Interactive comment on **"Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching"** ***by*** **A. D. Chukalla et al.**

Reply to Anonymous Referee #1

We thank Referee #1 for the comments and reply to each of the points below.

Reply to the two major comments

1) The current interest on irrigation techniques and strategies is mainly (but not only) due to present and future water scarcity (including trade-offs with other uses). I found it a pity that the study does not refer to this in any sense. Why not trying? E.g. by looking how much more production could be achieved with the saved water. Or upscaling somehow the results for a whole country/region and assessing how much "extra" water per capita would be available for households if the right combination of mulching and irrigation techniques and strategies is chosen. I think you are one little step away from having some nice and very relevant implications of your results; it would be a pity not to try to get something in that direction. In any case, it would be good to add a subsection in the discussion referring to how appropriate is your model for studies under climate change, i.e. do you think that the relationships you discover would hold under altered climate and CO_2 concentrations?

Yes, the relationships can be expected to hold true under altered climate. In the paper, the sensitivity of the water footprint to agricultural management in irrigated production systems was simulated and analysed for four climates, ranging from arid to sub-humid and for three typical years each (i.e. wet, normal and dry). With this sensitivity test, we show the effects if changing climate would entail dryer or wetter conditions. We did not simulate the effects of changes in CO_2 concentrations, but consider this outside the scope of the current study, which is focussed on the effects of improved irrigation and mulching.

Indeed, as suggested, the findings of this study will be very useful to study possible water savings (while producing the same crop amount) or possible crop production increases (without increasing water use). Results of this paper will be used in a subsequent paper, with the help of an appropriate model, to study at a basin scale the possible water saving and reduced water scarcity by implementing the irrigation and mulching strategies studied in the current paper at a larger scale. In the current paper we can add a reflection in the concluding section regarding this possible use of the findings of the current study.

2) I found the differentiation between organic and synthetic mulching a bit problematic. As you mentioned, your model does not account for the soil biochemistry. But in reality organic mulching frequently changes this aspect, supplying extra carbon, increasing fertility, decreasing requirements of fertilizer inputs, etc. At the end these changes affect also percolation, runoff, evaporation, and thus, water intake by plants and transpiration. If I understood right, the difference between synthetic and organic mulching in your study affects only soil evaporation by means of an arbitrary parameter. I found this too simplistic and am afraid that this could affect the validity of your results regarding the mulching type. Isn't there any possibility of adding a bit of complexity to this?

The AquaCrop model does simulate the effect of mulching on evaporation and represents effects of soil organic matter through soil hydraulic properties influencing the soil water balance. The model however does not simulate the effect of organic mulching on the organic content of the soil, nor does the model simulate the decomposition of organic materials. The current model doesn't allow for including these effects, but we agree with the referee that this is worth further exploring in future studies.

Reply to the minor comments

3)

a. Section 2.1. Please better explain how AQUACROP calculates yields.

Aquacrop first estimates the biomass (B) from a water productivity parameter (WP) and transpiration ($B = WP*\Sigma Tr$). The harvestable portion of the biomass (yield) is then determined by multiplying biomass with the harvest index, HI ($Y = B *HI$). WP is the water productivity parameter in units of kg (biomass) per m^2 (land area) per mm (water transpired), normalized for atmospheric evaporative demand and air CO_2 concentration. The harvest index (HI) is simulated starting from flowering to yield formation, depending on the growing conditions, crop species and cultivar (Steduto et al., 2009).

b. Section 2.2. Please better explain how capillary rise works in the model.

Aquacrop estimates capillary rise based on the depth of the water table and two parameters that are specific to hydraulic and textural characteristics of the soil (Janssens, 2006). The two parameters are estimated for different textural classes of the soil that have similar water retention curve (h-Θ). The capillary rise from AquaCrop is comparable with the estimate from the UPFLOW model; the latter approach uses the Darcy equation that considers the water retention curve (h-θ relationship) and the relationship between matric potential (h) and hydraulic conductivity (K) (Fereres et al., 2012).

c. Section 2.3.1. How is interception loss (evaporation from leaves) accounted for in the case of Sprinkler?

Sprinkler has interception losses unlike furrow, drip and subsurface drip techniques. The AquaCrop model does not explicitly account the interception losses from sprinkler. We will add this in the discussion.

d. Section 2.3.1 Does your model account for the influence of row spacing (planting density) in soil evaporation?

Yes, the AuqaCrop model accounts for the planting density in soil evaporation. Planting density is used to determine the canopy cover, which is a factor in the calculation of soil water evaporation.

e. "It uses the conservative behaviour of biomass water productivity (WP) to simulate biomass and yield responses of crops". What does that mean?

The conservative behaviour of biomass water productivity (WP) means that WP remains constant for a given crop species after normalization for evaporative demand of the atmosphere and air carbon dioxide concentration (Steduto et al., 2007).

f. P6954 L7. Please mention the source you used for adopting those values for fm.

The model considers the effect of mulch on crop evaporation by two factors: mulch material (fm) and percentage of soil cover. Quoting the paper by Allen et al. (1998), the values of the parameters for mulch material (fm) are suggested in the user guide manual to vary between 0.5 for mulches of plant material and close to 1.0 for plastic mulches (Raes et al., 2013).

The referee’s suggestions **4 to 7** are clear and valid. These suggestions will be considered in the revision of the article.

Interactive comment on **“Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching”** ***by*** **A. D. Chukalla et al.**

Reply to Anonymous Referee #2

We thank Referee #2 for the comments; below we give the reply to the comments.

The comments

This paper conducts an investigation on the effects of different management practices on the consumptive water footprint of three crops grown in three different soils considering four environments. The objective of the paper is clear, the writing is concise and the development of the argument can be followed well.

To my knowledge this is the one of the first papers regarding the study of the water footprint reduction using the AquaCrop model. Today many papers contribute to the literature on the water footprint; using databases as for example the one developed by Mekonnen and Hoekstra (2011, 2012), but little studies refer to the effects of different water management practices in the context of water scarcity. In my view, it is important to go deeper in the understanding and interpretation of water footprint input data. *Thus, as far as I am concerned, an original and relevant contribution is definitely present in the well-informed analysis of the different management practices on evapotranspiration, yield and consumptive water footprint as well as in the study on the variability of the ratio of green to blue water footprint. This contribution is very interesting, and should be highlighted in the abstract, introduction and conclusion.*

The introduction is concise, summarizes previous studies on the same line and clearly defines the main objective of the paper. *I suggest that the authors strengthen the contribution of this study on the existing literature and specify the relationship of their work with other studies on the water footprint at different scales (global, national, local). It would be interesting to see how this study could help to interpret and clarify the results on other work.* I personally believe that this work can contribute to the interpretation of scientific literature that utilizes the water footprint concept. The methodology is clearly explained and developed in detail. Similarly, the input data and their sources are well defined. *However, in my opinion the study lacks an assessment of the sources of uncertainty (accuracy of the databases used, methodology utilized, assumptions made, etc.). If possible, it might be better to develop this point. This discussion would add value to your study and would help to improve the understanding of the results observing the possible drawbacks for their interpretation.*

The discussion warns on the need to validate the model results with field experiments, which as the authors acknowledge is important but costly. This is in my view an important point that makes the reader to be cautious when drawing general conclusions from this study. *I would also develop on the possibility to extend this study for more crops and regions. Finally, the authors could go deeper in the recommendations for action to improve sustainable water use provided from the results obtained. Policy* *implications would be a plus, also looking at the possibility/caution when extending the findings to other scales (local, regional, national, global), since many studies on the water footprint have been carried out in this line over the last decade.*

Overall Recommendation: Considering the above strengths and weaknesses of the contribution it is recommended that the paper may be accept after minor revisions.

Reply to the comments: these remarks will be incorporated in the revised version of the paper.

We agree with the reviewer observation that the main contribution of the paper lies in the structured analysis of the influence of multiple factors in agricultural management on the water footprint and its components. We will edit abstract, introduction and conclusion to properly highlight this contribution.

The sensitivity of AquaCrop-simulated yields to model parameters, under diverse environmental conditions, was studied by Vanuytrecht et al. (2014). That study shows that the parameters describing crop responses to water stress were not often among those showing highest sensitivity. However, the particular root and soil parameters indeed need attention during calibration.

In our study we used the observed climatic data from the European Climate Assessment and Dataset, ECA (Klein Tank et al., 2002). The data in the ECA goes under homogeneity test and the missing data is filled with observations from nearby stations (i.e. within 12.5 km and with height differences less than 25m) (Klein Tank, 2007). The soil texture was identified from European Soil Database (Hannam et al., 2009). Observed soil data at one of the sites representing the humid environment (at Bologna, Italy) was shown to be comparable to the soil type and characteristics from the European Soil Database.

We did not perform a specific sensitivity analysis for these inputs or a specific uncertainty analysis propagating parameter uncertainty through the model, which both would be interesting. The current analysis, however, already shows the robustness of the AquaCrop-simulated effects of irrigation method, irrigation strategy and mulching for a large set of conditions for soil, crop, climate and weather. Together with the sensitivity results of Vanuytrecht et al. (2014), we believe the overall evidence to support the conclusions is strong.

Indeed, as suggested, it is worthy to extend this study to cover more crops and regions and to give recommendations for improving sustainable water use and give policy implications. By ranking of irrigation methods, irrigation strategies and mulching methods the paper is already meant to serve in this direction; formulations are still with caution as relevant considerations on grey water and e.g. possible economic trade-offs are outside the scope of the present paper. This will be studied in subsequent papers, with the help of a model that can handle additional management practices like fertilizer application scenarios, and on larger spatial scale, i.e. farm and/ or basin scale.

Interactive comment on **"Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching"** ***by*** **A. D. Chukalla et al.**

Reply to the comments from T. Trout #3

We thank T.Trout for the comments and below are the reply.

The comments (in coloured background) and the replies

This paper presents the results of an interesting and comprehensive simulation study using AquaCrop of the impacts of environment and management practices on crop water consumption and yield, with the results presented as water footprint (WF) of blue and green water. The methods were adequately described, with a couple exceptions (below). The results are well-presented and understandable. In general, the results are as would be expected from past work and general understanding of the physics. I compliment the authors on posing the problem in terms of water consumption rather than irrigation water applied.

As the authors point out, the effects simulated are essentially the result of differences in simulated surface evaporation. Thus, the ability of Aquacrop to correctly simulate surface evaporation is critical. Although AquaCrop has been extensively validated, it is not clear that the surface evaporation component of the model has been sufficiently validated. The authors should provide references or other evidence that the surface evaporation component is accurate under at least some of the conditions simulated.

