Crop yield and water saving potential for AquaCrop model under full and deficit irrigation managements

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Abstract

The study review selected researches related to full and deficit irrigation managements simulated with AquaCrop model for various field crops (group 1) and vegetables/spices (group 2). In order to evaluate the application of full and deficit irrigation *vs* crop yield and water use, publications from 1979 to 2018 were reviewed. With a view to find the significance variations in modelled crop yield, irrigation water use and yield reductions corresponding to water saving potential (WSP). Additionally, reporting brief summary of findings, recommendations linked to model simulation and proposed some gaps for further investigations. The findings confirm that there are significant differences in yield reductions corresponding to water saving with inference R^2 was 0.372 in crop group 1 and 0.117 in group 2 during study. Simulated yield in evaluated field crops and vegetables/spices varied between 14.44 to 0.012 t/ha in full ET$_c$ and 10.72 to 0.004 t/ha in deficit ET$_c$. The water saving potential, in the two groups of field and vegetable/spice crops revealed that, with acceptance of yield reduction equivalent 2.66 and 29.03% save irrigation water equal to 23.68 and 80% while the reduction of 41.79 and 26.86% of yield saved 28.87 and 82.1%. The maximum water save values are higher than that reported for deficit irrigation in previous publications. Some suggested points related to this research need further studies *e.g.* evaluating the big differences in crop yields and irrigation water applied resulted with AquaCrop under full and deficit irrigation management and justification of high WSP corresponding less crop yield reduction.

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Introduction

The real challenge of the agricultural sector is to be able of feeding world population that is rapidly growing over time and try to decrease the water usage in the sector. The world's population numbered nearly 7.6 billion as of mid-2017 and this number is projected to increase by slightly more than one billion people over the next years, reaching 8.6 billion in 2030, and to increase further to 9.8 billion in 2050 (UN-Population Division, 2017). Consequently, the food demand will rise by 60% in the same period (Alexandratos and Bruinsma, 2012). Agriculture accounts for roughly 70% of total freshwater withdrawals globally and for over 90% in the majority of least developed countries (FAO, 2011). Without improved efficiency measures, agricultural water consumption is expected to increase by about 20% globally by 2050 (WWAP, 2012) or predicts the world could face a 40% global water deficit by 2030 under a business-as-usual scenario (2030 WRG, 2009).

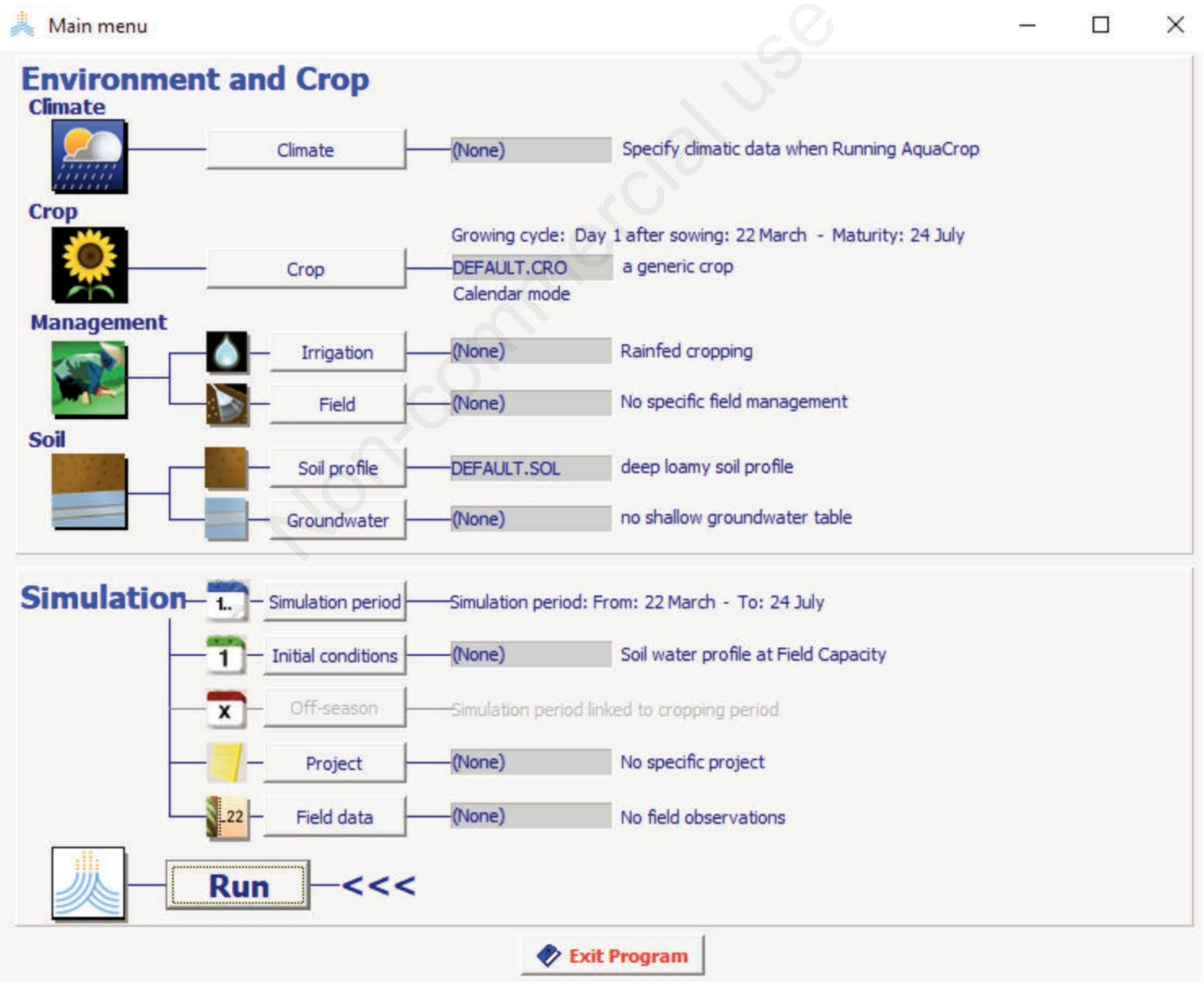
The functionality of irrigation is not only to provide sufficient water for crops in order to achieve better outcome in production, as implied in conventional irrigation definition. Irrigation must be also contributing in improve the features such as water use efficiency, crop productivity per any drop of water applied and water saving potential. These goals will not be reached if we have not considered the irrigation schedule and calculated the precise amounts of different crop water requirements as full irrigation magnitudes in order to control the amounts of water that can be withdrawal from rivers, lakes and aquifers for irrigation purposes. Irrigation scheduling is a planning and decision-making tool used for determining the amount and timing of irrigation application for maximising efficient water use and crop yield (Joel *et al.*, 2007). Full irrigation corresponds to the amount of water enabling the actual evapotranspiration of a crop to be equal to its potential evapotranspiration or the total water needed for evapotranspiration and cell construction, from planting to harvest for a given crop in a specific climate regime usually, addressed as crop water requirement (Frenken and Gillet, 2012). While, deficit irrigation (DI) is an optimisation strategy in which irrigation is only applied during drought-sensitive growth stages of a crop (Geerts and Raes, 2009).

