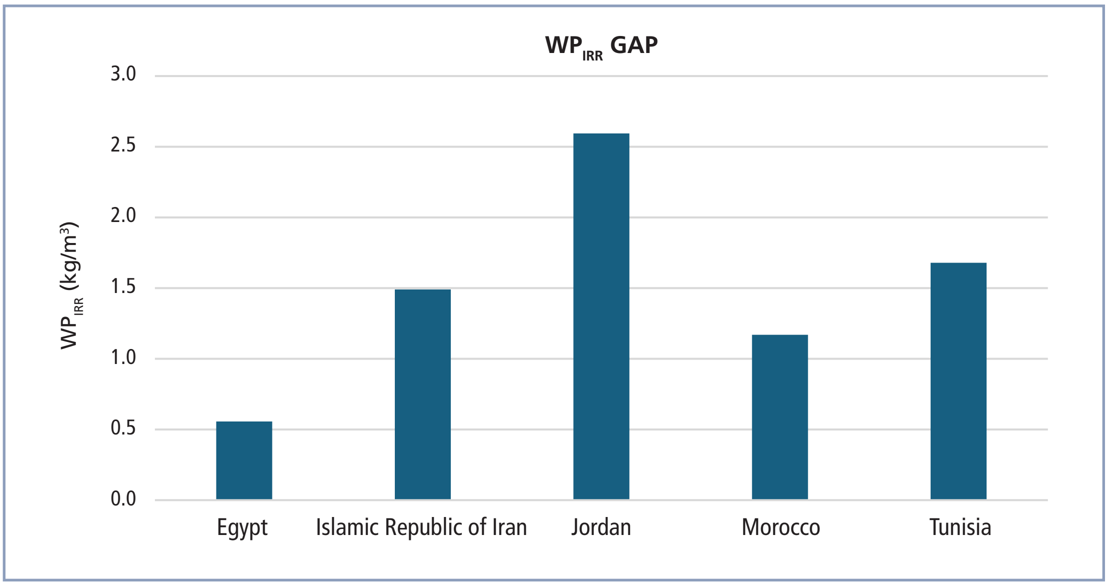
Among the project activities, a critical issue was the state and the benchmarking of WP in the NENA countries (Cabello-Leblic *et al.,* 2024). An extensive survey of literature was conducted in the region to determine the baselines that would quantify the range of WP values for the major crops in the different NENA countries (Cabello-Leblic *et al.,* 2024). Assessing the WP baselines in these NENA countries was challenging due to the diverse and complex nature of available data sources. To ensure consistency and facilitate a unified approach to data collection, a dedicated protocol and database were established. The case study involved consulting both digital and print resources, with no language restrictions. The review relied primarily on international and national peer-reviewed publications. However, other resources include information sources and experts at the national level, such as ministries of agriculture and water, universities, research institutions, and extension and development agencies. A database was finally built after several quality control measures were applied to all the WP publications (Cabello-Leblic *et al.,* 2024). Included in the database were 259 high-quality publications on different crops, with wheat being the most frequently mentioned (37 publications). The range of WP values found was extremely high, of several fold for all crops examined. This finding suggests that there is a wide WP gap – defined as the difference between attainable and actual WP – in the NENA region for all crops examined.

Attainable yields may be identified by selecting the highest values observed experimentally although this approach has a degree of uncertainty, given the nature of experimentation. A crop simulation model can provide an estimate of yield potential which would be only limited by the radiation and temperature regimes of the particular location. AquaCrop was used to establish the potential yield (optimal irrigation and soil fertility) of the major crops in the NENA countries to have a comparative level of potential production in the different NENA environments where experiments were carried out. The simulated yields also gave the potential WP levels, which varied among environments and required the normalization of the WP according to the variations in evaporative demand.

Taking into account the WP of ET, notable gaps in WP for wheat were identified in the Islamic Republic of Iran, Jordan, Tunisia and Palestine (Figure 31). Conversely, Morocco and Egypt exhibit relatively smaller gaps. It is enlightening to assess the WP of irrigation specifically for wheat, a crop heavily reliant on supplemental irrigation across many of the NENA countries. In terms of the actual values of WP of irrigation water ($WP_{IRR}$), results show that there remains a gap when compared with AquaCrop maximum values, except in the case of Egypt, where wheat is fully irrigated (Figure 31). Notably, Egypt's wheat crop exhibits remarkable productivity, evident in its attainment of actual $WP_{IRR}$ values nearing the theoretical potential.

**FIGURE 31**
**Gaps in water productivity of evapotranspiration and irrigation for wheat in the Near East and North Africa region**






*Source:* Adapted from **Cabello-Leblic, A., García Vila, M., Naglaa, A.L.G., Jomaa, I., Abdou, Q.M. *et al.*** 2024. Assessment of the water productivity baseline in Near East and North African countries. *Agronomy*, submitted.