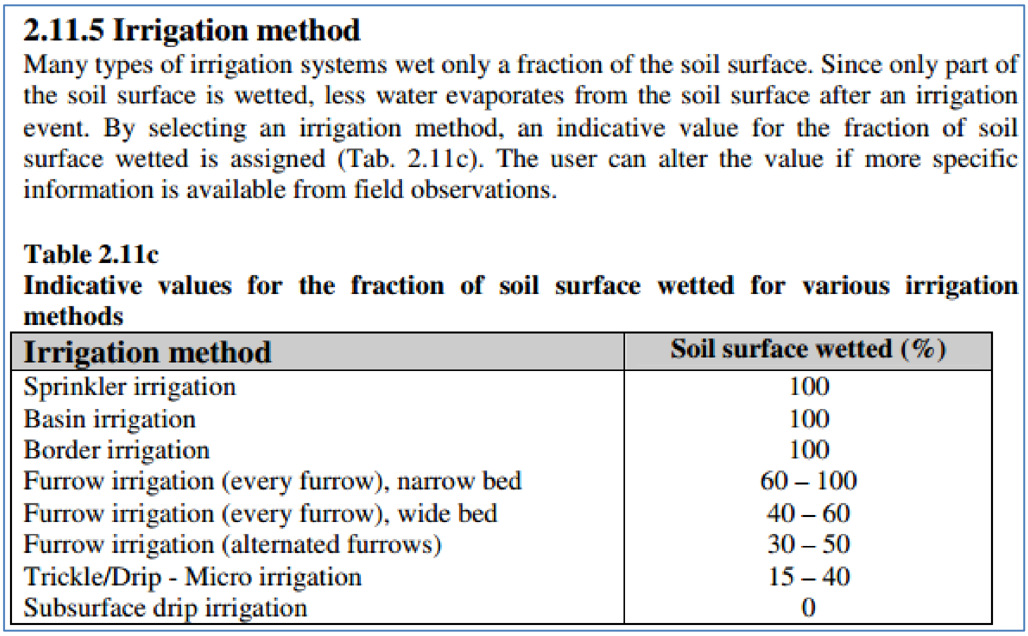
Indeed the simulated effect of various management practices on the consumptive water footprints depends on AquaCrop's skills in simulating evapotranspiration and yield. AquaCrop simulates soil evaporation in two stages: an energy limiting stage and a falling rate stage. This approach is well described and validated (Ritchie, 1972). In his study, Ritchie (1972) also confirmed the ability of the method to predict evaporation for a wide variety of soil types and climatic conditions. The parameters for estimating crop transpiration in AquaCrop are reported to be conservative for the studied crops: maize, potato and tomato (FAO, 2012).

Studies on experimental fields also confirm the ability of the model to reasonably simulate evaporation and transpiration for various conditions. A research conducted on potato for three levels of irrigation (100%, 75% and 50% plant water requirement) at experimental fields in eastern Iran shows that AquaCrop has good ability in simulating evaporation and transpiration of crops and yield (Afshar and Neshat, 2013). It was also indicated that AquaCrop is able to simulate the ET and yield of maize under different irrigation regimes (full and deficit) and mulching practices (plastic and organic mulching) in the North Delta of Egypt (Saad et al., 2014).

The study assumes 80% surface wetting with furrow irrigation. The most common furrow configuration in the U.S. would be alternate furrow irrigation, which results in about 50% surface wetting for most irrigation.

The paper chooses to make a generic assumption on the specific furrow irrigation method. The 80% wetting percentage for furrow irrigation is assumed to be representative for narrow bed (every furrow) from the indicative range 60% to 100% in the AquaCrop manual (Raes et al., 2013); the indicative values for specific furrow irrigation methods differ (see table below).

The rationale in assuming a fixed wetting percentage for furrow irrigation in a point-scale model like AquaCrop is to compensate for the extra surface wetting which occurs due to non-optimal distribution and application efficiency compared with other irrigation techniques.



2.11.5 Irrigation method

Many types of irrigation systems wet only a fraction of the soil surface. Since only part of the soil surface is wetted, less water evaporates from the soil surface after an irrigation event. By selecting an irrigation method, an indicative value for the fraction of soil surface wetted is assigned (Tab. 2.11c). The user can alter the value if more specific information is available from field observations.

Table 2.11c
Indicative values for the fraction of soil surface wetted for various irrigation methods

Irrigation method	Soil surface wetted (%)
Sprinkler irrigation	100
Basin irrigation	100
Border irrigation	100
Furrow irrigation (every furrow), narrow bed	60 – 100
Furrow irrigation (every furrow), wide bed	40 – 60
Furrow irrigation (alternated furrows)	30 – 50
Trickle/Drip - Micro irrigation	15 – 40
Subsurface drip irrigation	0

The irrigation strategies need better rationalization and description. The full irrigation strategy of irrigating at relatively small depletions (20 – 36% of RAW) would result in very high irrigation frequencies which would be impractical with furrow irrigation.

Full irrigation was simulated to obtain no water stress conditions, thus the full evaporative demand was assumed to be met. The no water stress condition for maize, potato and tomato is simulated by refilling the root zone to field capacity (FC) when the readily available moisture (RAW) of the soil is depleted by 20%, 36% and 30% respectively (FAO, 2012). We fully agree with the referee’s comment that this scheduling results in a high irrigation frequency, which is impractical in the case of furrow irrigation.

To circumvent such unrealistic simulation for the case of furrow irrigation, we firstly generated the irrigation requirement automatically for no water stress condition, which obviously results in high irrigation frequency especially for course texture soil type. Then the irrigation depths were aggregated and shifted a few days forward, practically allowing more depletion than the no water stress level, in such a way that a minimum of a week gap is maintained between two irrigation events. The appropriateness of the approach to represent overall no-stress conditions was checked by considering the resulting crop yields.

Since RAW is, by definition, the depletion level for minimal stress, why were smaller depletion levels used?

The depletion level for minimum stress (effect on the canopy expansion rate) in AquaCrop starts far before the soil moisture depletion reaches 100% RAW. AquaCrop simulates water stress response for three thresholds (Steduto et al., 2009), see the figure below for potato. The three water-stress responses at different levels of soil moisture depletion are canopy expansion rate, stomatal closure and senescence acceleration. For instance, the minimum stress for potato starts to develop when the soil moisture depletion exceeds 36% RAW, well before depletion reaches 100% RAW. This stress affects the leaf expansion and reached to the point where transpiration fully stops when the soil moisture depletion drops down to the stomata closure threshold.

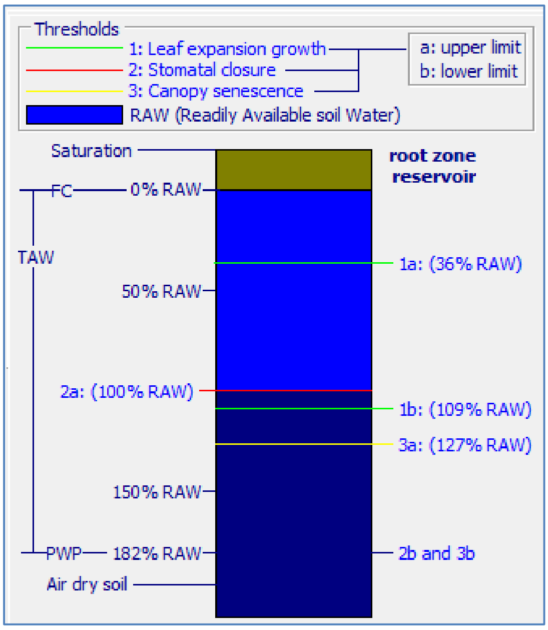


Fig: the three thresholds in water stress for potato: leaf expansion growth, stomata closure and canopy senescence.

The deficit irrigation strategy is not defined. Was it based on a depletion level or reduction in ET? The results indicate very little reduction in ET or Y with deficit irrigation, indicating very minor deficits.

We have used the definition for deficit irrigation (DI) from Fereres and Soriano (2007) and English (1990): it is defined as the artificial application of water below the evapotranspiration requirements by limiting water applications particularly during less drought-sensitive growth stages. Therefore, the deficit strategy is based on reduction of the irrigation supply from the full irrigation requirement.

We tested various deficit irrigation strategies (reduction of the irrigation supply) that fall under two broad categories: (1) regulated deficit irrigation, where a non-uniform water deficit level is applied during the different phenological stages; and (2) sustained deficit irrigation, where water deficit is uniformly distributed over the whole crop cycle. In general, the larger the deficit the smaller the yield was simulated, as expected. The non-linear relation between yield and ET (and thus irrigation supply) gives rise to the optimum point, i.e. the deficit irrigation strategy with the lowest consumptive WF in $m^3 t^{-1}$. In the analysis of simulations, the paper used the specific deficit strategy that is optimal according to the model experiments.

Supplemental irrigation is defined as limited applications, although the stated replacement of full depletions to FC whenever the depletion reaches RAW would be a common practice for full irrigation. Figure 6 indicates that, for this condition, only 21.5 mm of supplemental irrigation was used, and the deficit treatment reduced irrigation by only 14.4 mm. These are extremely small changes.

Oweis et al. (1999) defined supplementary irrigation (SI) as the application of a limited amount of water to increase and stabilize crop yields when rainfall fails to provide sufficient water for plant growth. In fact, this definition does not operationally describe the quantity and timing of supplementary irrigation. In our study we defined the timing of irrigation to be when stomata closure is triggered (100% of the RAW depleted), and the quantity is just one time refilling to field capacity (or a onetime full irrigation).

As the result in Figure 6 shows: the supplementary and deficit irrigation supply were 80 mm and 281 mm respectively (while deficit irrigation was 80 mm below full irrigation requirement). The effect of 80 mm supplementary irrigation allowed an additional ET of 51 mm of green water plus 21 mm of blue water, making a significant impact on crop growth. The 80 mm irrigation reduction by deficit irrigation as compared to full irrigation only led to a reduction of 14 mm in blue ET and (with a minor increase in greet ET) 12 mm in total ET; the significant reduction in total irrigation depth thus resulted in minor yield losses. The following table presents the values for Figure 6 plus the irrigation water amount (mm) that was not presented in the figure.

Table: The irrigation supply and ET values for supplementary, deficit and full irrigation plus rainfed

	Rain (mm)	**Irrigation supply (mm)**	**ET-green (mm)**	**ET- blue (mm)**
Rain-fed	63	0	171	0
Supplementary irrigation	63	80	222	21
Deficit irrigation	63	281	117	224
Full irrigation	63	361	115	238

Provide information on the percent covered by mulch in the simulations. It appears that 100% ground cover was used? This is not a feasible practice for furrow or sprinkler irrigation (or rainfall), and is not the normal practice for synthetic mulches.

In our study, the mulch covers the fraction of soil surface that gets wet with irrigation (moisture) but not the whole soil surface. A mulch cover of 100% for organic and 80% for synthetic materials was assumed. In fact the combination of the percentage of mulch cover and the value for type of mulch material translated into a factor that reduces evaporation accordingly. Indeed, not all combinations of irrigation method, mulching practices and crop are practical in reality, even when AquaCrop still consistently simulates what consequences could emerge.

For me, presentation of results in terms of WF clouds my evaluation of the simulations. The simulation of yield and surface evaporation are relatively separate processes. Thus, when small differences in WF are reported, it is difficult to know if it results from changes in yield or evaporation.

It is true that the reported smaller consumptive WF can arise either from a reduction in ET or from an increase in yield or combination of the two. The main objective of the paper is, to assess irrigation practices on their effect on the water consumption embedded in the resulting produce, adding a dimension to literature and explaining the choice for these figures. Illustrations of underlying effects on Y and ET individually are therefore restricted to a few examples.

It is difficult to understand the first sentence on P 6960.

The first sentence on P6960 is on the comparison of ET versus Y (yield) as resulting from our study with earlier studies under comparable condition. The ET versus Y plot made based on our model experiment results (Figure 2) is comparable with the production function in earlier studies (Amarasinghe and Smakhtin, 2014;Wichelns, 2015).

