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3.2 *AquaCrop* applications

INTRODUCTION

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

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

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

- **Days to weeks**: Decisions made at the **operational level** refer to those taken within a growing season, on a scale of days to few weeks, such as determining the date and amount of next irrigation or of a fertilizer topdressing application.

- **Weeks to months**: Tactical farming decisions have a time frame of weeks to months and are typically made at the start or different times during

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

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

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

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

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

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

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

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

APPLICATIONS TO IRRIGATION MANAGEMENT AT THE FIELD AND FARM SCALES

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

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

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

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

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

CASE 2 - Determining the date of next irrigation with AquaCrop

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

Approach:

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

Outputs:

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

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

Specific data requirements

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

Approach:

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

Outputs:

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

CASE 4 - Benchmarking current irrigation practices

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

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

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

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

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

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

Output

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

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

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

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

Approach

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

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

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

The approach should be the same as above. However, in this case, the number of irrigations must also be reduced during the beginning of the season and concentrated from early flowering to early fruit set, leading to an early senescence and a shorter growing season. This should have some yield penalty relative to full irrigation supply. Several simulations should be

conducted (and saved to disk) to reach the best solution in terms of maximum harvest index which would lead to the maximum yield for the given IW.

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

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

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

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

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

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

✔ Box 1 Simulating deficit irrigation in cotton production

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

AquaCrop simulation
Simulations were performed for cotton sown in rows on raised beds and with the furrows diked to store irrigation and precipitation. Irrigation was either Full (FI), indicating that soil water was replenished to replace that lost to ET, or one half of that (Deficit, DI). Irrigation scheduling was performed assuming a lateral-move sprinkler irrigation system that applies ~25 mm per irrigation. The sowing rate was at 21 seeds/m². Late in the season, FI was reduced relative to the crop-water requirement (ET_c demand), so as to enhance crop maturation.

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

Results
Simulated yields were in the range of 3.3 to 3.6 tonne/ha, (equivalent to 1.3 to 1.4 tonne/ha of lint) and were comparable to values reported in the region. Deficit irrigation (DI) seed-lint yields were ~95 percent of full irrigation (FI) yields. The water productivity of DI cotton was ~10 percent greater than that of FI (both in the range of 0.49 to 0.54 kg/m³(seed plus lint), or 0.19 to 0.21 kg lint/m³). Crop ET was about 15 percent greater for FI than for DI, both in the range of 625 to 720 mm, which matches well observed values in several regions. However, DI received 240 mm of irrigation, only 43 percent of the FI amount.

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

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

CASE 7 - Influence of field management on rainfed agriculture

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

Approach

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

Output

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

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

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

Approach

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

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

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

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

Approach

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

Output

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

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

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

Approach:

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

Output

Once the yields for every year and for the different planting dates (keeping all other parameters the same) have been simulated, the values are organized from lowest to highest,

for each planting date. If there are 20 years of simulations, each value represents a 5 percent probability. Then, the yield can be plotted against the cumulative probability graphically, and it is possible to choose the most favourable option with least risk from the graph or compare different options for years with differing conditions, say amounts of rainfall or El Niño phases.

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

☑ **Box 2** Determining the optimal sowing date for wheat

Background

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

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

Location and simulation experiments

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

▼

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

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

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

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

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

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

▼

FIGURE 1 Differences in simulated grain yields between the first and the second sowing opportunity as a function of the seasonal rainfall at different initial soil water (0, 30 and 60 mm) for the period between 1999 and 2008 at Buntine, Western Australia.
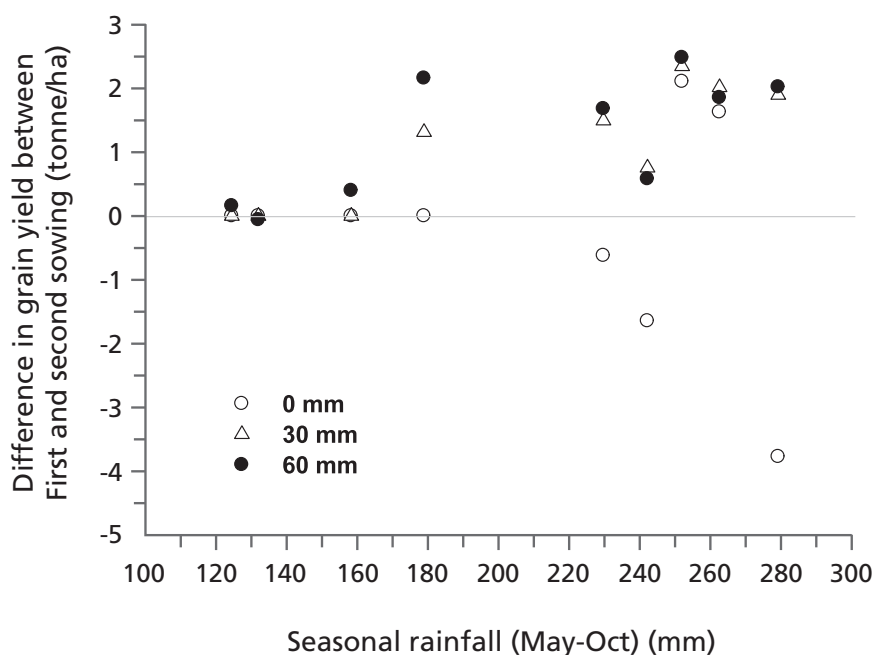
In similar regions, but with water resources available for irrigation, applying a small amount of water (about 30 mm) before sowing will significantly reduce the risk of crop failure with an early sowing opportunities and would allow to maximize yield potential in such an environment.