AquaCrop was also used to determine the water-limited potential yields of cases where the irrigation water supply was less than that needed for maximum yields. Where experiments were conducted under deficit irrigation, the simulated yields of different deficit treatments provided an upper boundary of the water-limited yields. Experimental values below such boundary suggest that variables other than water (soil fertility, pests and diseases) were limiting yields. The model was used to assist in the interpretation of the trade-offs between water allocation to different irrigated crops.

The water needs of sugar production in Egypt were examined in detail with two different crops: sugar cane and sugar beet. Sugar beet is a C3 plant with lower intrinsic WP than sugar cane, which, as a C4 plant, has higher WP. In principle, sugarcane WP should be higher than that of sugar beet. However, other factors come into play in the WP determination, such as the season length and the time when the crop is grown, which are important. The growing cycle of sugar cane is 12 months while sugar beet grows during the 7–8 months of low evaporative demand (fall–winter–spring). Having a shorter growing season and avoiding the high evaporative demand of summer makes the WP of sugar beet higher than that of sugar cane.

AquaCrop was used to simulate sugar production in Egypt using either sugar cane or sugar beet. Another important factor is that sugar cane is grown in the Upper and Middle Egypt governorates, which have higher reference ET ($ET_o$) than those in the Lower Egypt where sugar beet is grown. Simulations indicated that sugarcane annual ETc is 2 100 to 2 300 mm while sugar beet ETc is 750 to 840 mm. The yield differences between the two crops (sugar cane gives a higher yield) are insufficient to balance the water use differences, pointing to sugar beet as having higher WP, thus producing more sugar/m3 of irrigation water. Nevertheless, other important economic and social factors come into play, favouring sugar cane. Reducing the area planted with sugar cane in Egypt would negatively impact the livelihood of many smallholders that live directly off this crop, as well as the large number of ancillary businesses that have been built around sugarcane production, particularly in the Upper Egypt where it is a main component of the regional economy. All these factors must be considered when assessing possible changes in cropping patterns dictated by the productivity of water.


# 7. Assessing climate change effects on crop production and water use and identifying adaptive strategies

## 7.1. OVERVIEW OF SPECIFIC POTENTIAL APPLICATIONS

Water resources are intricately connected to global challenges such as climate change. One of the critical sectors affected by climate change is agriculture, particularly crop production. As global temperatures rise, extreme weather events become more frequent, and precipitation patterns shift, farmers face unprecedented challenges that threaten food security worldwide (IPCC, 2022). Rising temperatures may affect crop growth and development; increase the atmospheric evaporative demand; and even alter the life cycles of pests and diseases, exposing crops to new threats. The shifts in precipitation patterns brought about by climate change may disrupt planting and harvesting schedules and affect water availability and irrigation schedules. The changes in the frequency and intensity of extreme weather events, such as drought, floods and heatwaves, can also stress the agricultural systems. This stress affects both soil and crop and puts the entire agricultural landscapes at risk. On the other hand, the rise in $CO_2$ atmospheric concentration benefits crops by increasing photosynthesis, particularly for C3 plants like wheat and rice. Furthermore, there may be a reduction in cold waves and frost events in the future, potentially lowering the chances of crop losses due to frost damage. To address these challenges posed by climate change, farmers, technicians and policymakers must identify, develop and implement appropriate adaptation strategies. This may involve improving water management practices, developing new climate-resilient crop varieties or changes in crop varieties, altering sowing/planting dates, and enhancing crop nutritional status and soil health, among others.

A thorough understanding of the impacts of climate change will assist scientists and technicians in advising farmers so they can make effective crop management decisions. The impacts of climate change on crop production in any region can be determined by combining the use of climate data for different shared socioeconomic pathways or SSPs (Riahi *et al.,* 2017) and crop models. Crop models serve as the primary instruments for evaluating the effects of climate change and other factors that prepare crop productivity, a critical element of ensuring food security. Nevertheless, it is crucial to ensure that models are accurately calibrated and validated for local conditions and to quantify model uncertainty (Challinor *et al.,* 2009). For a model to be suitable for impact assessments, it should at least be able to respond to the main climatic variables that are expected to affect the cropping systems. It should also be capable of modelling the main crops and management strategies.

### 7.1.1. AquaCrop modelling of climate change effects

AquaCrop considers the effects of temperature on various processes, specifically in development, reference evapotranspiration ($ET_o$), cold stress on transpiration, and cold and heat stress effects on pollination. Simulations during the warmer period allow for hastened development by the increase in growing-degree days. Temperature increases also increase $ET_o$ as temperature mildly influences the FAO Penman-Monteith equation (Allen *et al.,* 1998). For crop transpiration, low temperatures reduce stomatal conductance, and if the growing degrees simulated in a day drop below an upper threshold, crop transpiration becomes limited by air temperature (Raes *et al.,* 2023c). If pollination fails due to cold and heat stress and if the minimum air temperature drops below a threshold or the maximum air temperature rises above a threshold, pollination might be affected (Raes *et al.,* 2023c).