Figs 2 and 3: These figures appear to present yields at some moisture content of the yield. Since potato and tomato are mostly water, the graphs indicate very high yield and low WF, and maize with low yield hand high WF. Are moisture contents normalized to a standard value (for example, maize yield is often normalized to 15.5% moisture in the U.S.). Only if the yield is represented in terms of dry matter can the crops be compared. This would also allow graph scales that can be read.

With Figures 2 and 3 we aim to present ET and yield (marketable) in the form that they are used as input in regular water footprint accounting. AquaCrop simulates dry yield. Unlike maize, the marketable yield for tomato and potato are in their fresh form. Therefore we need to convert the dry yield of tomato and potato to their fresh yield form.

A study from FAO that compiles the yield response for 16 herbaeous crops (Steduto et al., 2012) reports the dry matter content of fresh tomato and potato to be in the range of 4 to 7% and 20 to 25% respectively. We calculated the markatable yield of tomato and potato by assuming the dry matter of tomato and potato to be 7% and 25% respectevely.

In the revised paper, as it was also suggested by the second referee, the figure will be separated into three, each showing the ET vs yield relationship of a single crop.

I am concerned that these results show yield with less than 200 mm of ET. I do not believe you can produce a consistent yield for these crops in an arid or semi-arid climate with less than 200 mm of ET. In my semi-arid environment with drip irrigation, maize requires about 200 mm of well-timed transpiration to produce the first unit of yield. I recognize that these results represent a wide range of climates, but I do not expect yield production at very low ET values, and thus question the validity of AquaCrop in this range.

The yields for ET less than 200 mm in Fig. 2 are under rainfed (in semi-arid environment) and high deficit irrigation (drip/subsurface drip techniques), both with synthetic mulching practice. In such condition the evaporation is almost zero and transpiration takes if not all the lion share of ET. The corresponding yield is also very small, less than one third of the maximum possible. This illustrates that, to our opinion, the simulations in the paper are consistent with the information provided by the reviewer.

Figs 4 and 5: Define the meaning of the colored lines.

In Fig. 4 the lines show the individual simulations by irrigation strategy: red and black for the full and deficit irrigation strategies respectively. Similarly, in Fig. 5 the lines show the individual simulations by irrigation strategy: red, blue, light green and green denote full irrigation, deficit irrigation, supplementary irrigation and rain-fed production.

Fig 7. Define which figure (b, c) is for which treatment (deficit, full).

Adding the word "respectively" in the caption, Figure 7 will be corrected as follows: "Fig 7: Figures (b) and (c) zoom in for the practices of full and deficit irrigation, **respectively,** without mulching, showing specific WF changes per type of environment."

Was synthetic mulching simulated only for drip and SDI irrigation? Why?

AquaCrop under synthetic mulching practice simulates the reduction in evaporation and application of the irrigation water in the root zone water balance. Indeed, the paper presented the simulation results for synthetic mulching only with drip and subsurface drip irrigation, though it was done for all irrigation techniques including furrow and sprinkler. This is because drip and subsurface drip irrigation techniques can be laid under the mulch to fully consider the irrigation application to the root zone.

I don't understand your explanation for the lower impact of SDI than drip under full, no mulch conditions. This indicates to me a problem in the simulation.

The lower impact of SDI than drip under full, no mulch conditions is the result from the physical description of processes in the water balance, as contained in AquaCrop. We believe that these result are plausible, as they are consistent with findings from an earlier study (Dehghanisanij and Kosari, 2011) on the energy vs. moisture limitations on ET. The study by Dehghanisanij and Kosari (2011) explains that the net energy available for soil evaporation for SSD irrigation is larger than drip. This is due to heat convection or the higher soil heat flux along with droplets of water moving from the soil surface into the soil in the case of drip. According to that study, when the available moisture is limited the ET from SSD exceeds that from drip. This explains, that when moisture is limiting (e.g. in an arid environment using a deficit irrigation strategy – Fig.7(c)) SSD reduces the consumptive WF more than drip. When the net radiation energy available for evaporation is limiting (e.g, in a humid environment or using a full irrigation – Fig. 7 (b)), drip reduces the consumptive WF more than SSD.

These suggestions of the reviewer will be considered in the revision of the article, as indicated above and in particular where they make clear that additional explanations would be helpful to the reader.

Green and blue water footprint reduction in irrigated agriculture: Effect of irrigation techniques, irrigation strategies and mulching

A.D. Chukalla, M.S. Krol and A.Y. Hoekstra

Twente Water Centre, University of Twente, Enschede, The Netherlands
Correspondence to: A. D. Chukalla (a.d.chukalla@utwente.nl)

Abstract

Consumptive water footprint (WF) reduction in irrigated crop production is essential given the increasing competition for fresh water. This study explores the effect of three management practices on the soil water balance and plant growth, specifically on evapotranspiration (ET) and yield (Y) and thus the consumptive WF of crops (ET/Y). The management practices are: four irrigation techniques (furrow, sprinkler, drip and subsurface drip (SSD)); four irrigation strategies (full (FI), deficit (DI), supplementary (SI) and no irrigation); and three mulching practices (no mulching, organic (OML) and synthetic (SML) mulching). Various cases were considered: arid, semi-arid, sub-humid and humid environments in Israel, Spain, Italy and UK, respectively; wet, normal and dry years; three soil types (sand, sandy loam and silty clay loam); and three crops (maize, potato and tomato). The AquaCrop model and the global WF accounting standard were used to relate the management practices to effects on ET, Y and WF. For each management practice, the associated green, blue and total consumptive WF were compared to the reference case (furrow irrigation, full irrigation, no mulching). The average reduction in the consumptive WF is: 8-10% if we change from the reference to drip or SSD; 13% when changing to OML; 17-18% when moving to drip or SSD in combination with OML; and 28% for drip or SSD in combination with SML. All before-mentioned reductions increase by one or a few per cent when moving from full to deficit irrigation. Reduction in overall consumptive WF always goes together with an increasing ratio of green to blue WF. The WF of growing a crop for a particular environment is smallest under DI, followed by FI, SI and rain-fed. Growing crops with sprinkler irrigation has the largest consumptive WF, followed by furrow, drip and SSD. Furrow irrigation has a smaller consumptive WF compared with sprinkler, even though the classical measure of 'irrigation efficiency' for furrow is lower.

Key words: Water footprint, soil water balance, crop growth, AquaCrop, irrigation techniques, irrigation strategies, mulching

1. Introduction

One of the important prospects to relieve increasing water scarcity is to reduce the consumptive water use in the agricultural sector, which takes the largest share in global freshwater consumption (Hoekstra and Mekonnen, 2012) . In crop production substantial gains can be achieved by increasing yield and reducing water losses, with the latter referring to the non-beneficial consumptive water use at field level and the non-recoverable losses at system level (Steduto et al., 2007;Hoekstra, 2013;Perry et al., 2009;Falkenmark and Rockström, 2006). At field level, the focus is to decrease the field evapotranspiration (ET) over the growing period per unit of yield (Y), a ratio that is called the consumptive water footprint (WF) (Hoekstra et al., 2011). Decreasing this ratio ET/Y is the same as increasing the inverse (Y/ET), which is called the water productivity (WP) (Amarasinghe and Smakhtin, 2014;Molden et al., 2010).

The soil moisture status in the root zone regulates plant growth and influences ET. Management practices that influence soil moisture include irrigation techniques, irrigation strategies and mulching practices. The particular irrigation technique influences the way irrigation water is applied, which influences for instance the percentage of surface-wetting, which again influences ET (Raes et al., 2013). The particular irrigation strategy applied determines how much and when irrigation is applied. The mulching practice determines soil cover and in this way influences non-productive evaporation.

Various previous studies considered the effects of management practices on the amount of irrigation water to be applied, drainage, ET and yield (Gleick, 2003;Perry et al., 2009;Perry, 2007). Most studies varied only irrigation technique, only irrigation strategy or only mulching practice, or considered only a few combinations. Besides, most studies are confined to just one crop and one specific production environment (soil, climate). For example, Rashidi and Keshavarzpour (2011) show the effects of three management practices for one specific crop in Iran, showing yields to increase from surface irrigation to drip irrigation and finally to drip irrigation with mulching. Al-Said et al. (2012) show the effect of drip versus sprinkler irrigation on vegetables yield in Oman, showing that the yield per unit of irrigation water applied is higher for drip irrigation. The effect of irrigation strategies such as deficit or supplementary irrigation on ET and Y were studied by different scholars (Igbadun et al., 2012;Qiu and Meng, 2013;Jiru and Van Ranst, 2010;Bakhsh et al., 2012;Jinxia et al., 2012). In a literature review, Geerts and Raes (2009) point out that deficit irrigation strategy decreases the consumptive water use per unit of yield compared to full irrigation. Supplementary irrigation is a strategy to apply some irrigation water when most needed, to overcome drought periods; this increases yield compare to rain-fed conditions without much increase in ET (Oweis and Hachum, 2006;Oweis et al., 1999;Tadayon et al., 2012). Mulching is a method of covering the soil surface that otherwise loses moisture through evaporation. Various studies show the importance of mulching to decrease ET per unit yield in crop production (Ogban et al., 2008;Zhao et al., 2003;Zhou et al., 2011;Mao et al., 2012;Jalota and Prihar, 1998).

Previous studies can be distinguished into two categories: they either focus on the relation between Y and blue water applied (irrigation water applied) or on the relation between Y and total transpiration (T) or total ET. The former category of studies has two caveats: they ignore green water use and, by focussing on irrigation water *application*, they ignore the fact that, through return flow (drainage and surface runoff) some of the blue water applied will return to the water system from which it was withdrawn. The caveat of the latter category of studies is that, by considering *total* T or ET, they do not explicitly distinguish between T or ET from rainwater (green T or ET) and T or ET from irrigation water (blue T or ET). Understanding water resources use in crop production by source (rainwater, irrigation water from surface and groundwater, water from capillary rise) is vital for water resources management.

In this regard, the concepts of green versus blue water by Falkenmark and Rockström (2006) and green versus blue water footprint by Hoekstra et al. (2011) is a useful advance.

The objective of this study is to explore the potential of reducing the green and blue water footprint of growing crops by using a systematic model-based assessment of management practices in different environments. We systematically consider the effect of a large number of management practices, considering four irrigation techniques, four irrigation strategies and three mulching practices. We do so in a large number of different cases: arid, semi-arid, sub-humid and humid environments; wet, normal and dry years; three soil types; and three crops. This is the first systematic model study analysing the effect of field management practices on green and blue ET, Y and green and blue WF under a variety of conditions. The advantage of a model study is that field experiments on the effects of a comprehensive list of management practices in range of cases would be laborious and expensive (Geerts and Raes, 2009). Our cases, however, are based on four real environments, in Israel, Spain, Italy and the UK.

2. Method and data

2.1. Soil water balance and crop growth modelling

To balance simplicity, accuracy and robustness of simulating soil water balance, crop growth and yield process, we use the AquaCrop model (version 4.1) (Steduto et al., 2009a). AquaCrop is available as standalone Windows-based software and as plug-in to GIS software; both run with daily time steps using either calendar or thermal time (Raes et al., 2011). In this study, the Plug-in version was applied with daily thermal time.