Nowadays, in spite of the huge numbers of research results availability and extension services for the farmers and farm owners around the world, still there are some proposed questions which are needed to be answered such as: how the farm owners can increase production and optimise their water used, why the optimal yields are not being obtained despite the available water and required nutrient applications, what exact crop and/or water factors that are responsible for increasing or decreasing the yields in global case or regionally and how can make a pre-simulation to the crop growth and production behaviours as in real crop field for imaging the possibility of benefits and profits instead of wasting time, efforts and costs as well as contributing in save agricultural water. As objective for this study, we reviewed and analyses most of the scientific literature, which had investigated full and deficit irrigation managements in relation with crop yield and water use for different crops and regions, that were simulated with AquaCrop model. The evaluated crops are sorted into two different crop groups as following: field crops (group 1) and vegetables/spices (group 2). After comprehensive evaluation for reviewed cases and inferences, we concluded valuable observations and findings, which will be explained later in details.

AquaCrop model

Model concept and comparison to other crop models

AquaCrop (Figures 1 and 2) is a crop water productivity model developed by Food and Agriculture Organisation (FAO) (Hsiao *et al.*, 2009; Raes *et al.*, 2009a; Steduto *et al.*, 2009) to predict crop productivity, water requirement, and water use efficiency under water limiting conditions (Raes *et al.*, 2009b). The model evolved from the concepts of crop yield response to water, developed by Doorenbos and Kassam (1979). It seeks the balance among simplicity, accuracy and robustness to facilitate wide application, this multi-crop and water model requires only a relatively small number of explicit parameter values and mostly intuitive input variables, which are obtainable by straightforward methods (Raes *et al.*, 2009b; Steduto *et al.*, 2009; Vanuytrecht *et al.*, 2014). AquaCrop version 5.0 interface and the main components of the soil-plant-atmosphere continuum and others useful driving parameters (Figures 1 and 2). Continuous lines indicate direct links



Climate: (None) Specify climatic data when Running AquaCrop

Growing cycle: Day 1 after sowing: 22 March - Maturity: 24 July

Crop: DEFAULT.CRO a generic crop

Calendar mode

Irrigation: (None) Rainfed cropping

Field: (None) No specific field management

Soil profile: DEFAULT.SOL deep loamy soil profile

Groundwater: (None) no shallow groundwater table

Simulation period: Simulation period: From: 22 March - To: 24 July

Initial conditions: (None) Soil water profile at Field Capacity

Off-season: Simulation period linked to cropping period

Project: (None) No specific project

Field data: (None) No field observations

Figure 1. Main menu of AquaCrop model version 5.0, October, 2015.

between variables and processes, while dashed lines indicate feedbacks (Steduto *et al.*, 2007, 2009).

Use of models can assist for evaluating and reducing time intensive and expensive field tests (Whisler *et al*., 1986). Model results with regard to crop performance, management, and yield estimates will help decision makers to decide which management system is suited best for a particular field, by estimating the yield and crop water productivity optimum (Pawar *et al.*, 2017). Some of the frequently applied crop models are: CropWat, CropSyst, AquaCrop, CERES, EPIC and DSSAT (Hunink and Droogers, 2011; Droogers and Hunink, 2012), APSIM and SPAC (Zhang *et al.*, 2013). CropWat, AquaCrop and are specifically strong on the relationship between water availability, crop growth and climate change. In addition, these two models are in the public domain, have been applied worldwide frequently, and have a user-friendly interface (Hunink and Droogers, 2011). In contrast, the other models are complicated, require a large number of parameters and also require advanced skills from end-users for model calibration and operation (Heng *et al.*, 2009). These disadvantages partly inhibit their developments and extensive applications for those models (Zhang *et al.*, 2013).

Some specific features that distinguishes AquaCrop from other crop models as pointed out in available literature are: i) its focus on water; ii) use of canopy cover instead of leaf area index; iii) use of water productivity (WP) values normalised for atmospheric evaporative demand and CO_2 concentration (Figures 1 and 2) that confer the model an extended extrapolation capacity to diverse locations, seasons, and climate, including future climate scenarios; iv) require relatively low number of parameters; v) input data which requires only explicit and mostly intuitive parameters and variables; vi) a well-developed user interface; vii) its considerable balance between accuracy, simplicity, and robustness; viii) its applicability to be used in diverse agricultural systems that exists worldwide.

In spite of the fact that, the model is relatively simple, it emphasises the fundamental processes involved in crop productivity and in the responses to water deficits, both from a physiological and an agronomic perspective.