Regarding the increased atmospheric $CO_2$ concentration, AquaCrop simulates the impact on biomass WP and transpiration. By considering WP, the model derives the aboveground biomass from the simulated transpiration. WP is normalized for atmospheric $CO_2$, considering a reference value of 369.41 ppm (atmospheric $CO_2$ concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii, USA) and with a correction coefficient. To prevent an inaccurate simulation of biomass production when $CO_2$ concentrations exceed 550 ppm, the correction coefficient for WP is refined. However, it is important to note that this adjustment is purely theoretical and lacks validation from field experiments (Raes *et al.,* 2023c). A correction for crop type is also applied, assuming the different responses of C3 and C4 crops. Regarding decreased crop transpiration via reductions in stomatal conductance due to elevated $CO_2$, AquaCrop adjusts the crop transpiration coefficient. This adjustment is performed by considering a T reduction of 5 percent when the $CO_2$ increases from 370 to 550 ppm. Most models do not consider this effect, leading to an overemphasis on possible future drought.

The impacts of the projected changes in precipitation pattern and amount can also be easily simulated due to the robust water balance performed by the model and the diverse water stress parameters (deficit and excess) considered. AquaCrop has better coverage in this matter compared to other models (Tenreiro *et al.,* 2020).

### 7.1.2. Constraints of AquaCrop in evaluating climate change effects and determining adaptive strategies

Although AquaCrop accounts for the effects of heat stress on various processes, it still does not address all the impacts. The model does not consider heat stress effects on leaf senescence and grain development, the latter being of paramount importance. Furthermore, like most models, AquaCrop neglects the influence of alterations in the diurnal temperature range on grain yields. A rise in the diurnal temperature range has been linked to decreased yields of rice and maize in several agricultural regions globally (Lobell, 2007). The combined effects of different stresses, such as the interactions of raised $CO_2$ with high temperature and/or drought stress, are also not sufficiently tested. This is true with other models as well. The acclimation response to warming and elevated $CO_2$ simultaneously is another gap not addressed by AquaCrop due to the complex interaction of biochemical, respiratory and stomatal regulation (Rogers *et al.,* 2017). The model should also account for the potential influence of other climatic factors and extreme events that may become more significant in the future, such as ozone levels, frost, snow, hail and wind damage. However, accurately predicting these factors poses a huge challenge.

Obvious gaps include the simulation of the observed subdued effects of climate change on the yield quality of some crops, such as cereal crops (e.g. glutenin aggregation), oil crops (e.g. fatty acid composition), vegetables, fruits and aromatic plants. Alterations in the temperature and rainfall pattern may also alter the life cycles of pests and diseases, which is not addressed. The effects of climate change on many soil dynamics, such as nitrogen dynamics, are not considered. Increased soil temperatures from global warming can enhance nitrogen mineralization; however, nitrogen availability may diminish due to losses from volatilization and denitrification processes.

### 7.1.3. Potential applications of AquaCrop in climate change studies

Considering its features and limitations, AquaCrop can be applied in climate change studies. Applications include the use of modelling to evaluate the impact of the projected changes in climate on crop yield and irrigation water requirements. AquaCrop can also be used to optimize management practices, develop new crop rotations, and assist in breeding programmes. The analysis of the climate change impacts is the most prominent model application, being covered by 17 percent of AquaCrop publications from 2009 to 2019 (Salman *et al.,* 2021). Evaluations of climate change impacts are prominently featured on the policy agenda, influencing the utilization of crop models in research. Some examples of AquaCrop applications found in recent literature are presented here.

#### *Impacts on crop yield at large scale*

The most common application of crop models in climate change studies is estimating the impact of the projected changes in crop yield, from subnational to global scale. Numerous instances of this application are documented in the literature. AquaCrop was employed to forecast the impact on rainfed rice yield in the Lower Lancang-Mekong River Basin based on the latest CMIP6 climate projection data and considering three emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5), showing a strong impact (Xie *et al.,* 2023). The model has also been used to assess the impacts on crop production in food-insecure regions, such as the Niger (Alvar-Beltrán *et al.,* 2023). The productivity of major crops is threatened, showing a decrease/increase yield trends for millet (0 to −50 percent), sorghum (+5 to −20 percent) and cowpea (+11 to +18 percent) by the end of the century, depending on the agroclimatic zone, sowing date and climate change scenarios. This may have potentially dire consequences for national food security and the income of millions. By integrating AquaCrop with other tools and methodologies, its applications can be enhanced. In Srikanth and Umamahesh (2024), the model was combined with sensitivity analysis and optimization processes to evaluate accurately the impact on Indian cotton yields. Another example of interesting combinations can be found in Alvar-Beltrán *et al.* (2023), where AquaCrop and the Python Agro-ecological Zoning tool were implemented to assess climate change impacts on crop yields in Nepal.