AquaCrop keeps track of the soil water balance over time by simulating the incoming and outgoing water fluxes with well-described subroutines. The AquaCrop model enables to simulate various degrees of water supply to the plant, varying from rain-fed and supplementary irrigation to deficit and full irrigation. AquaCrop considers capillary rise to the root zone from shallow groundwater. It estimates capillary rise based on the depth of the water table and two parameters that are specific to hydraulic and textural characteristics of the soil (Raes et al., 2012). The two parameters are estimated for different textural classes of the soil that have similar water retention curve. The capillary rise from AquaCrop is comparable with the estimate from the UPFLOW model, using the Darcy equation and relating matric potential to hydraulic conductivity (Fereres et al., 2012). Water limitations to plant growth are modelled through three sorts of water-stress response: canopy expansion rate, stomatal closure and senescence acceleration (Steduto et al., 2009b).

The crop growth engine of AquaCrop first estimates the biomass (B) from a water productivity parameter (WP) and transpiration (T): $B = WP \times \Sigma T$. The harvestable portion of the biomass (yield Y) is then determined by multiplying biomass with a crop-specific harvest index (HI): $Y = B \times HI$. WP is the water productivity parameter in kg (biomass) per m^2 (land area) per mm (water transpired), normalized for atmospheric evaporative demand and atmospheric CO_2 concentration (Steduto et al., 2009a). The modelling of biomass water productivity (WP), which remains constant for a given crop species after normalization, forms the core of the AquaCrop growth engine (Steduto et al., 2007;Raes et al., 2009).

AquaCrop separates the actual evapotranspiration (ET) into non-productive and productive water fluxes, viz. soil evaporation (E) and crop transpiration (T). Hence, AquaCrop can simulate the effect of the management practices on these two types of consumptive water use distinctively.

AquaCrop calculates soil evaporation (E) by multiplying evaporative power of the atmosphere (ET_o) with factors that consider the effect of water stress, and the fraction of the soil surface not covered by canopy. Crop canopy expands from the initial canopy cover, which is the product of plant density and the size of the canopy cover per seedling. The canopy is considered in the evaporation calculation after adjustment for micro-advective effects. The soil moisture conditions determine evaporation from the soil surface not covered by canopy in two stages. In the first stage, when the soil surface is wetted by rainfall or irrigation, the evaporation rate is fully determined by the energy available for soil evaporation until the Readily Evaporable Water. In the second stage, the falling rate stage, the evaporation is not only determined by the available energy but depends also on the hydraulic properties of the soil. The two-stages approach for calculating evaporation is described in detail and validated in Ritchie (1972), who confirmed the ability of the method to predict evaporation for a wide variety of soil types and climatic conditions.

The soil evaporation is adjusted for withered canopy, mulches and partial wetting by irrigation. The AquaCrop model simulates the effect of mulching on evaporation and represents effects of soil organic matter through soil hydraulic properties influencing the soil water balance. Soil evaporation under mulching practice is simulated by correcting E with a factor that is described by two variables (Raes et al., 2013): soil surface covered by mulch (from 0 to 100%); and mulch material (f_m). Quoting the paper by Allen et al. (1998), the values of the parameters for mulch material (f_m) are suggested to vary between 0.5 for mulches of plant material and close to 1.0 for plastic mulches (Raes et al., 2013). The correction factor for mulching is calculated as:

$$\text{Correction factor for mulching} = (1 - f_m \frac{\text{percent covered by mulch}}{100}) \quad (1)$$

Soil evaporation is also corrected with a factor that is equivalent to the fraction of the surface wetted by irrigation. The adjustment for partial wetting is not applied when the soil surface is wetted by rain. If the soil surface is covered by mulches and at the same time partially wetted by irrigation, only one of the correction factors, the minimum value of the two, is applied.

Experimental field studies confirm the ability of the AquaCrop model to reasonably simulate evaporation and transpiration for various conditions. Research on potato for three levels of irrigation (100%, 75% and 50% of plant water requirement) at experimental fields in eastern Iran shows that AquaCrop has good ability in simulating evaporation and transpiration of crops and yield (Afshar and Neshat, 2013). Another study found that AquaCrop is able to simulate ET and yield of maize under different irrigation regimes (full and deficit) and mulching practices (plastic and organic mulching) in the North Delta of Egypt (Saad et al., 2014).

2.2. The green and blue water footprint of growing crops

The green WF (m^3 t^{-1}) and blue WF (m^3 t^{-1}) of crops were obtained following the definitions and methodological framework of the global WF accounting standard (Hoekstra et al., 2011). They are calculated by dividing the green ET (m^3 ha^{-1}) and blue ET (m^3 ha^{-1}) over the growing season by the marketable crop yield (t). AquaCrop simulates yield in kg ha^{-1} of dry matter. Unlike maize, the marketable yield for tomato and potato are in their fresh form. We calculated the marketable yield of tomato and potato by assuming the dry matter of tomato and potato to be 7% and 25% respectively (Steduto et al., 2012). The AquaCrop output was post-processed to partition soil water content and the various ingoing and outgoing water fluxes into green and blue components. In addition, the blue soil water content and the blue water fluxes were further separated into blue water originating from irrigation water ($S_{b\text{-}I}$) and blue water originating from capillary rise ($S_{b\text{-}CR}$). This partitioning enables to track what fractions of ET originate from rainwater, irrigation water and capillary rise, respectively (Fig. 1).

In the daily green-blue soil water balance calculation, the next procedures are followed: rainfall (R) adds to the green soil water stock; irrigation (I) adds to the blue soil water stock originating from irrigation; capillary rise (CR) adds to the blue soil water stock originating from capillary rise; evaporation (E), transpiration (T) and drainage (Dr) in a certain day are partitioned into the three ‘colours’ (green, blue from irrigation, blue from capillary rise) based on the relative colour composition of soil water content in that day; runoff (RO) in a particular day is partitioned into two colours (green and blue from irrigation) in proportion to the amount of rainfall and irrigation, respectively. Changes in the green (S_g), blue from irrigation ($S_{b\text{-}I}$) and blue from capillary rise ($S_{b\text{-}CR}$) soil water stocks are described in the following three equations:

$$\frac{dS_g}{dt} = R - (Dr + ET)\left(\frac{S_g}{S}\right) - RO\left(\frac{R}{I+R}\right) \quad (2)$$

$$\frac{dS_{b-CR}}{dt} = CR - (Dr + ET)\left(\frac{S_{b-CR}}{S}\right) \quad (3)$$

$$\frac{dS_{b-I}}{dt} = I - (Dr + ET)\left(\frac{S_{b-I}}{S}\right) - RO\left(\frac{I}{I+R}\right) \quad (4)$$

where *d*t is the time step of the calculation (1 day), R rainfall [mm], I irrigation [mm], RO surface runoff [mm], ET (E+T) evapotranspiration [mm], Dr drainage (percolation) [mm], and CR capillary rise [mm].

The simulations with AquaCrop were initialized with typical soil moisture content. This was determined by running the model for each case for a successive period of twenty years (1993 to 2012) and taking the average soil moisture content at the start of the growing period over the full period as the initial condition for another run for the same period of twenty years. We did this iteratively, until the twenty-year average output stabilized. We thus used the twenty-year average soil moisture content at the start of the growing season as initial condition for our simulations. The partitioning of the soil moisture content into green and blue water components was initialized based on a similar procedure. The green and blue water footprints were finally calculated by dividing the green and blue ET over the growing period by the yield.

In the Appendix we provide an illustration of the simulation of green and blue soil moisture content over time for a specific case.

2.3. Experimental setup

A comprehensive set of simulations was carried out, applying different management practices in an extensive number of cases (Table 1).

2.3.1. Management practices

Irrigation techniques

Irrigation techniques can be classified based on various themes: energy or pressure required, how or where the irrigation water is applied and wetted area by irrigation (Ali, 2011). Based on the wetted surface area, irrigation techniques can be listed as flood irrigation, trickle or localised irrigation and sprinkler irrigation. The first of these, flood irrigation comprises furrow, border and basin irrigation. The second, trickle irrigation comprises drip and subsurface drip. Given the existing irrigation practices in the four environments that we consider, we analyse four irrigation techniques: furrow (with 80% surface wetting), sprinkler (100% surface wetting), drip (30% wetting) and subsurface drip (0%

wetting). Generic assumptions have been made on the specific details of the different irrigation techniques, following default settings in the model. For furrow irrigation, an 80% wetting percentage is assumed to be representative for every furrow (narrow bed) from the indicative range of 60% to 100% in the AquaCrop manual (Raes et al., 2013). Alternative field management choices would connect to other (lower) wetting percentages: alternated furrow (30% to 50%) and every furrow for wide beds (40% to 60%).

Irrigation strategies

Irrigation strategy concerns the timing and volume of artificial soil water replenishment. Four irrigation strategies were considered: full irrigation, deficit irrigation, supplementary irrigation and no irrigation (rain-fed). Irrigation scheduling, when and how much to irrigate, is central to defining these irrigation strategies. Full irrigation is an irrigation strategy in which the full evaporative demand is met; this strategy aims at maximizing yield. It was simulated through automatic generation of irrigation requirement for no water stress condition. AquaCrop simulates water stress response for three thresholds of soil moisture depletion (Steduto et al., 2009b), relating to affected canopy expansion, stomatal closure and senescence acceleration. The depletion level for minimum stress (effect on canopy expansion) in AquaCrop starts far before the soil moisture depletion reaches 100% of the readily available moisture (RAW). The irrigation scheduling in the no water stress condition is crop dependent. The soil moisture was refilled to the field capacity (FC) when 20%, 36% and 30% of RAW of the soil is depleted for maize, potato and tomato respectively (FAO, 2012). This scheduling results in a high irrigation frequency, which is impractical in the case of furrow and sprinkler irrigation. To circumvent such unrealistic simulation for the case of furrow and sprinkler irrigation, we firstly generated the irrigation requirement automatically for no water stress condition, which obviously results in high irrigation frequency especially for course texture soil type. Then the irrigation depths were aggregated and shifted a few days forward, practically allowing more depletion than the no water stress level, in such a way that a time gap of a week is maintained between two irrigation events.

Deficit irrigation (DI) is the application of water below the evapotranspiration requirements (Fereres and Soriano, 2007) by limiting water applications particularly during less drought-sensitive growth stages (English, 1990). The deficit strategy is established by reducing the irrigation supply from the full irrigation requirement. We extensively tested various deficit irrigation strategies that fall under two broad categories: (1) regulated deficit irrigation, where a non-uniform water deficit level is applied during the different phenological stages; and (2) sustained deficit irrigation, where water deficit is uniformly distributed over the whole crop cycle. In general, the larger the deficit the smaller the simulated yield, as expected. The non-linear relation between yield and ET (and thus irrigation supply) gives rise to the existence of an optimum, i.e. the deficit irrigation strategy with the lowest consumptive

WF in m^3 t^{-1}. In the analysis of simulations, the paper used the specific deficit strategy that is optimal according to the model experiments.

Supplementary irrigation (SI) is defined as the application of a limited amount of water to increase and stabilize crop yields when rainfall fails to provide sufficient water for plant growth (Oweis et al., 1999). Supplementary irrigation was simulated to be a one-time event of refilling the root zone to field capacity when 100% of the RAW was depleted or when the threshold for stomata closure was triggered.