Operation and calculations

Figure 3 depicts the model calculation scheme in a daily time step of simulations, and the model simulates sequentially the following parameters.

Soil water balance

The water stored in the root zone is simulated according for incoming and outgoing water fluxes at its boundaries. While, the depletion of root zone determines the magnitude of a set of water stress coefficients (Ks), which are affecting: i) green canopy (CC) expansion; ii) stomatal conductance and hence transpiration (Tr) per unit CC; iii) canopy senescence and decline; vi) the harvest index (HI); and v) the root system deepening rate.

Crop development

AquaCrop uses canopy cover to describe crop development instead of leaf area index. The model is generally separated canopy expansion from the expansion of the root zone during simulation of crop development; therefore, the interdependence between shoot and root is indirect via water stress. CC is a crucial feature of AquaCrop through its expansion, ageing, conductance and senescence, it determines the amount of water transpired (Tr),

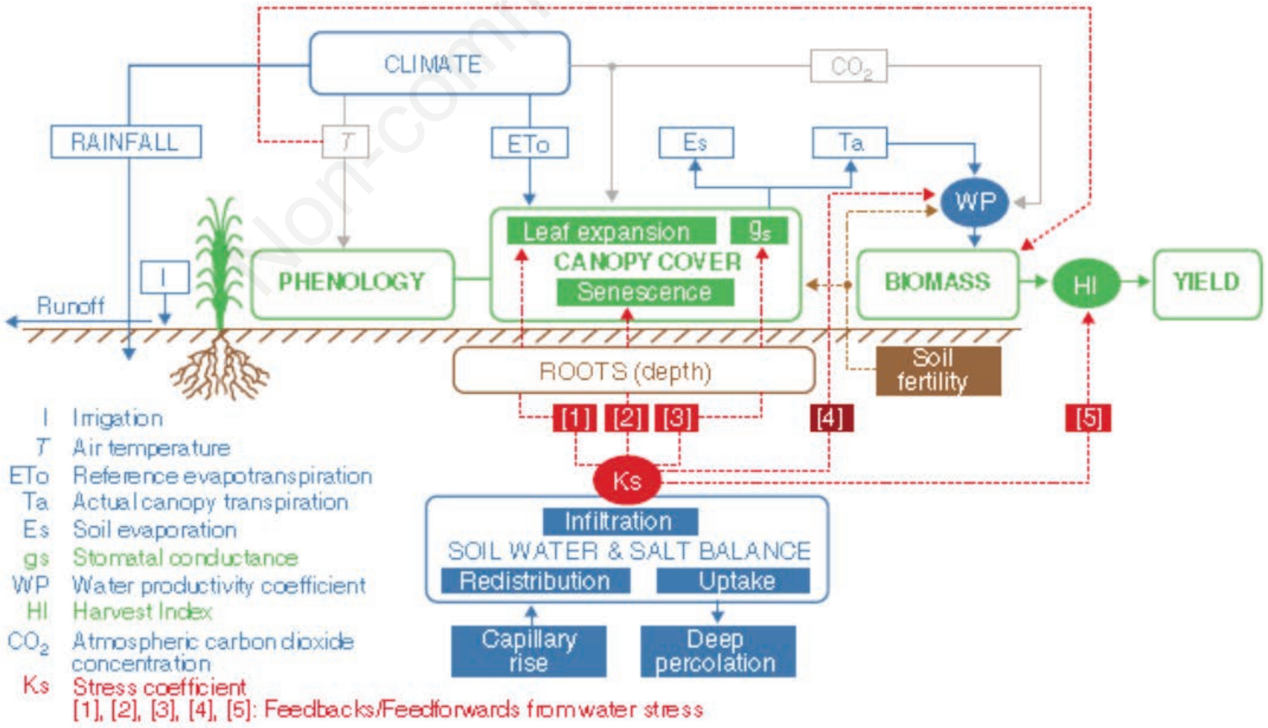


Figure 2. Flowchart of the AquaCrop model indicating the main components of the soil-plantatmospheric continuum (adapted from Abdul-Ganiyu *et al.*, 2018 after a little modification from Raes *et al.*, 2011).

which in turns determines the amount of biomass produced (B) and the final yield (Y). In circumstance of water stress, the simulated CC will be less than the potential canopy cover (CC_{pot}) for the none stress conditions and the maximum rooting depth might not be reached (see the dark shaded areas in Figure 3) (Raes *et al*., 2011).

Crop transpiration

Crop transpiration is calculated by multiplying the evaporating power of the atmosphere (ET_o) with a crop coefficient. The crop coefficient (K_{cb}) is proportional to CC and hence continuously could be adjusted. The evaporating power is expressed by the reference grass evapotranspiration (ET_o) as determined by the FAO Penman-Monteith equation (Allen *et al.*, 1998). If water stress induces stomatal closure, the water stress coefficient for stomatal conductance (Ks) reduces transpiration accordingly.

Above ground biomass

The cumulative amount of Tr translates into a proportional amount of biomass (B) produced through the biomass WP as in Eq. 1 (Steduto *et al*., 2007):

$$B=WP.\sum T_r \tag{1}$$

In AquaCrop the water productivity normalised for atmospheric demand and air CO_2 concentrations (WP*) is used. It expresses the strong relationship between photosynthetic CO_2 assimilation or biomass production and transpiration independently of the climatic conditions. Further away than the partitioning of biomass into yield described in the next paragraph, there is no partitioning of aboveground biomass among various organs.

Partitioning of biomass into yield

Crop yield is obtained with assistance of HI in case of simulated above ground B is available (Raes *et al.,* 2011) as in Eq. 2:

$$Y=HI.B \tag{2}$$

Conditionally, the HI is continuously adjusted during yield formation in circumstance of crop yield response to water and/or temperature stresses.