### *Evaluation of adaptive irrigation strategies*

Given AquaCrop's emphasis on crop yield responses to water, it is clear that a primary application lies in evaluating irrigation strategies considering climate change. Recently, deficit irrigation strategies for tomatoes were explored in Egypt to enhance WP under various climate change scenarios (Hendy *et al.,* 2023). Similarly, two different irrigation schedules (less/more frequent irrigation and higher/lower volume) for wheat and sugar cane along the Indus River Basin in Pakistan were evaluated under two climate change scenarios (Alvar-Beltrán *et al.,* 2021). Optimizing root-zone water depletion thresholds is essential for aligning irrigation management with anticipated changes, as illustrated by Zhang *et al.* (2023), who optimized these thresholds to enhance both the yield and WP of wheat in the North China Plain, coupling AquaCrop with genetic-simplex algorithms.

### *Management of groundwater resources*

The importance of groundwater resources would be amplified in the context of climate change. Groundwater serves as a critical buffer during climatic extremes, offering a more stable and reliable water supply compared to surface water sources. In many areas, it acts as a reservoir that captures and stores excess precipitation during periods of abundance to provide a vital resource during dry spells. Therefore, sustainable management practices of groundwater, coupled with innovative strategies for recharge and conservation, are paramount. In this, AquaCrop can serve a significant role, as evidenced by recent publications. In the study by Jadav and Yadav (2023), the model was employed to assess excess canal water supply for irrigating sugar cane in a heavily exploited river basin and to pinpoint an appropriately managed aquifer recharge strategy. Coupling AquaCrop and MODFLOW models, the changes in groundwater resources in a rice-wheat-dominated cropping region of northwestern India were also assessed under different climate change scenarios (Kumar *et al.,* 2023).

### *Adaptation through agronomic practices*

The changing temperature and precipitation patterns resulting from climate change underscore the need for modifications in agronomic practices, encompassing adjustments to sowing/planting dates, seeding rates, crop cycles, and other relevant factors. In Viet Nam, AquaCrop was applied to evaluate rice sowing dates as a pivotal adaptation strategy (Phung and Dang *et al.,* 2023). Similarly, in the North China Plain, research identified optimal sowing dates in conjunction with seeding rates amid projected climatic shifts (Wen *et al.,* 2023). However, it is essential to emphasize that the efficacy of altering planting dates as an adaptation measure is intrinsically tied to cultivar selection. This integrated approach was exemplified in a study by Feleke *et al.* (2023), who utilized AquaCrop to jointly assess both strategies for maize cultivation in Ethiopia. AquaCrop offers a valuable tool for assessing adaptive practices related to soil management.

For instance, Setti *et al.* (2023) examined the efficacy of tied ridges for maize cultivation as an in situ water harvesting technique in Senegal in response to changes in temperature and precipitation. The potential of film-mulched drip irrigation to enhance future irrigation efficiency was also investigated in Central Asia by Zhu *et al.* (2023).

### *Analysis of climatic hazards*

Understanding and characterizing climatic hazards are essential steps to bolster preparedness against anticipated rise in extreme weather events. In this endeavour, crop models like AquaCrop play a crucial role. For example, a study by Bhatti *et al.* (2023) in Pakistan correlated future drought indices' magnitude with crop yield simulations using AquaCrop. This linkage offered valuable insights into the appropriateness of different drought indices for characterizing agricultural drought conditions. Likewise, in India, Dixit *et al.* (2023) correlated projected crop yields for maize, cotton and wheat derived from the model with the temporal progression of the Standard Precipitation Evapotranspiration Index. This correlation aimed to assess the efficacy of crop yields projection as a criterion for identifying drought onset and offset.