Mulching practices

Mulching has various purposes: reduce soil evaporation, control weed incidence and its associated water transpiration, reduce soil compaction, enhance nutrient management and incorporate additional nutrients (McCraw and Motes, 1991;Shaxson and Barber, 2003). The mulching practice in AquaCrop considers mainly evaporation reduction from the soil surface. Three mulching practices were distinguished: no mulching, organic mulching with f_m=0.5 and synthetic mulching with f_m=1. A mulch cover of 100% for organic and 80% for synthetic materials was assumed.

2.3.2. Cases

We carry out the model experiments for four different locations: Israel (arid), Spain (semi-arid), Italy (sub-humid) and the UK (humid). Per location we consider wet, normal and dry years, three soil types (loam, sandy loam, silty clay loam), and three crops (maize, potato and tomato). This yields a number of cases as summarised in Table 2.

2.4. Data

The input data to run the AquaCrop were collected for four sites: Eilat in Israel (29.33 ^{0}N, 34.57 ^{0}E; 12m above mean sea level), Badajoz in Spain (38.88 ^{0}N, -6.83 ^{0}E; 185m amsl), Bologna in Italy (44.57 ^{0}N, 11.53 ^{0}E; 19m amsl) and Eden in the UK (52.26° N, 0.64°E; 69m amsl).

The daily rainfall, minimum and maximum temperatures, reference evapotranspiration (ET_o) and the mean annual atmospheric carbon dioxide concentration are the input climatic data to run AquaCrop. Daily observed rainfall and temperature data (for the period 1993-2012) were extracted from the European Climate Assessment and Dataset (ECAD) (Klein Tank et al., 2002). The ECAD data undergo homogeneity testing and the missing data is filled with observations from nearby stations (i.e. within 12.5 km and with height differences less than 25m) (Klein Tank, 2007). Daily ET_o was derived with the FAO ET_o calculator (Raes, 2012), which uses the FAO Penman-Monteith equation. The evapotranspiration and precipitation of the research sites are summarized in Table 3.

Data on soil texture were extracted from the 1×1km^2 resolution European Soil Database (Hannam et al., 2009). The type of soils were identified using the Soil Texture Triangle Hydraulic Properties Calculator from (Saxton et al., 1986). The physical characteristics of the soils were adopted from AquaCrop, which includes a soil characteristics database of FAO. Observed soil data at one of the sites representing the humid environment (at Bologna, Italy) was shown to be comparable to the soil type and characteristics from the FAO and European Soil Database. Soil fertility stress was assumed to not occur. Regarding crop parameters, we take the default values as represented in AquaCrop, except for the maximum rooting depth for maize in Italy, which was limited to 0.7 m to account for the actual local conditions. Moisture supply from capillary rise to the root zone was considered only for Bologna, because the local groundwater table at the Bologna site is shallow (average 1.5 m). Chemical applications, such as fertilisers and pesticides, were assumed optimal.

3. Results

3.1. Overview of experimental results

The outcomes for ET (mm), Y (t ha^{-1}) and consumptive WF (m^3 t^{-1}) in the full set of model experiments are plotted in scatter diagrams in Figures 2a, 2b, 2c and 3. The ET-Y plot in Figures 2a, 2b and 2c show an increase in yield with increasing ET for all three crops, though there is no increase in Y anymore at larger ET values. The yields for ET less than 200 mm in Figures 2a, 2b and 2c are under rain-fed conditions (in semi-arid environment) and high deficit irrigation (with drip/subsurface drip techniques), with synthetic mulching practice. In such conditions, the evaporation is almost zero and transpiration takes the lion share of ET. The corresponding yield is very small, less than one third of the maximum. Fig. 3 illustrates the ET-WF relationship: small ET is associated with the large WFs due to the low yields resulting from water stress. Smallest WFs can be found at intermediate ET values, where yield still is not optimal, but additional ET goes along with decreasing productivity.

3.2. Effect of the management practice on ET, Y and consumptive WF

Figure 4 illustrates the effect of the four irrigation techniques on ET and Y under full, deficit and supplementary irrigation conditions for the case of potato production on loam soil in a normal year in Spain. We see that under full irrigation, moving from sprinkler to furrow and then to drip and subsurface drip irrigation will stepwise reduce ET in quite a substantial way, while yield remain at the same high level. The reduction in ET fully refers to a reduction in the unproductive E; the productive T remains constant. Under deficit irrigation, moving from sprinkler through furrow and drip to subsurface drip irrigation, ET will slightly decrease, while Y increases. The Y can increase because it is the non-productive soil evaporation component in ET that decreases, while the productive transpiration component increases. Under supplementary irrigation, the irrigation technique applied affects neither ET nor Y, because irrigation is applied only during a short period of time (the drought period), which hardly affects ET over the growing period as a whole.

The effect of mulching on ET and Y is illustrated in Fig. 5, for the same case of potato production on loam soil in a normal year in Spain. Under full irrigation, moving from no mulching through organic to synthetic mulching will reduce ET (through reduced soil evaporation) with Y remaining constant. Under deficit irrigation, we observe the same trend. Under supplementary irrigation, moving from no mulching through organic to synthetic mulching, ET will slightly decrease, while Y increases. The Y increases because it is the non-productive E that decreases, while the productive T increases. Under rain-fed conditions, organic and synthetic mulching do not affect total ET much, but E decreases while T increases, which leads to an increase in Y.

The effect of different irrigation strategies on ET, Y and consumptive WF is illustrated in Figure 6 for the case of potato growth under drip irrigation on a loam soil for a normal year in Spain. Table 4 shows the amount of rainfall and irrigation supply during the growing period of potato for the same case. There is an increase in both ET and Y when we shift from rain-fed to supplementary irrigation and further on to deficit and full irrigation. The consumptive WF is smallest with deficit irrigation, followed by full irrigation, supplementary irrigation and finally rain-fed. The change from rain-fed to supplementary irrigation takes a modest amount of irrigation water, 80 mm. The supplementary irrigation allowed an additional ET of 51 mm of green water plus 21 mm of blue water, making a significant impact on crop growth, thus making a small blue WF, but the resultant yield increase leads to a decrease of the overall (green plus blue) WF.

The deficit irrigation supply was 281 mm (80 mm reduction as compared to full irrigation). The change from full irrigation to deficit irrigation slightly reduces yield (by 1.5%), but reduces blue ET (by 14 mm or 6%), with a slight decrease of the consumptive WF as a result (by 2%). The significant reduction in total irrigation depth in the case of the deficit irrigation thus resulted in only minor yield losses. In the case of full irrigation, blue ET and total ET is larger, but green ET is slightly smaller than in the case of deficit irrigation. This results from the fact that irrigation water saturates the soil, causing a larger fraction of rainwater to run off. Deficit irrigation thus makes more effective use of rainwater.

3.3. Relative changes in green and blue WF compared to the reference case

We compared the effects of all different management practices on the green and blue WF against the reference case of furrow and full irrigation and no mulching practice. We present the results in six groups, whereby each group has a specific irrigation strategy and mulching practice, with the irrigation technique as a variable. We consider the following six combinations of irrigation strategy and mulching practice:

- Full irrigation (FI), no mulching practice (NoML);
- Deficit irrigation (DI), no mulching practice (NoML);
- Full irrigation (FI), organic mulching (OML);
- Deficit irrigation (DI), organic mulching (OML);
- Full irrigation (FI), synthetic mulching (SML); and
- Deficit irrigation, (DI), synthetic mulching (SML).

The change in total consumptive WF from the reference for all management practices is shown in Figure 7. Given a particular mulching practice, the largest WF is found for sprinkler, followed by furrow, drip and subsurface drip irrigation. Only for the case of full irrigation and no mulching, drip irrigation results in a smaller WF than for subsurface drip irrigation. The effect of drip and subsurface drip irrigation on consumptive WF depends on two variables limiting soil evaporation: energy and soil moisture. Under full irrigation, as can be seen in Fig. 7b, drip irrigation reduces the consumptive WF more than subsurface drip irrigation, with the largest difference in the humid environment. The reason is that energy is here the limiting factor to evaporation. Under deficit irrigation, as can be seen in Fig. 7c, subsurface drip irrigation reduces the consumptive WF more than drip irrigation, with the largest difference in the arid environment. This is explained by the fact that now moisture is the limiting factor to evaporation.

Compared to the reference case of no mulching, organic mulching substantially reduces the consumptive WF, and synthetic mulching even further. In the case of full irrigation, organic mulching results, on average, in an additional consumptive WF reduction compared to no mulching of 17% with sprinkler, 13% with furrow, 7% with drip and 11% with subsurface drip irrigation. In the case of deficit irrigation, these additional reductions are slightly lower: 14% with sprinkler, 11% with furrow, 6% with drip and 7% with subsurface drip irrigation. Considering drip and subsurface drip irrigation, synthetic mulching results, on average, in an additional consumptive WF reduction of 10% compared to organic mulching.

Figure 8 shows the average changes in consumptive WF for management practices, specified per type of environment. The average reduction in the consumptive WF is: 8-10% if we change from the reference to drip or subsurface drip irrigation; 13% when changing from the reference to organic mulching; 17-18% when moving to drip or subsurface drip irrigation in combination with organic mulching; and 28% when shifting to drip or subsurface drip irrigation with synthetic mulching. All before-mentioned reductions increase by one or a few per cent when moving from full to deficit irrigation. In our case of the sub-humid environment, with the selected location in Italy having shallow groundwater, we find relatively small WF reductions when we have no mulching, because capillary rise keeps feeding the soil moisture content, resulting in continued soil evaporation.

The average change in green, blue and total consumptive WF from the reference for all management practices is presented in Figure 9. Relative changes in blue WF are always larger than relative changes in the total consumptive WF, while the relative changes in green WF are always smaller. In other words, when management practices reduce the total consumptive WF they do so particularly by reducing the blue WF and to a lesser extent by reducing the green WF. The latter even increases in the practice that combines sprinkler irrigation without mulching. In all cases, overall consumptive WF reduction goes together with an increasing green/blue ratio for the WF of a crop. Given a certain irrigation technique and mulching practice, deficit irrigation will always reduce the blue WF of the crop, when compared to the practice of full irrigation.

4. Discussion

An interesting result from this study is that sprinkler irrigation does have a larger consumptive WF in $m^3\ t^{-1}$ (i.e., smaller water productivity in $t\ m^{-3}$) than furrow irrigation, while sprinkler irrigation is known to have larger so-called irrigation efficiency compared to furrow irrigation (Brouwer et al., 1988). With sprinkler irrigation, a larger soil surface is wetted than in the case of furrow irrigation (Ali, 2011). Thus, for an equal level of production, sprinkler irrigation results in larger ET (because of larger soil evaporation) and consumptive WF than furrow irrigation. Compared to sprinkler, furrow irrigation has higher percolation and runoff fluxes, variables that define irrigation efficiency. These fluxes return to the catchment and are not a loss from the system and therefore not considered to contribute to consumptive WF (Hoekstra et al., 2011).

The findings of this study indicate that subsurface drip irrigation is most useful for consumptive WF reduction in the arid environment. The reason is that with subsurface drip irrigation moisture content in the topsoil will be smaller and thus limit soil evaporation. In the other environments, the difference between drip and subsurface drip irrigation is minor. With full irrigation in the humid environment, subsurface drip irrigation even results in a larger consumptive WF than in the case of drip irrigation. We believe that these result are plausible, as they are consistent with findings from (Dehghanisanij and Kosari, 2011). Dehghanisanij and Kosari (2011), who explain that the net energy available for soil evaporation for SSD irrigation is larger than for drip. The reason is that drip irrigation gives a cooling effect on the topsoil, reducing the energy available for evaporation, thus limiting soil evaporation. This is due to heat convection or a higher soil heat flux along with droplets of water moving from the soil surface into the soil in the case of drip. Therefore, with full irrigation in the humid environment where the net radiation energy for evaporation is limiting, drip results in smaller consumptive WF than SSD.