AquaCrop contribution on crop production and water use under different irrigation managements

Recently, many studies have used the AquaCrop model to simulate various crops growth and production response to irrigation water and environments for different crops and regions maize

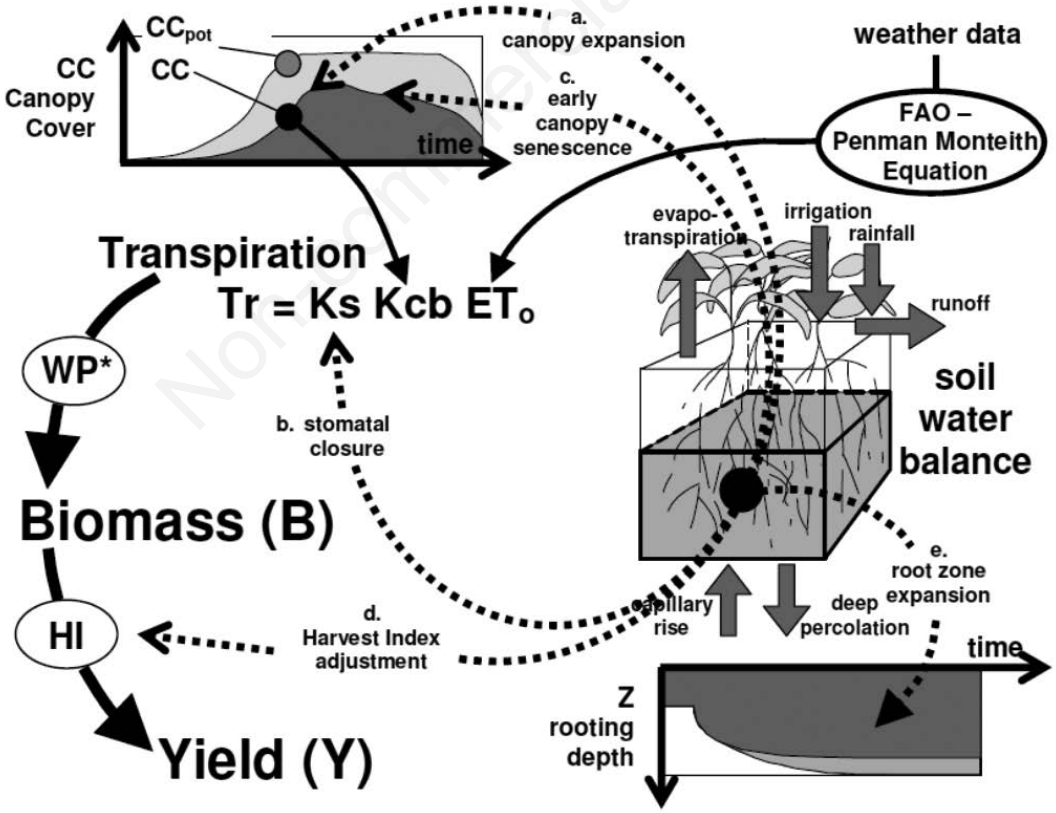


Figure 3. Calculation scheme of AquaCrop with indication (dotted arrows) of the processes (a to e) affected by water stress. [Source: Reference Manual, Chapter 1 - AquaCrop, Version 3.1plus January 2011, page 1-5 (adapted from Raes *et al.*, 2011)]. CC, canopy cover; CC_{pot}, potential canopy cover; K_s, water stress coefficient; K_{cb}, crop coefficient; ET_o, reference evapotranspiration; WP*, normalised crop water productivity; HI, harvest index.

(Heng *et al*., 2009; Hsiao *et al*., 2009; Salemi *et al*., 2011; Flores-Gallardo *et al*., 2013; Mhizha *et al*., 2014; Ahmadi *et al*., 2015; Greaves and Wang, 2016), cotton (Farahani *et al*., 2009; Garcia-Vila *et al*., 2009), sunflower (Stricevic *et al*., 2011), potato (Domínguez *et al*., 2011), cabbage (Wellens *et al*., 2013; Pawar *et al*., 2017), tef (Tsegay *et al*., 2012), wheat (Jamieson *et al*., 1991; Xiangxiang *et al*., 2013; Iqbal *et al*., 2014; Kumar *et al*., 2014), tomato (Rinaldi *et al*., 2011; Katerji *et al*., 2013; Linker *et al*., 2016), bambara groundnut (Karunaratne *et al*., 2011), quinoa (Geerts *et al*., 2009), barley (Araya *et al*., 2010; Abrha *et al*., 2012), canola (Zeleke *et al*., 2011), soybean (Khoshravesh *et al*., 2012), sugar beet (Stricevic *et al*., 2011) and rice (Lin *et al*., 2012; Shrestha *et al*., 2013b; Amiri *et al*., 2014).

Several tests have been done with AquaCrop in the term of deficit irrigation simulation and crop yield response to different water stress applications across wide regions in the world. Araya *et al.* (2010) tested AquaCrop for improving crop water use in East Africa (Ahmadi *et al*., 2015) simulated crop growth and soil water content under full and deficit irrigation managements in South of Iran (Greaves and Wang, 2016) evaluated irrigation management strategies for improving agricultural water use in Southern Taiwan. Pawar *et al.* (2017) used AquaCrop to improve water productivity of different irrigation strategies in India.

Many studies suggested more tests for calibration's key parameters in diverse climates, soils, crops, irrigation and field managements (Heng *et al*., 2009; Hsiao *et al*., 2009; Stricevic *et al.,* 2011; Katerji *et al*., 2013; Zhang *et al*., 2013; Linker *et al*., 2016).

Optimising water use in irrigation

In several publication findings, authors stated some problems of relevance to irrigation practices and managements, such as: i) in many world areas irrigation delivery at the farm outlet is less or more than what is exactly required (Fereres and Soriano, 2006); ii) the high costs of irrigation and networks limit its benefits to reach the highest possible number of farmers; iii) inadequate estimation of the crop water requirements in large projects is another problem (English *et al*., 2002). On other hand, irrigated agriculture is still practiced in many areas in the world with complete disregard to basic principles of resource conservation and its sustainability. Therefore, irrigation water use in an era of water scarcity will have to be carried out more efficiently, aiming at saving water and at maximising its productivity (Fereres and Soriano, 2006) in order to optimise water use in irrigation (as explained later in Section *Deficit irrigation and crop water response models*).