## 7.2. CASE STUDIES

### *The effect of climate change on crop production in West Africa*

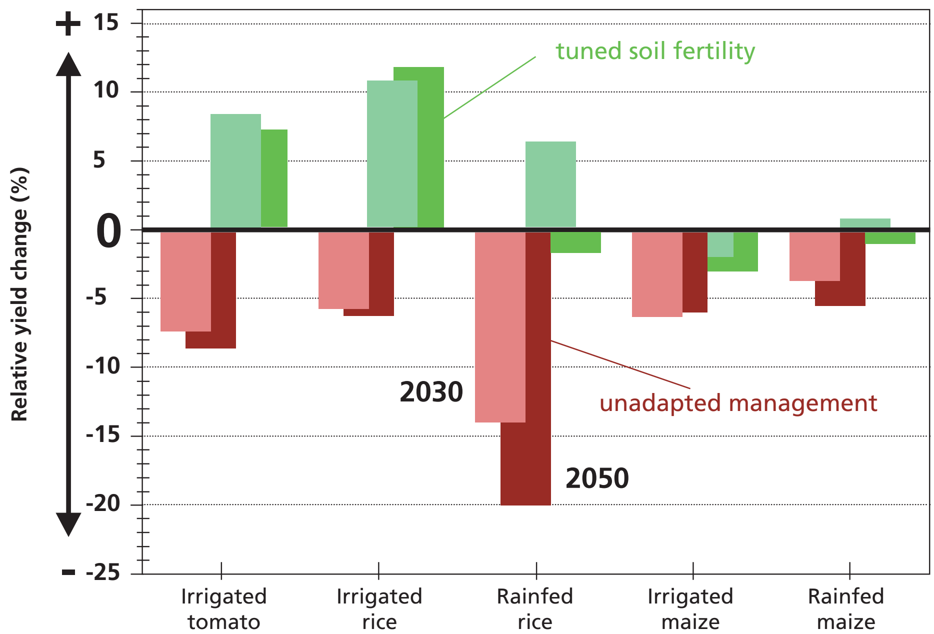
The case study describes a quantitative assessment of the impacts of climate change on crop yield in smallholder farms in West Africa. Crop yields under current conditions and future climatic scenarios were simulated using AquaCrop. The study was part of the project "Adapting Small-Scale Irrigation to Climate Change in West and Central Africa" (AICCA) implemented by FAO in collaboration with the International Fund for Agricultural Development (IFAD), national governments, and the AGHRYMET Regional Centre. The project aimed to provide governments, international organizations, financing institutions, and project managers with evidence-based information on the effects of climate change on small-scale agriculture in West Africa and Central Africa to support investment designs.

Through a participatory process involving national teams, eight project sites were selected in three different climatic zones in the Niger, Mali, the Gambia and Côte d'Ivoire. Four crops and two typical cultivation systems were considered: irrigated tomato, rainfed sorghum, and irrigated and rainfed rice and maize. For each cropping system, simulations were run with a calibrated field management and the actual irrigation strategy (for irrigated crops) of the successive years with observed climatic data. The simulated yields agreed well with the reported yields obtained in the region.

Future climatic data for each site were provided by the three best-performing combinations of regional climate models and global climate models (RCM-GCM). A moderate (RCP 4.5) and a more pessimistic (RCP 8.5) greenhouse gas emissions scenario were considered. Although the interannual variability in rainfall is projected to be substantial, the median projected total rainfall is predominantly slightly positive in future years. However, the positive effect of the small increase in rainfall on yield changes is rather small when compared with the negative effect of the high interannual rainfall variability in West Africa. This causes yield variability and income uncertainty for farmers. The small relative mean change in rainfall is in contrast with the strong warming effect (temperature increase of 1.0°C to 2.5°C and associated increase in evapotranspiration of 3 percent to 7 percent), which is the most important driver of yield changes.

For the future climatic conditions, crop yields were simulated for the 20-year periods of two time horizons (2030 and 2050) under current, improved (i.e. better soil fertility with and without deficit irrigation), and optimal conditions (Figure 32). The simulation results indicated that the changes in precipitation patterns under future climatic conditions – particularly the increase in air temperature and associated increase in evapotranspiration – will result in more severe water stress and a substantial reduction in crop yield unless soil fertility is addressed. Without adapting soil fertility management, crops cannot fully benefit from the fertilization effect of increased atmospheric $CO_2$ concentration (which leads to higher biomass production if crops can take up enough nutrients from the soil). Only if soil fertility is improved crops can benefit from $CO_2$ fertilization and offset the negative impacts of other climatic changes.

**FIGURE 32**
**Mean relative change in crop yield under climate change scenarios in West Africa**




The mean relative change in crop yield for the multimodel ensemble of three regional climate models under current (red bars) and improved (green bars) management conditions for 2030 (light colour) and 2050 (dark colour), for irrigated tomatoes, rice and maize, and rainfed rice and maize in the pessimistic emission scenario (RCP 8.5)

*Source:* Authors' own elaboration.

As illustrated in Figure 32, the main findings related to current management conditions indicate that:

- Crop yield is expected to fall by 5–20 percent under current management conditions.
- Improving soil fertility by at least 15– 20 percent could lead to an increase in crop yields of 5–14 percent for irrigated tomato and 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.