The ET versus Y plots made based on our model experiment results (Figures 2a, 2b and 2c) are comparable with the production function in earlier studies (Amarasinghe and Smakhtin, 2014;Wichelns, 2015). Amarasinghe and Smakhtin (2014) derived the production function from observed data under various agro-ecological conditions, water availability constraints and management practices.

Net irrigation supply simulated using AquaCrop for our semi-arid case in Spain is consistent with the values reported by the Guadiana river basin authority. We simulate net irrigation supply in the range of 200-600 mm for full irrigation under different irrigation techniques and soil types for a normal year for the case of tomato in our Spanish site, which is within the observed range of 150-650 mm as reported by the Guadiana river basin authority (CHG – Confederación Hidrográfica del Guadiana, 2013). Our simulated values for net irrigation supply for the same site are also consistent with the reported values for maize and potato. The simulated net irrigation supply for potato is in the range of 180-350 mm and the reported range is 150-380 mm. For maize we find a simulated range of 450-600 mm and a reported range of 450-630 mm.

The AquaCrop model has been validated for herbaceous crops at diverse locations in different environments (Steduto et al., 2011). It is designed to be applicable under various climate and soil conditions, with no need for calibration once it has been parameterized for a specific crop species (Hsiao et al., 2011). This study is made for crops that had already been parameterized in AquaCrop. The sensitivity of AquaCrop-simulated yields to model parameters, under diverse environmental conditions, was studied by Vanuytrecht et al. (2014). That study shows that the parameters describing crop responses to water stress were not often among those showing highest sensitivity. The particular root and soil parameters indeed need attention during calibration. We did not perform a specific sensitivity analysis for these inputs or a specific uncertainty analysis propagating parameter uncertainty through the model, which both would be interesting. The current analysis, however, already shows the robustness of the AquaCrop-simulated effects of irrigation method, irrigation strategy and mulching for a large set of conditions for soil, crop, climate and weather. Together with the sensitivity results of Vanuytrecht et al. (2014), we believe the overall evidence to support the conclusions is strong.

We note that AquaCrop has inherent limitations, including for instance the neglect of lateral water flows in the field, the inability to simulate the effects of nutrient limitation, fertilizer application, effect of organic mulching on the organic content of the soil and decomposition of organic materials, interception losses from sprinkler and the inability to define the depth at which subsurface drip irrigation takes place. These limitations put a disclaimer to the results of our study, but we believe that the results of this study can provide a useful reference to similar future studies with other models. We see the need for further validation of our model results with field experiments, but this is costly and will generally need to focus on varying just a few management practices under a limited number of cases. In our model experimental setup we varied a large number of variables (irrigation techniques, strategies, mulching practices, environments, soils, crops, dry versus wet years) in all possible combinations, which is impossible in a field experiment.

By focussing on the effect of irrigation and mulching, we excluded from this study the effects of other agricultural practices such as the use of agrochemicals and tillage. Besides, by focussing on management practices at field level, we have excluded measures that could be applied to reduce consumptive WF in the stages before irrigation water is applied to the field, like measures to reduce evaporative losses from storage reservoirs and distribution canals.

5. Conclusion

Water footprint reduction in irrigated crop production is the way forward for efficient and sustainable water resource use. This paper provides the first detailed and comprehensive study regarding the potential for reducing the consumptive WF of a crop at field level by changing management practice such as irrigation technique, irrigation strategy and mulching practice. The effect of the various combinations of irrigation technique and strategy and mulching practice were compared to the reference of furrow and full irrigation without mulching. We found the largest WF reduction (average of 35% for different soils and years) for tomato production under drip or subsurface drip irrigation with synthetic mulching under the semi-arid environment. If we consider all the cases of drip or subsurface drip irrigation with synthetic mulching, including all crops and environments, we find an average consumptive WF reduction of 28% for full irrigation and 29% for deficit irrigation. In the latter case, the corresponding blue WF reduction is 44% and the green WF reduction 14%.

Irrigation techniques and strategies and mulching practices can be ordered based on their potential to reduce the blue or total consumptive WF, from low to high potential:

- Irrigation techniques: sprinkler, furrow, drip / subsurface drip irrigation.
- Irrigation strategies: rain-fed, supplementary irrigation, full irrigation, deficit irrigation.
- Mulching practices: no mulching, organic mulching, synthetic mulching.

The percentage of blue WF reduction is always larger than the percentage of total consumptive WF reduction. Generally, reduction in the total consumptive WF includes a reduction in the green WF as well. However, when we move from full to deficit irrigation (other things equal), the green WF will increase. Note still that deficit irrigation reduces the blue WF and the overall consumptive WF. The increased blue water and overall water productivity achieved through deficit irrigation thus slightly reduces the green water productivity.

This study can be used as a reference in future studies regarding the potential effect of management practices on the consumptive WF. The results can contribute to making strategic choices to achieve greater crop water productivity and setting WF benchmarks for crop production. The findings of this paper can be used in subsequent studies at a basin scale, with the help of an appropriate model that can simulate the effects of additional management practices like fertilizer application as well, to study the possible water saving (while producing the same crop amount) and water scarcity reduction at basin scale or the possible crop production increase without increasing water use. The ranking of irrigation methods, irrigation strategies and mulching practices as provided in this paper gives a first indication of what can be done to increase water productivity and the potential gains that can be achieved through certain combinations of practices. Formulations are still with caution as relevant considerations such as fertilizer application and associated grey water footprints and possible economic trade-offs are outside the scope of the present paper. However, although our conclusions regarding the effectiveness of different irrigation techniques and strategies and mulching practices are generally valid, we must be careful in translating the general findings to very specific cases, because the precise WF reduction that can be achieved in a particular case will always be context specific.

Appendix: Illustration of the simulation of green and blue soil moisture content

Initial soil moisture was quantified for the four environments as follows: 10% green and 90% blue for the arid environment; 35% green and 65% blue for the semi-arid environment; 48% green, 37% blue from capillary rise and 15% blue from irrigation water for the sub-humid environment (with shallow groundwater); and 98% green and 2% blue for the humid environment.

Figure A1 illustrates the development of green and blue soil water content over the growing period as simulated with AquaCrop and our additional module partitioning the soil water content and fluxes into green and blue components.

Acknowledgments

This research was conducted as part of the EU-FP7-funded project FIGARO. The authors wish to thank all consortium partners. We thank Adriano Battilani, CER in Italy, and Julian Gruzelier, Eden Irrigation in the UK, for sharing data and background information on their respective research sites. Thanks to Dirk Raes, Division of Soil and Water Management, KU Leuven University in Belgium, for the useful discussion and advice in using AquaCrop. The paper was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS).

References

Afshar, A., and Neshat, A.: Evaluation of Aqua Crop computer model in the potato under irrigation management of continuity plan of Jiroft region, Kerman, Iran, International journal of Advanced Biological and Biomedical Research, 1, 1669-1678, 2013.

Al-Said, F. A., Ashfaq, M., Al-Barhi, M., Hanjra, M. A., and Khan, I. A.: Water productivity of vegetables under modern irrigation methods in Oman, Irrig Drain, 61, 477-489, 2012.

Ali, M. H.: Water Application Methods, in: Practices of Irrigation & On-farm Water Management, Springer, New York, USA, 35-63, 2011.

Allen, R., Pereira, L., Raes, D., and Smith, M.: Crop evapotranspiration. FAO irrigation and drainage paper 56, FAO, Rome, Italy, 10, 1998.

Amarasinghe, U. A., and Smakhtin, V.: Water productivity and water footprint: misguided concepts or useful tools in water management and policy?, Water Int, 39, 1000-1017, 2014.

Bakhsh, A., Hussein, F., Ahmad, N., Hassan, A., and Farid, H. U.: Modeling deficit irrigation effects on maize to improve water use efficiency, Pak J Agr Sci, 49, 365-374, 2012.

Brouwer, C., Prins, K., Kay, M., and Heibloem, M.: Irrigation water management: irrigation methods. Training manual no 5, Food and Agriculture Organization of the United Nations, Rome, Italy, 1988.

CHG – Confederación Hidrográfica del Guadiana: Plan Hidrológico de la parte española de la demarcación hidrográfica del Guadiana, Memoria, Summary of the Guadiana River Basin Management Plan, Guadiana River Basin Authority, Spanish Ministry of the Environment and Rural and Marine Affairs, Badajoz, Spain, 2013.

Dehghanisanij, H., and Kosari, H.: Evapotranspiration partitioning in surface and sbsurface drip irrigation systems, INTECH Open Access Publisher, Rijeka, Croatia, 2011.

English, M.: Deficit irrigation. I: Analytical framework, Journal of irrigation and drainage engineering, 116, 399-412, 1990.

Falkenmark, M., and Rockström, J.: The new blue and green water paradigm: Breaking new ground for water resources planning and management, Journal of water resources planning and management, 3, 129-132, 2006.

FAO: Annex I Crop parameters, AquaCrop reference manual, Food and Agriculture Organization of the United Nations, Rome, Italy, 2012.

Fereres, E., and Soriano, M. A.: Deficit irrigation for reducing agricultural water use, J Exp Bot, 58, 147-159, 2007.

Fereres, E., Walker, S., K. Heng, L., C. Hsiao, T., Steduto, P., Raes, D., Izzi, G., Asseng, S., and R. Evett, S.: AquaCrop applications, Food and Agriculture Organization of the United Nations, Rome, Italy, 2012.

Geerts, S., and Raes, D.: Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas, Agr Water Manage, 96, 1275-1284, 2009.

Gleick, P. H.: Global freshwater resources: soft-path solutions for the 21st century, Science, 302, 1524-1528, 2003.

Hannam, J. A., Hollis, J. M., Jones, R. J. A., Bellamy, P. H., Hayes, S. E., Holden, A., an Liedekerke, M. H., and Montanarella, L.: SPE-2: The soil profile analytical database for Europe, Beta Version 2.0, http://eusoils.jrc.ec.europa.eu/projects/spade/spade2.html (last access: June 2014), 2009.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., and Mekonnen, M. M.: The Water Footprint Assessment Manual: Setting the Global Standard, Earthscan, London, UK, 2011.

Hoekstra, A. Y., and Mekonnen, M. M.: The water footprint of humanity, P Natl Acad Sci USA, 109, 3232-3237, 2012.

Hoekstra, A. Y.: The Water Footprint of Modern Consumer Society, Routledge, London, UK., 2013.

Hsiao, T., Fereres, E., Steduto, P., and Raes, D.: AquaCrop parameterization, calibration, and validation guide, Crop yield response to water. Irrig. Drain. Pap, 66, 70-87, 2011.

Igbadun, H. E., Ramalan, A. A., and Oiganji, E.: Effects of regulated deficit irrigation and mulch on yield, water use and crop water productivity of onion in Samaru, Nigeria, Agr Water Manage, 109, 162-169, 2012.

Jalota, S., and Prihar, S. S.: Reducing soil water evaporation with tillage and straw mulching, Eurospan Group, London, UK, 1998.