In fact, optimisation of irrigation water use cannot be achieved without great effort due to the fact that some of the water losses are unavoidable. For example, water is needed to maintain the salt balance because irrigation waters contain salts and, as water evaporates, salts concentrate in the soil profile and must be displaced below the root zone before they reach a concentration that limits crop production. Salt leaching is achieved by the movement of water applied in excess of ET (Fereres and Soriano, 2006). Actually, for optimising water use must be controlled or minimised the two main losses components: one due to evaporation losses from the soil, and the other that includes all the losses resulting from the distribution of water to the land. As well as, reducing ET without a penalty in crop production is much more difficult, however, because evaporation from crop canopies is tightly coupled with the assimilation of carbon (Tanner and Sinclair, 1983; Monteith, 1990; Steduto *et al*., 2007). Furthermore, in any attempt to optimise water use for irrigation, there is significant uncertainty in the anticipated results and, often, the alternatives that anticipate higher net returns also have higher risks (English *et al*., 2002). To reduce uncertainty and risk, computer models that simulate irrigation performance (Lorite *et al*., 2005) *e.g.* AquaCrop model, together with social research, can aid in assisting water managers to optimise a limited supply of irrigation water (Fereres and Soriano, 2006). Finally, many investigations have been conducted to gain experiences in irrigation of crops to maximise performance, efficiency and profitability (Shankar *et al*., 2013). Some authors announced that, the amount of irrigation optimisation that can be achieved is crop-dependent and generally governed by amount of water extracted by plant roots (Ahmadi *et al*., 2011). So, investigations into water saving irrigation practices are still needed (Sleper *et al*., 2007).

Deficit irrigation managements

The concept

The conventional concept of DI is to provide irrigation water below the ET_c requirements of the crops throughout the growing season. Nowadays the irrigation understanding replaced from maximise yield per planted area to yield per amount of water used. Therefore, the recent concept of DI is an optimisation strategy in which irrigation is applied during drought-sensitive growth stages of a crop (English, 1990; Geerts and Raes, 2009). Outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water. Water restriction is limited to drought tolerant stages, often the vegetative stages and the late ripening period (English, 1990). Indeed, while DI maximises irrigation water productivity, it also occurs inevitably results in plant stress and consequently in production loss due to unequal proportional quota of irrigation requirements throughout the crop cycle.

Features of deficit irrigation

Most irrigation systems are eligible to provide only between 30 to 50% of water that can be taken up by the plant (Sadras *et al*., 2007), while the DI is capable to increase this ratio to more than 90% in case of well-designed and management for the system (English, 1990; Sadras *et al*., 2007). DI is not only of high relevance in water-scarce areas or in dry seasonal periods; it also has the potential to optimise and reduce water use in irrigated systems for the humid and arid zones (Sadras *et al*., 2007). Deficit irrigation plays important role in drought periods, in regions with chronic water scarcity and the areas facing scarce resources like water. In mentioned situations, the water supply is restricted; therefore the farmers are often faced with having to use DI to achieve the highest possible returns or for trying to stabilise their productions. Even though the economics of DI are relatively straightforward (English, 1990), the reality is that, there are many engineering, social, institutional, and cultural issues that determine the distribution and the management of irrigation water (Fereres and Soriano, 2006). Finally, DI technique is maximising water productivity and enhanced harvest quality (Spreer *et al*., 2007). Additionally, since water use is reduced, the irrigated area can be increased and additional crops can be irrigated amplifying the diversity of the household production, which decreases the farmers' risks. The application of less water reduces the leaching effects of nutrients from the root-zone and agrochemicals, and the groundwater quality is preserved (Pandey *et al*., 2000). Furthermore, it reduces the risk of the development of certain diseases linked with high humidity that are common in other irrigation systems.

Deficit irrigation and crop water response models

The relationship between crop yield and water (Table 1) (Doorenbos and Kassam, 1979) used for AquaCrop model, is explained by a simple equation where relative yield reduction is related to the corresponding relative reduction in ET. This relationship in Eq. 3 is the following:

$$\left(1-\frac{Y_a}{Y_x}\right) = K_y * \left(1-\frac{ET_a}{ET_x}\right) \quad (3)$$

where Y_a and Y_x are actual and maximum yield (ton/ha), $(1-Y_a/Y_x)$ is relative yield reduction, ET_a and ET_x are actual and maximum evapotranspiration (mm), $(1- ET_a/ET_x)$ is relative water stress, and K_y is yield response factor (proportionality factor between relative yield reduction and relative reduction in evapotranspiration. The yield response factor (K_y) captures the essence of the complex linkages between production and water use by a crop, where many biological, physical and chemical processes are involved (Ismail *et al.*, 2015).

Crop water productivity

In most of literature the crop water productivity defined as water use efficiency and calculated as the marketable crop yield over actual evapotranspiration (Zwart and Bastiaanssen, 2004), Eq. 4:

$$CWP = \frac{Y_{act}}{ET_{act}}\,(kgm^{-3}) \quad (4)$$

where Y_{act} is the actual marketable crop yield (kg ha^{-1}) and ET_{act} is the actual seasonal crop water consumption by evapotranspiration (m^3 ha^{-1}).