### *Moving from field scale to gridded simulations for assessing the impacts of climate change*

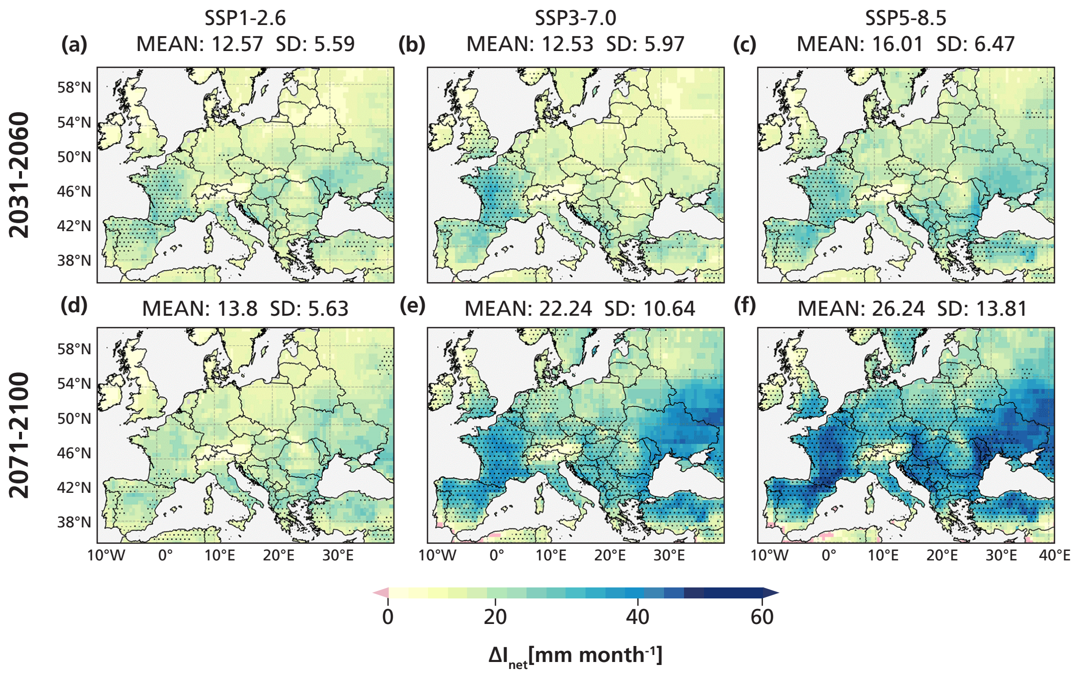
Over the last decades, the expansion of global crop production caused the irrigated areas to largely increase, emphasizing the need for efficient water management in agriculture (Siebert *et al.*, 2015). Projections of irrigation requirements are essential for planning. In this context, Busschaert *et al.* (2022) used AquaCrop spatially over the main European continent to estimate future net irrigation requirements ($I_{net}$).

Following de Roos *et al.* (2021), the study also pioneers the transition from field-scale AquaCrop simulations to larger-scale simulations. The model is run at a 0.5° x 0.5° latitude-longitude resolution and is done with meteorological forcings from the Inter-Sectoral Impact Model Intercomparison Project, simulation round 3 (ISIMIP3; Rosenzweig *et al.,* 2017; Warszawski *et al.,* 2014), which considers a baseline period (1985–2015) and two future periods: 2031–2060 (near future) and 2071–2100 (end of the century). Three emission scenarios were considered – SSP1-2.6, SSP3-7.0, and SSP5-8.5 – representing low, high and extreme emission scenarios, respectively. To account for climate modelling uncertainties, projections from five General Climate Models (GCMs) were used, resulting in 15 (3 scenarios x 5 GCMs) spatial AquaCrop simulations in mainland Europe. A generic C3 crop was used for all simulations and the change in $I_{net}$ was computed over the peak summer months (June, July, August).

Figure 33 shows the change in $I_{net}$ ($\Delta I\_{net}$) for two future time windows compared to the baseline period (1985–2015) for the three emission scenarios. High and extreme emissions will lead to an increase exceeding 20 mm per month, more than 30 percent compared to the baseline. It was found that the $I_{net}$ projections depend on the emission scenario, yet they show a stronger variability within the scenario (strong dependence on the GCMs), demonstrating the uncertainty in future climate projections. Nevertheless, the higher the emissions, the better the agreement between the GCMs on significant increases in $I_{net}$, as shown by the stippled areas in Figure 33.

**FIGURE 33**

**Changes in summer $I_{net}$ ($\Delta I\_{net}$) in mm per month, median across five global climate models for two future time horizons (rows) and three scenarios (columns) with reference to the baseline period**