Jinxia, Z., Ziyong, C., and Rui, Z.: Regulated deficit drip irrigation influences on seed maize growth and yield under film, Procedia Engineering, 28, 464-468, 2012.

Jiru, M., and Van Ranst, E.: Increasing water productivity on Vertisols: implications for environmental sustainability, J Sci Food Agr, 90, 2276-2281, 2010.

Klein Tank, A., Wijngaard, J., Können, G., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., and Kern‐Hansen, C.: Daily dataset of 20th‐century surface air temperature and precipitation series for the European Climate Assessment, International journal of climatology, 22, 1441-1453, 2002.

Klein Tank, A.: EUMETNET/ECSN optional programme: European Climate Assessment & Dataset (ECA&D) Algorithm Theoretical Basis Document (ATBD), version 4, Royal Netherlands Meteorological Institute KNMI, 2007.

Mao, L. L., Zhang, L. Z., Li, W. Q., van der Werf, W., Sun, J. H., Spiertz, H., and Li, L.: Yield advantage and water saving in maize/pea intercrop, Field Crop Res, 138, 11-20, 2012.

McCraw, D., and Motes, J. E.: Use of plastic mulch and row covers in vegetable production, Cooperative Extension Service. Oklahoma State University, USA, OSU Extension Facts F-6034, 1991.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., and Kijne, J.: Improving agricultural water productivity: Between optimism and caution, Agr Water Manage, 97, 528-535, 2010.

Ogban, P. I., Ogunewe, W. N., Dike, R. I., Ajaelo, A. C., Ikeata, N. I., Achumba, U. E., and Nyong, E. E.: Effect of tillage and mulching practices on soil properties and growth and yield of Cowpea (Vigna Unguiculata(L), Walp) in southeastern Nigeria, Agro-Science, 7, 118-128, 2008.

Oweis, T., Hachum, A., and Kijne, J.: Water harvesting and supplemental irrigation for improved water use efficiency in dry areas, International Water Management Institute, Colombo, Sri Lanka, 1999.

Oweis, T., and Hachum, A.: Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa, Agr Water Manage, 80, 57-73, 2006.

Perry, C.: Efficient irrigation; Inefficient communication; Flawed recommendations, Irrig Drain, 56, 367-378, 2007.

Perry, C., Steduto, P., Allen, R. G., and Burt, C. M.: Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities, Agr Water Manage, 96, 1517-1524, 2009.

Qiu, Y. F., and Meng, G.: The Effect of water saving and production increment by drip Irrigation schedules, Third International Conference on Intelligent System Design and Engineering Applications (ISDEA), Hong Kong, 16-18 Jan 2013.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E.: AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description, Agron J, 101, 438-447, 2009.

Raes, D., Steduto, P., C. Hsiao, T., and Fereres, E.: Reference Manual AquaCrop plug-in program, Food and Agriculture Organization of the United Nations, Land and Water Division, Rome, Italy, 2011.

Raes, D.: The ETo Calculator. Reference Manual Version 3.2, Food and Agriculture Organization of the United Nations, Rome, Italy, 2012.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E.: Chapter 3 – AquaCrop, Version 4.0, Food and Agriculture Organization of the United Nations, Land and Water Division, Rome, Italy, 2012.

Raes, D., Steduto, P., and C. Hsiao, T.: Reference manual, Chapter 2, AquaCrop model, Version 4.0, Food and Agriculture Organization of the United Nations, Rome, Italy, 2013.

Rashidi, M., and Keshavarzpour, F.: Effect of different irrigation methods on crop yield and yield components of cantaloupe in the arid lands of Iran, World Appl. Sci. J, 15, 873-876, 2011.

Ritchie, J.: Model for predicting evaporation from a row crop with incomplete cover, Water Resour Res, 8, 1204-1213, 1972.

Saad, A. M., Mohamed, M. G., and El-Sanat, G. A.: Evaluating AquaCrop model to improve crop water productivity at North Delta soils, Egypt, Advances in Applied Science Research, 5, 293-304, 2014.

Saxton, K., Rawls, W. J., Romberger, J., and Papendick, R.: Estimating generalized soil-water characteristics from texture, Soil Science Society of America Journal, 50, 1031-1036, 1986.

Shaxson, F., and Barber, R.: Optimizing soil moisture for plant production. The significance of soil porosity, Food and Agriculture Organization of the United Nations, Rome, Italy, 2003.

Steduto, P., Hsiao, T. C., and Fereres, E.: On the conservative behavior of biomass water productivity, Irrigation Sci, 25, 189-207, 2007.

Steduto, P., Hsiao, T. C., Raes, D., and Fereres, E.: AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles, Agron J, 101, 426-437, 2009a.

Steduto, P., Raes, D., Hsiao, T., Fereres, E., Heng, L., Howell, T., Evett, S., Rojas-Lara, B., Farahani, H., Izzi, G., Oweis, T., Wani, S., Hoogeveen, J., and Geerts, S.: Concepts and Applications of AquaCrop: The FAO Crop Water Productivity Model, in: Crop Modeling and Decision Support, edited by: Cao, W., White, J., and Wang, E., Springer, Berlin, Germany, pp. 175-191, 2009b.

Steduto, P., Hsiao, T. C., Raas, M., Fereres, E., G., Izzi, G., Heng, L., and Hoogeveen, J.: Performance review of AquaCrop - The FAO crop-water productivity model, ICID 21st International Congress on Irrigation and Drainage, 15-23 October 2011, Tehran, Iran, R.56.2.19, 2011.

Steduto, P., Hsiao, T. C., Raes, D., and Fereres, E.: Crop yield response to water, Food and Agriculture Organization of the United Nations Italy, Rome, 2012.

Tadayon, M., Ebrahimi, R., and Tadayyon, A.: Increased water productivity of wheat under supplemental irrigation and nitrogen application in a semi-arid region, Journal of Agricultural Science and Technology, 14, 995-1003, 2012.

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

Wichelns, D.: Water productivity and food security: considering more carefully the farm-level perspective, Food Sec., 7, 247-260, 2015.

Zhao, G. Q., Zhu, Z. X., Zheng, Y. F., and Fang, W. S.: Water-saving techniques in Chinese agriculture - water-saving irrigation and straw mulching for winter wheat, P Soc Photo-Opt Ins, 5153, 195-199, 2003.

Zhou, J. B., Wang, C. Y., Zhang, H., Dong, F., Zheng, X. F., Gale, W., and Li, S. X.: Effect of water saving management practices and nitrogen fertilizer rate on crop yield and water use efficiency in a winter wheat-summer maize cropping system, Field Crop Res, 122, 157-163, 2011.

Table 1. Research model: management practices considered in a number of cases to simulate the effect on ET, Y, and consumptive WF.

Management practices	Modelling	Effects
Four irrigation techniques: furrow, sprinkler, drip and subsurface drip;	Soil water balance and crop growth model (AquaCrop)	- ET - Yield - Consumptive WF
Three irrigation strategies: full, deficit and supplementary irrigation; + rain-fed;		
Three mulching practices: no mulching, organic and synthetic mulching.	Global WF accounting standard	
Cases		
Four environments (arid, semi-arid, sub-humid and humid), three crops (maize, potato and tomato), three soils (loam, sandy loam and silty clay loam), three types of years (wet, normal and dry)		

Table 2. Research cases.

Arid (Eilat, Israel)	Loam	Dry	Maize, potato and tomato	Deep
	Sandy loam	Normal		
	Silty clay loam	Wet		
Semi-arid (Badajoz, Spain)	Loam	Dry	Maize, potato and tomato	Deep
	Sandy loam	Normal		
	Silty clay loam	Wet		
Sub-humid (Bologna, Italy)	Loam	Dry	Maize, potato and tomato	Average 1.5 m
	Sandy loam	Normal		
	Silty clay loam	Wet		
Humid (Eden, UK)	Loam	Dry	Maize, potato and tomato	Deep
	Sandy loam	Normal		
	Silty clay loam	Wet		

[a] A deep groundwater table means that capillary rise does not contribute moisture to the root zone.

Table 3. Evapotranspiration and precipitation in the four environments.

Environments	**ET$_o$**	**Precipitation**	**Precipitation**			**Actual E and ET** [a]			
						Rain-fed		Irrigated [b]	
	20-year average		Wet	Normal	Dry	E	ET	E	ET
	(mm year^{-1})		(mm per growing season)			(mm per growing season)			
Arid	2476	16	60	11.3	2.4	16	16	85	322
Semi-arid	1308	449	129	76	62	49	171	108	393
Sub-humid [c]	977	585	359	170	147	87	314	85	312
Humid	688	722	834	665	657	79	282	128	390

[a] E is evaporation in a normal year; ET is actual evapotranspiration.

[b] Under conditions of full irrigation, furrow irrigation, potato, loam soil and no mulching practice.

[c] The groundwater table in the selected sub-humid environment is shallow, at 1.5m, which implies that capillary rise feeds moisture to the root zone.

Table 4. The irrigation supply and ET values for supplementary, deficit and full irrigation plus rain-fed of the potato production.

	Rain (mm)	**Irrigation supply (mm)**	**ET-green (mm)**	**ET- blue (mm)**
Rain-fed	63	0	171	0
Supplementary irrigation	63	80	222	21
Deficit irrigation	63	281	117	224
Full irrigation	63	361	115	238

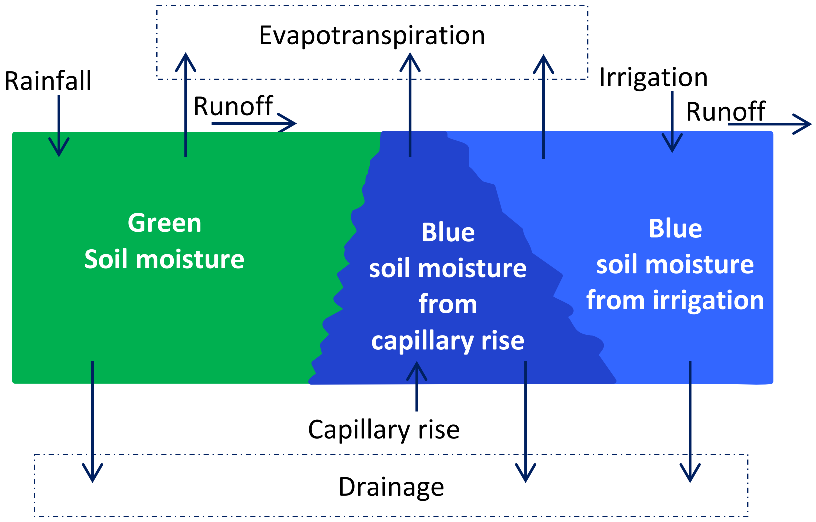


Figure 1. Incoming and outgoing water fluxes of the green (S_g) and blue ($S_b = S_{b\text{-}I} + S_{b\text{-}CR}$) soil water stocks.