Crop yield and irrigation water used of modelled crops

Table 1 summarised researches data of recent publications related to full and deficit irrigation managements simulated with AquaCrop model. The study focused on modelled findings due to similarity of evaluated variables and methodologies used (testing/calibration, validation, evaluation and there is no possibility for unknown mistakes) where their results can help to figure out robust judgments for the model performance in related variables. Whereas the mentioned facts are not available for field observed results. The data describes various field crops (maize, wheat, soybean, sorghum, rice, cotton and quinoa) and vegetables/spices (Tomato, onion, potato, taro, cabbage, hot pepper and saffron) in different regions. Group 1, is usually used as edible, eaten by human and animals, its grains are highly nutritious. While, group 2, is normally used by human, eaten as fresh vegetables or spice and flavoured sources (Table 1). The reduction in yields in Table 1, calculated as variation in percentage of less yield obtained in that study and its yield in full ET_c (Eq. 5). Similarly, the water saved obtained as percentages of variation in maximum deficit water and full ET_c used (Eq. 6). The two methods of calculations were found in previous publications (Rinaldi *et al.*, 2011; Katerji *et al.*, 2013; Linker *et al.*, 2016; Pawar *et al.*, 2017) as following:

$$Yield\ reduction\ (\%) = \left(1-\frac{Simulated\ DI\ yield\ (t/ha)}{Simulated\ yield\ of\ full\ irrigation\ (t/ha)}\right) * 100 \quad (5)$$

$$WSP\ (\%) = \left(1-\frac{DI\ water\ applied\ (mm)}{Full\ irrigation\ water\ used\ (mm)}\right) * 100 \quad (6)$$

The yield in full irrigation management varied from 13.2 to 3.3 and 14.44 to 0.012 t/ha for groups 1 and 2, respectively. In same line for deficit irrigation were ranged between 10.3 to <0.1 and 10.72 to 0.004 t/ha (Table 1). While, the water applied as full ET_c and maximum deficit in both groups 1 and 2 increased from 76-843 and 95-1288 mm (min-max full ET_c) and 55(25%)-596 (70%), 17 (17%)-800 (30%) mm (min-max deficit ET_c) for groups 1 and 2, respectively. The big differences in crop yields and irrigation water applied refer to diverse climates and non-conservative crop parameters.

Water saving potential

For all studied publications the deficit irrigation managements varied between 80-17% water levels for hot pepper and potato crops respectively. Specifically, the variation of deficit percentages was 75-20% and 80-17% for crop groups 1 and 2, sequentially (Table 1). The diagrams in Figure 4 show the polynomial functions of simulated water saving and yield reduction for the previous publications. The highest correlation was 0.372 in group 1 followed by 0.117 in crop group 2, the relations are not strong but statistically reasonable in case of different type of evaluated crops and regions. Therefore, we recommend similar further studies for each crop as individual in the future. Regarding group 1, with accepting reduction in crop yield 2.66% can lead to save irrigation water equal to 23.68%, while, when increasing the ratio to 29.03% help to gain 80% of water saving, this high percentage value refers to different climate for studied crops. In respecting group 2, 41.79% of crop

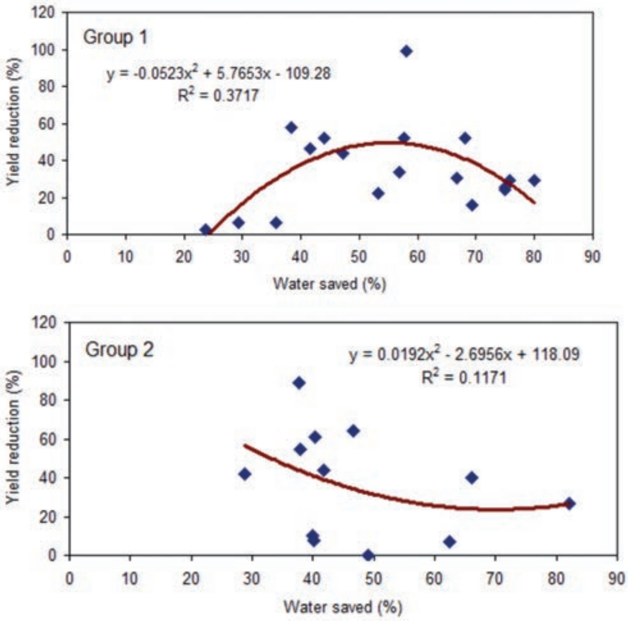


Figure 4. Relationship between irrigation water saving and yield reductions for crop group 1 and 2.

yield reduction saved 28.87% of water used and acceptance of 26.86% in yield reduction increased the water saving potential (WSP) equal to 82.1%. The reason of obtained high WSP in less yield reduction in group 2, refer to the differences in full irrigation water requirements for various studied crop type. Therefore, when deciding to use the findings of this study, we strongly recommended for considering the diverse of local climates and differences in non-conservative crop parameters when simulate the deficit irrigation with AquaCrop model. The WSP obtained in this study higher than 20 to 50% that was reported by Shrestha *et al.* (2013a) for different deficit irrigation managements.

Some findings, recommendations and proposed gaps

Table 2, concludes brief of some published results and recommendations related to full and deficit irrigation managements in wide ranges of regions (humid, sub-humid and dry) around the world. For judging of overall performance of simulation model in full and deficit irrigation conditions, straightforward evaluation was made for the publication results in (Table 2). The authors used root mean square error, normalised root mean square error, coefficient of determination (R^2), model efficiency and index of agreement (D-index) in their evaluations (Loague and Green 1991; Jamieson *et al.*, 1991; Bouman and Van Laar, 2006; Shabani *et al.*, 2014; Stricevic *et al.*, 2017). The overall performance varied between (acceptable and satisfactory) in full ET_c and includes (less satisfactory, acceptable and satisfactory) for deficit ET_c.

Finally, the study suggests some points related to full and deficit irrigation management with AquaCrop model may need further studies as follows; A review investigation for each crop as individual either in Group 1 or Group 2 of this study and evaluate the big differences in crop yields and irrigation water applied simulated with AquaCrop under full and deficit irrigation management

Table 1. Effect of full and deficit irrigation on crop yield and water saving potential of different modelled crops.