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

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

Approach
Two approaches may be used: (i) with the average climatic records, the user will simulate the yield response to different amounts of applied irrigation (IW) changing the level of application in 30-50 mm step intervals ('Irrigation Events' tab sheet in 'Irrigation Management'); (ii) if a

climate dataset is available as historical series, simulate the yield response to different amounts of IW using each year of the available climate records. This will yield a family of curves from which a mean curve and probabilities of exceeding a certain yield value could be derived (see Case 10).

Output

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

FIGURE 2 Simulation of potato yields as a function of applied irrigation water with *AquaCrop* for 25 years of data at Cordoba, Spain. The three yield-response curves represent the average response and the expected response on a good (wet and relatively warm) and bad (dry and cold) climatic year (García-Vila and Fereres, 2012).
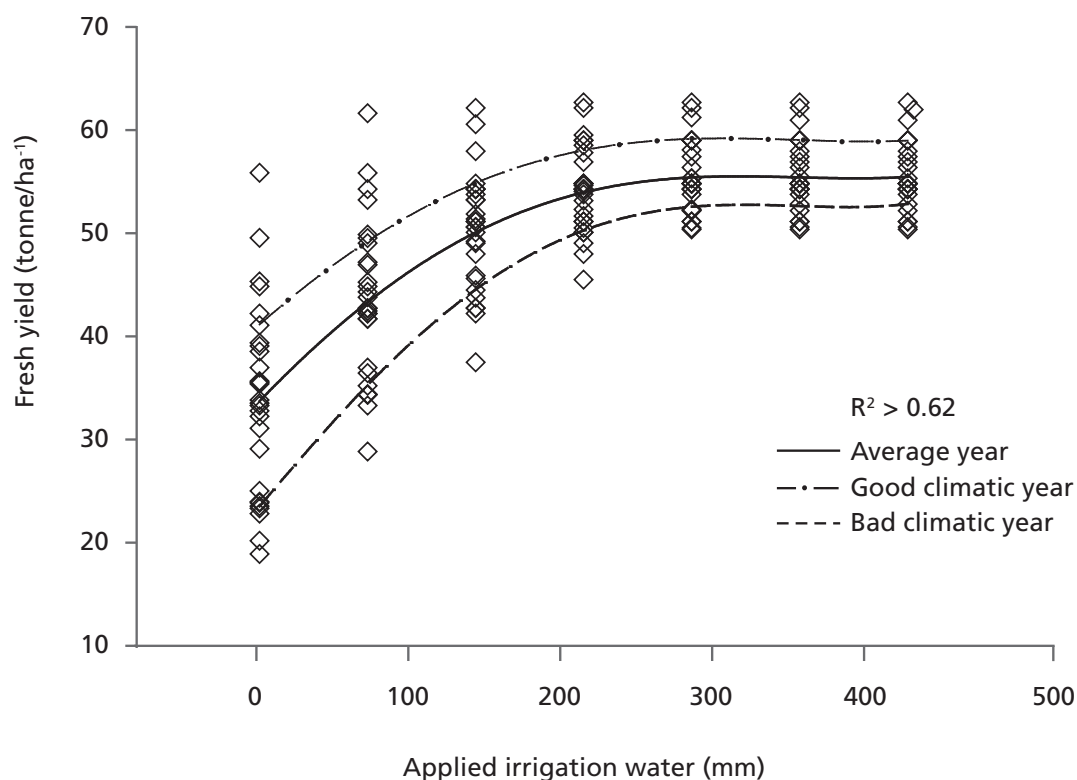
FIGURE 3 (a) Simulated yields of quinoa with *AquaCrop* as a function of ET, from rainfed to full irrigation, and for different deficit irrigation regimes; (b) Water productivity as a function of ET, showing the optimal levels for intermediate levels of ET induced by optimal DI regimes (Geerts *et al.*, 2009).
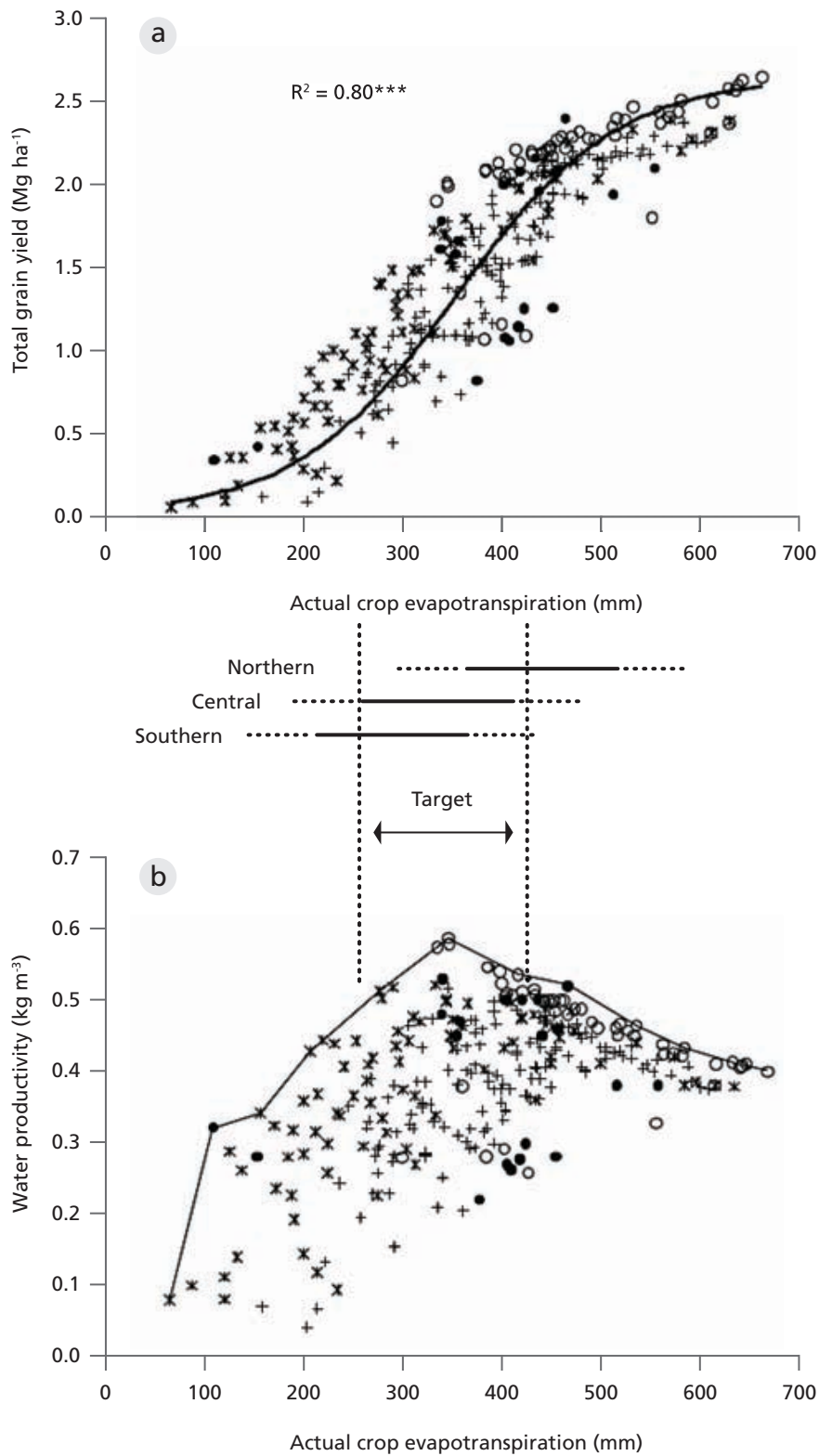
CASE 12 - Assessing the effects of plant density on yield

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Approach

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

Conclusion

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

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