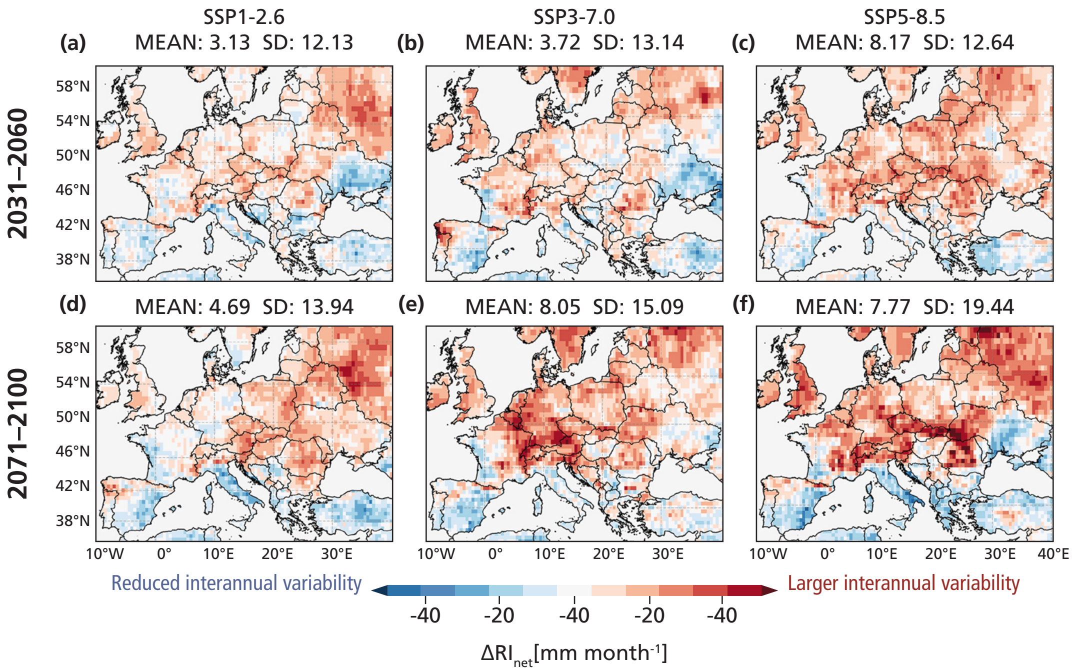

Notes: The stippled areas represent pixels where all five GCMs present statistically significant changes (t-test; p<0.05).
Refer to the disclaimer on page ii for the names and boundaries used in this map.

*Source:* **Busschaert, L., de Roos, S., Thiery, W., Raes, D. & De Lannoy, G. J. M.** 2022. Net irrigation requirement under different climate scenarios using AquaCrop over Europe. *Hydrology and Earth System Sciences,* 26, 3731–3752.

On top of the absolute increase in $I_{net}$, the results show that the interannual variability will also be affected, depending on the region. Figure 34 presents the maps of the change in interannual variability of $I_{net}$, quantified by the range in $I_{net}$ ($RI_{net}$). This range is defined as the difference between the maximum and minimum summer $I_{net}$ over the 30-year time window. Red colours indicate a larger range compared to the baseline, i.e. the interannual variability is increased, while blue colours correspond to a reduced variability. While areas in northern Europe will encounter a heightened variability, southern Europe is projected to consistently face high $I_{net}$ in the future.

**FIGURE 34**

**Changes in the interannual variability of net irrigation water requirement ($I_{net}$), represented by the change in range in net irrigation requirements ($RI_{net}$) ($\Delta RI_{net}$) in mm per month for two future time horizons (rows) and three scenarios (columns) with reference to the baseline period**




Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.

*Source:* Adapted from **Busschaert, L., de Roos, S., Thiery, W., Raes, D. & De Lannoy, G. J. M.** 2022. Net irrigation requirement under different climate scenarios using AquaCrop over Europe. *Hydrology and Earth System Sciences,* 26, 3731–3752.

The evolution in the absolute amount of $I_{net}$ and its variability illustrates the different practical strategies that will vary across the continent. Northern regions, currently experiencing relatively low $I_{net}$ levels, may require large investments to maintain their current crop production in the future. Meanwhile, southern regions, commonly already equipped with irrigation systems, will need to focus on enhancing irrigation efficiencies and exploring other irrigation strategies, such as deficit irrigation (Geerts and Raes, 2009; Mushtaq and Moghaddasi, 2011).


# 8. Conclusions

The AquaCrop model was designed to assist in making decisions aimed at improving water use and productivity in agriculture. In the 15 years since it was published (Steduto *et al.,* 2009), many diverse applications have been formulated, well beyond those originally indicated in Steduto *et al.* (2012).

Crop simulation models are mere simplifications of the complex reality of crop production, and AquaCrop is no exception. Therefore, it is important to always compare model results with alternative assessments of crop productivity. The confidence in model predictions greatly increases if high-quality experimental data is available for the parameterization, calibration and validation of the model. It is, thus, recommended that parameters provided in the model for every crop are carefully checked and their values to local conditions are adjusted.

In assessing the behaviour of agricultural systems, crop simulation models are just a brick in a building aimed at integrating many components. AquaCrop has been combined with many other tools, presenting valuable examples of combinations aimed at preparing input files more effectively or visualizing outputs efficiently. The model has also been combined with other tools to run in a spatially distributed way, to plug in web applications, to automate the calibration of parameters, or to more generally interface the model with in *situ* or satellite-based observations.

Water allocation applications are presented, not only to allocate water within the agricultural sector but also to consider the sharing of water between agriculture and other sectoral users. Such applications focus on optimization with certain boundary conditions where the yield prediction capabilities of AquaCrop are crucial at farms, catchment and higher scales. The ability to carry out spatial analyses using the model is critical for the assessment of situations and trade-offs at the higher scales, as demonstrated in several case studies (see Section 3.2).