Crops	Exp. year	Full ET_c (mm)	Max. defic. (mm)	Y. at full ET_c (t/ha)	Y. at max. defic. (t/ha)	Reduc. in yield (%)	Water saved (%)	References
Maize	1995	568	174 (33%)*	11.4	9.6	15.79	69.37	Heng *et al.* (2009)
	2010-2011	310 (Sl)	75.0 (25%)	≈3.4	≈2.4	29.41 24.32	75.81	Shrestha *et al.*
		360 (L&cl)	90.0 (25%)	≈3.7	≈2.8		75.00	(2013a)
	2014-2016	555 (Exp.1)	235 (33%)	11.0	5.3	51.82 21.97	57.66	Greaves and Wang
		300 (Exp.2)	140 (33%)	13.2	10.3		53.33	(2016)
	1996-1997	509	372 (≈50%)	10.4	NA	NA	26.92	Katerji *et al.*
		498	338 (≈50%)	9.8	NA	NA	32.13	(2013)
	2009-2010	481.4 (Vali. N.L.F.L.)	447.4 (50%)	5.85	5.89	–0.68	7.06	Abedinpour *et al.* (2012)
Wheat	2010-2011	220	55 (25%)	≈4.3	≈3.2	25.58	75.00	Shrestha *et al.* (2013a)
	2000- 2005	300	100 (33%)	6.3	4.4	30.16	66.67	Andarzian *et al.* (2011)
	2008-2009 (N.Y)	375	75 (20%)	8.68	6.16	29.03	80	Xiangxiang *et al.* (2013)
	2005-2006	534	282 (50%)	NA	NA	44.1	47.19	Mohammadi *et al.* (2016)
Soybean	2011	393	138 (52%)	NA	NA	NA	64.89	Khoshravesh *et al.* (2012)
Sorghum	2013-2014	500 (S.S)	210 (58%)	8.0	<0.1	98.75	58.0	Araya *et al.* (2016)
		600 (S.L)	370 (38%)	8.4	3.55	57.74	38.33	
Rice	2008-2009	843	596 (70%)	6.06	5.67	6.44	29.30	Maniruzzaman *et al.* (2015)
Cotton	2005	212	136 (64%)	5.11	4.78	6.46	35.85	Linker *et al.* (2016)
	2008	329	142 (56%)	5.30	3.50	33.96	56.84	
	2008	797	466 (50%)	5.4	2.9	46.30	41.53	Hussein *et al.* (2011)
	2009	758	425 (50%)	5.2	2.5	51.92	43.93	
	2010	76	58 (75%)	3.38	3.29	2.66	23.68	Qiao (2012)
	2011	635	203 (33%)	3.86	1.85	52.07	68.03	
Tomato	2007-2008	485	345 (≈50%)	6.7	3.9	41.79	28.87	Katerji *et al.* (2013)
		486	290 (≈50%)	6.7	2.6	61.19	40.33	
	2012	259	88 (34%)	7.26	4.34	40.22	66.02	Linker *et al.* (2016)
Onion	2008	492	295 (60%)	3.05	2.81 (B.D)	7.87	40.04	Nagaz *et al.* (2012)
	2009	474	285 (60%)	3.27	2.94 (B.D)	10.09	39.87	
Potato	2012	216.6 (Exp.1)	110.2 (49%)	9.58	9.55	0.31	49.12	Gebremedhin *et al.* (2015)
		220 (Exp.2)	82.5 (62.5%)	11.52	10.72	6.95	62.5	
	2013	95	17 (17%)	11.84	8.66	26.86	82.10	Linker *et al.* (2016)
	2011-2012	791.1	550.7 (60%)	14.44	10.06	30.33	30.39	Montoya *et al.* (2016)
Taro	2010-2011	1288	800 (30%)	1.14	0.52	54.39	37.89	Mabhaudhi *et al.* (2014a); Mabhaudhi *et al.* (2013b)
Hot pepper	2010- 2011	452	282.0 (80%)	1.94	0.21	89.17	37.61	Sam-Amoah *et al.* (2013)
Saffron	2004- 2005	≈300	≈160 (50%)	0.012	0.0043	64.17	46.67	Mirsafi *et al.* (2016)
Quinoa	2005-2006	137	80 (≈60%)	NA	NA	NA	41.61	Geerts *et al.* (2009)
Cabbage	2013-2014	247	144 (60%)	1.43	0.80	44.10	41.70	Pawar *et al.* (2017)

*Values in parentheses are percentages of maximum deficient from full evapotranspiration (ETc); Reduc., Reduction; Max. defic., maximum deficient; adequ, adequate; Experimental year(s); NA, not available; Sl., sandy loam; L&cl., loam and clay loam; Exp.1, Experiment (1); Vali. N.L.F.L., validation for non-limiting fertilised level; N.Y, normal year; S.S and S.L, Sandy Soil and Silt loam; B.D, bulbs dry yield.

Table 2. Summary of overall performances and findings for AquaCrop model used in different locations.

References	Location	Overall model perfor. in full ETc	Overall model perfor. in deficient conditions	Findings and Recommendations
Paredes *et al.* (2014); Alves *et al.* (1991)	Portugal	A good performance	Adequacy performance	The default parameters show less good performance with acceptable errors which can be use when field data are absence
Araya *et al.* (2010)	Ethiopia	Adequate performance	Low performance	The model can be used in the evaluation of irrigation strategies and optimal planting time. The possibility of obtaining more grain yield under deficit irrigation
Mebane *et al.* (2013)	USA	NA	NA	Model was accurately simulated the progression of cumulative grain yield with time and reasonably well in simulating the SWC at the six studied depths from (0.18- 1.70 m)
Ahmadi *et al.* (2015)	Iran	Satisfactorily	Insufficient accuracy	Considered the model as a useful decision-making tool for investigating deficit irrigations and suggested the model should be included some calibrating parameters about the root distribution pattern in the soil for more benefit
Mkhabela and Bullock (2012)	Canada	NA	NA	Recommended to evaluate, validate and fine-tuned the performance of the model under the wider range of conditions and crops
Farahani *et al.* (2009)	Syria	Accurate	Accurate	Study provides first estimate values of cotton parameters, it is useful for future model testing and use. The key calibrated parameters are site-specific, which they must to be tested under different climate, soil, variety, irrigation methods, and field management
Trombetta *et al.* (2016)	Italy	NA	NA	The model shows good estimations of the CC development of winter wheat when used MODIS LAI images as a measure of the vegetation cover retrieved by remote sensing. Using remote sensing with AquaCrop may lead to important improvements in the evaluation of wheat yield at the regional scale and to obtain acceptable estimates of each hydrologic balance component, such as a space and temporal variability of soil moisture
Mabhaudhi *et al.* (2013a, 2014b)	South African	Well	Reasonable	The minimal data requirements of model make it particularly beneficial within the greater and broader context of encouraging adoption of models, as decision-making support tools in places were access to extensive data sets might be limited. The model should be used for modeling other neglected and underutilised crops
Karunaratne *et al.* (2011)	UK	Satisfactory	Satisfactory	The validation results underestimated Y and other crop parameters in variable climates. variation in the quality and quantity of solar radiation have indirect effects on simulations through ET0 calculations
Geerts *et al.* (2009, 2010)	Bolivia	Satisfactory	Satisfactory	Study derived DI schedules for quinoa in Bolivia. Recommended a methodology to avoid drought stress during the sensitive growth stages and to guarantee maximum water productivity. This methodology can be an illustrative decision support tool for sustainable agriculture based on DI in case it needs to applied on other crops and regions. Finally, further improvements of the model for soil nutrient depletion, pests, diseases, and frost are also possible

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Table 2. Continued from previous page.

References	Location	Overall model perfor. in full ETc	Overall model perfor. in deficient conditions	Findings and Recommendations
Tavakoli *et al.* (2015)	Iran	Acceptable	Acceptable	This model is able to optimise planting date under water constraint environment for barley. Also, can be used in the evaluation of crop irrigation strategies
Toumi *et al.* (2016)	Morocco	Acceptable	Acceptable	The results proved that, early sowing is more adequate than late sowing in saving water and obtaining adequate grain yield. value 0.6 of Dr, threshold is an appropriate threshold of water depletion to improve the wheat irrigation management. The model can be useful tool for planning irrigation schedules in arid and semi-arid regions after validation under real conditions. For appropriate decisions, other studies relative to economic and environmental analysis should be performed in future
García-Vila and Fereres (2012)	Spain	Satisfactory	Satisfactory	The findings can support the suitability of the crop parameters recommended by FAO (2010), and illustrate the robustness and the general applicability of AquaCrop. That beside the model predicted a strong negative impact on farm income of delaying a decision on the level of seasonal water allocation by the water authority, reaching up to 300 € ha^{-1} in the case of the study area
Adeboye *et al.* (2017)	Nigeria	Accurate	Accurate	Good ability to optimise water productivity of soybeans at farm level and basin scale in dry and sub humid regions
Gebreselassie *et al.* (2015)	Ethiopia	Adequate	Less satisfactory	The model is less qualified for simulating treatments with severe or prolonged water deficit below 50% of ET. For improving crop yield in water deficit regions, the model proved the possibility of obtained more maize yield from less water used

ETc, evapotranspiration; NA, not available; CC, canopy cover; LAI, leaf area index; DI, deficit irrigation; FAO, Food and Agriculture Organisation.

as well as justification of high WSP corresponding less crop yield reduction. Application of the model with fruit trees in order to optimise its water use (Ismail *et al.*, 2015). Testing the economic values and environmental analysis of the different irrigation schedules that were derived from the model simulation (Toumi *et al.*, 2016). The effect of high temperature stress coefficient on HI to control overestimations of yield (Montoya *et al.*, 2016). Further studies to define the terminology of severe water stress in deficit irrigation of major crops as numeric range, to avoid the mis-simulation of crop yield and water use.

Conclusions

Precise evaluations were made for data published from 1979 to 2018 related to full and deficit irrigation managements simulated with FAO-AquaCrop model. The objective was to evaluate the application of full and deficit irrigation *vs* crop yield and water use for different crops (group 1 and 2) and regions around the world. In order to find the significance variations in modelled crop yield, irrigation water use and yield reductions corresponding to water saving potential. As well as, reporting brief summarise of findings, recommendations linked to model simulation and proposed some gaps for further investigations. The analysis showed that, there are significant differences in yield reductions corresponding to water saving. The polynomial correlation of R^2 was 0.372 in group 1 and 0.117 in crop group 2, were not strong relation but acceptable due to the different type of studied crops and the big variation in their water needs. Model performance varied between (acceptable and satisfactory) in full ET_c and (less satisfactory, acceptable and satisfactory) for deficit ET_c managements. Simulated yield varied between 13.2 to 3.3 and 14.44 to 0.012 t/ha in full ET_c, and between 10.3 to <0.1 and 10.72 to 0.004 t/ha in deficit ET_c for groups 1 and 2, respectively. In the term of WSP, accepting reduction in crop yield equivalent 2.66 and 29.03% save irrigation water equal to 23.68 and 80% in groups 1, while the reduction of 41.79 and 26.86% of yield in crop groups 2 saved 28.87 and 82.1% of water used. The two maximum of water saving values are higher than water saved value that was reported for deficit irrigation in previous publications. The study also suggested some significant points related to full and deficit irrigation management with AquaCrop model need further studies *e.g.* evaluating the big differences in crop yields and irrigation water applied as well as justification of high WSP corresponding less crop yield reduction, testing the economic values and environmental analysis of the different irrigation schedules that were derived from the model simulation and defining the terminology of severe water stress in deficit irrigation of major crops as numeric range, to avoid the mis-simulation of crop yield and water use.

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