One of the original goals of AquaCrop was to have it as an irrigation scheduling tool to define the timing and amount of irrigation. Many applications have been carried out with this objective in mind. The determination of irrigation requirements when the water supply is not limiting (which has been given at scales from field to continent in Europe) and the evaluation of actual schedules relative to optimal ones are important achievements demonstrated in this publication (see Section 4.2). AquaCrop is also best suited to formulate schedules when the water supply is below the crop requirements. Optimizing a limited water supply for irrigation is perhaps one of the most frequent uses of AquaCrop on the ground so far.

Salinity is very often associated with water scarcity. Given the design of AquaCrop, it was deemed necessary to simulate the impact of salinity on crop productivity in the model. While crop response to soil and water salinity has been documented, in the real world, the spatial variability that arises due to salinity makes it difficult to accurately simulate the response. Nevertheless, the model has been successfully applied in a number of cases where salinity affects production (see section 4.2).

The use of AquaCrop to evaluate agronomic measures aimed at improving production has been quite extensive, as it is one of the main issues targeted by model. The evaluation of the impact of changing planting dates or of the limited fertility was shown in a number of case studies (see Section 5.2). The model runs assuming that soil fertility is not limiting production, but it is well known that nutrient supply to crops is often limiting, particularly in developing countries. It is recommended that the nutrient limitation is considered, using the module that the model has for that purpose. One of the future improvements of AquaCrop should be the upgrade of the soil fertility module and/or the calibration of the existing module – which already has a solid basis – through systematic field experimentation.

Yield gaps between potential and actual yields indicate the trajectory of the agricultural systems around the world. AquaCrop is well suited to define potential and water-limited yields which are needed to define yield gaps. The examples clearly demonstrate where the model is used dynamically with actual inputs at specific times to orient farmers regarding agronomic practices to fill in the yield gaps (Nepal case study), and to advise policymakers on defining baselines in crop water productivity (NENA region).

Among different applications related to the environment, climate change effects on yield predictions have been one of the most popular applications of AquaCrop in recent years (Salman *et al.* 2021). AquaCrop has one feature related to the prediction of future elevated $CO_2$ concentration on crop productivity and water use that makes the model well-adapted to climate change studies. Applications include the assessment of adaptive measures to decrease the negative impact of elevated air temperatures and possible rainfall reductions (see Section 7.2). It is likely that as climate change assessments become more widespread, the use of AquaCrop for such assessments will expand in the future.

Finally, this report comes only a few years after the initial AquaCrop assessment by Salman *et al.* (2021). It is quite positive that the number of new publications focused on implementing and applying the model has increased markedly and that they show only a glimpse of the huge and diverse AquaCrop users' community worldwide.

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# AquaCrop on the ground

## Model applications for sustainable agricultural water management

In the face of rising global challenges such as water scarcity, climate variability and the growing demand for food, efficient agricultural water management has become a cornerstone of sustainable development. Addressing these challenges requires innovative tools that bridge scientific research and practical application.

AquaCrop, the crop–water productivity model developed by FAO in collaboration with leading scientific institutions, embodies a rigorous, research-driven approach to agricultural water management, demonstrating its transformative potential in optimizing water use and enhancing crop productivity. The model has been specifically designed to support water management in agriculture under limiting conditions, empowering farmers, policymakers and researchers with actionable insights to enhance water-use efficiency and maximize crop yields. Since its launch in 2009, AquaCrop has gained widespread recognition for its simplicity, scientific rigor and adaptability across diverse agroecological contexts.

Through an engaging collection of real-world applications and case studies, this report highlights how AquaCrop has been implemented in varying environments, from arid regions grappling with acute water shortages to areas managing excess moisture. These examples underscore the model's versatility and its ability to support decision-making processes, optimize irrigation scheduling, and promote sustainable intensification of agricultural production.

The report further emphasizes the importance of collaboration in achieving meaningful results. Drawing on the collective expertise of FAO, national agricultural agencies, research institutions and farming communities, it provides practical insights, success stories and lessons learned from on-the-ground implementation. These experiences demonstrate how AquaCrop facilitates evidence-based decision-making, fosters stakeholder engagement, and aligns interventions with local needs and aspirations.

By integrating climate-smart practices and adopting a holistic approach to resource management, AquaCrop emerges as a critical tool in addressing the interconnected challenges of food security, environmental sustainability and economic stability. It supports farmers in adapting to climate variability, enhances resilience to water-related risks, and contributes to sustainable resource management at both local and global scales.

This report serves as a testament to FAO's commitment to advancing innovative research and practical solutions for agricultural water management. It aims to inspire further collaboration, innovation and action to optimize water use in agriculture, ensuring food security and environmental sustainability for generations to come.

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