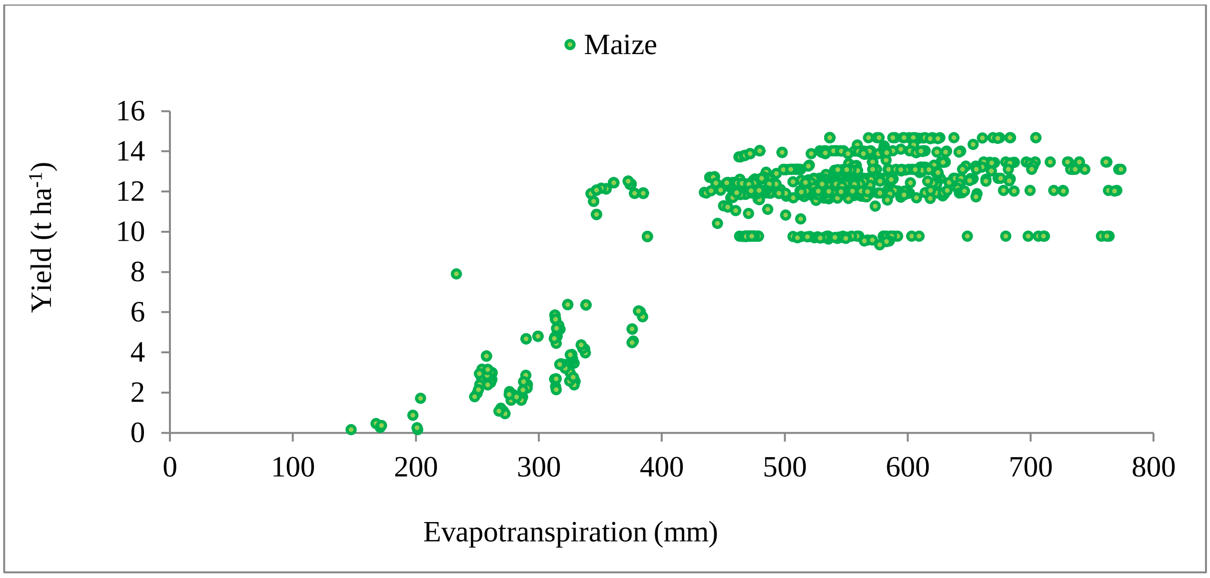


Figure 2a. The resultant ET and Y of maize for all experiments: different management practices for all cases.

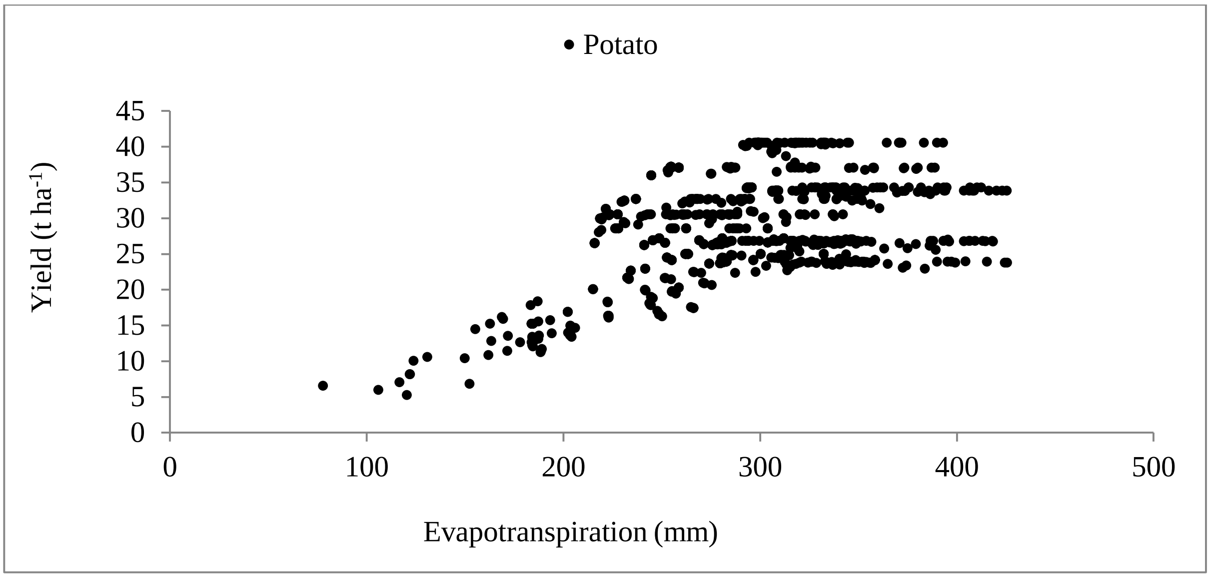


Figure 2b. The resultant ET and Y of potato for all experiments: different management practices for all cases.

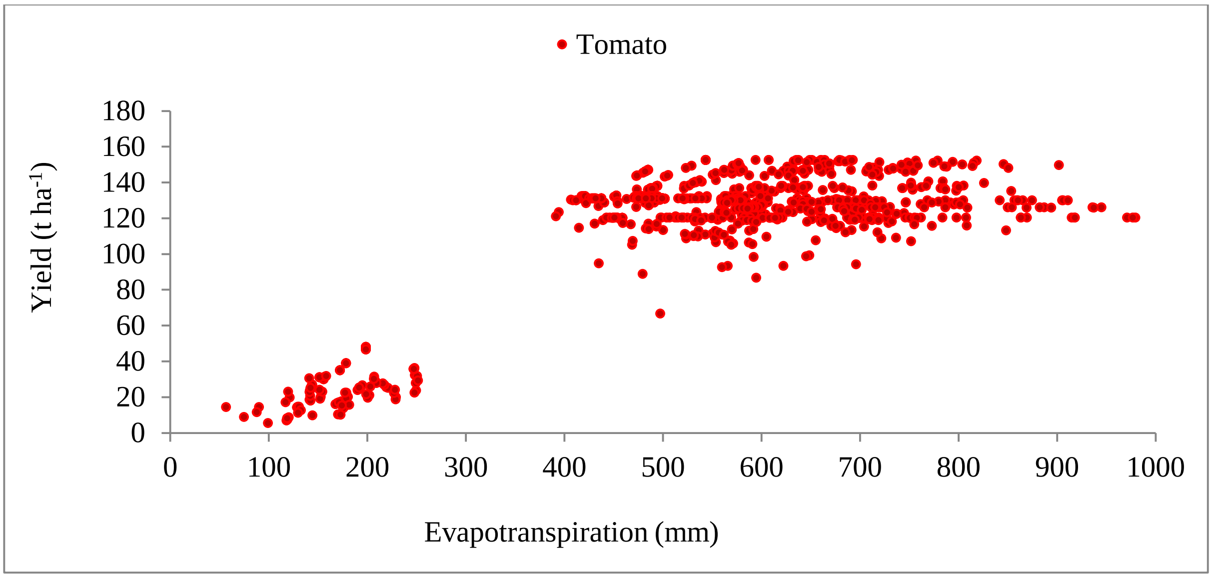


Figure 2c. The resultant ET and Y of tomato for all experiments: different management practices for all cases.

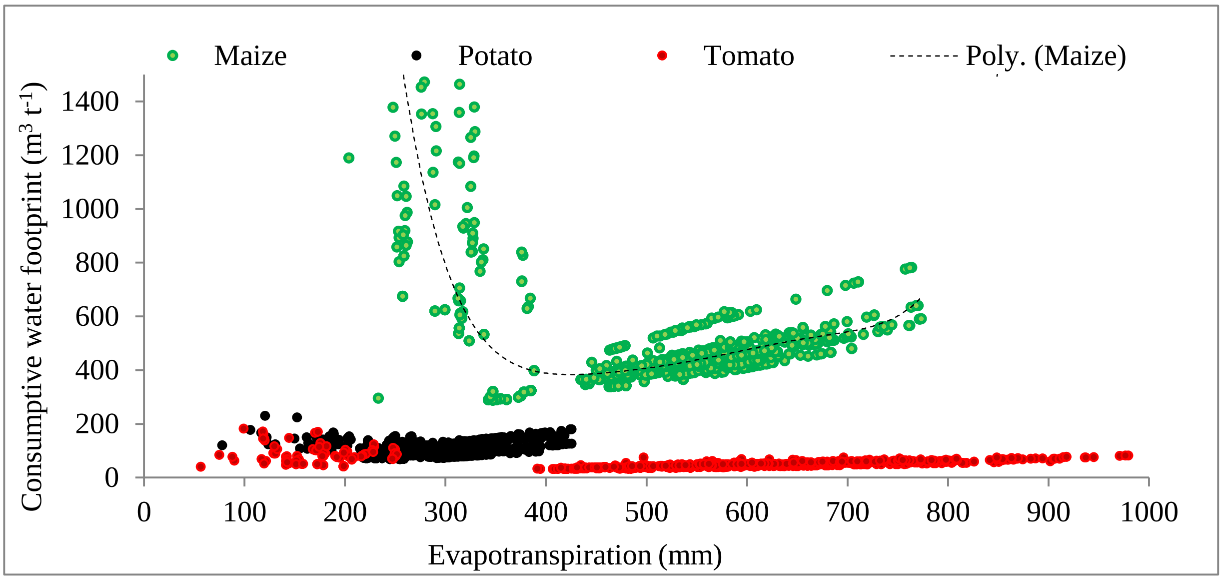


Figure 3. The resultant ET and consumptive WF for all experiments: different management practices for all cases. The dotted line is a polynomial fit to data points for maize.

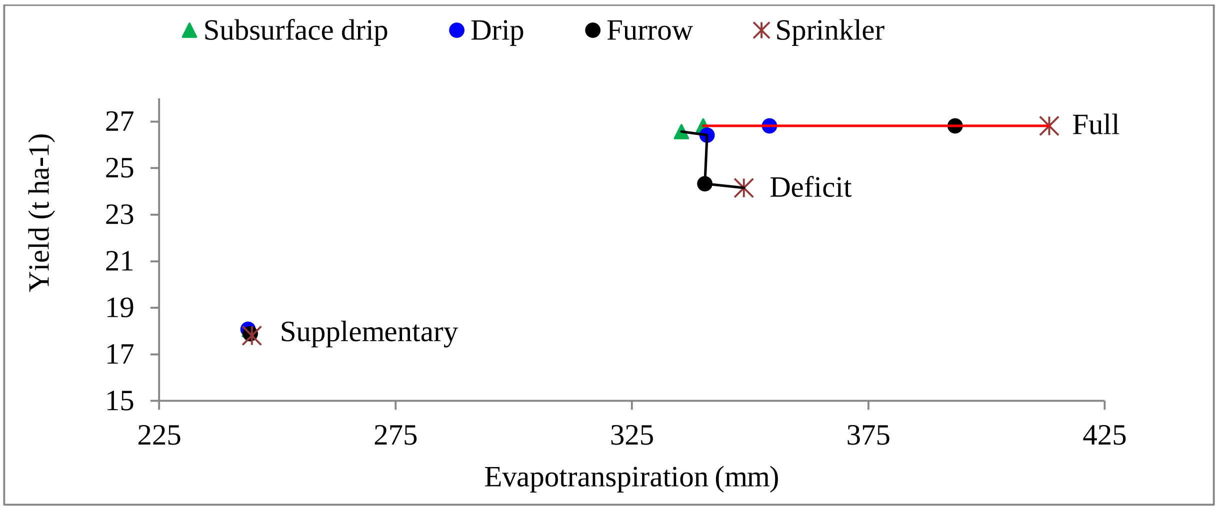


Figure 4. ET-Y plot for four irrigation techniques, three strategies and no mulching practice for the case of potato on a loam soil, a normal year in a semi-arid environment (Badajoz, Spain). The lines connect cases with one particular irrigation strategy: red and black for the full and deficit irrigation strategies, respectively.

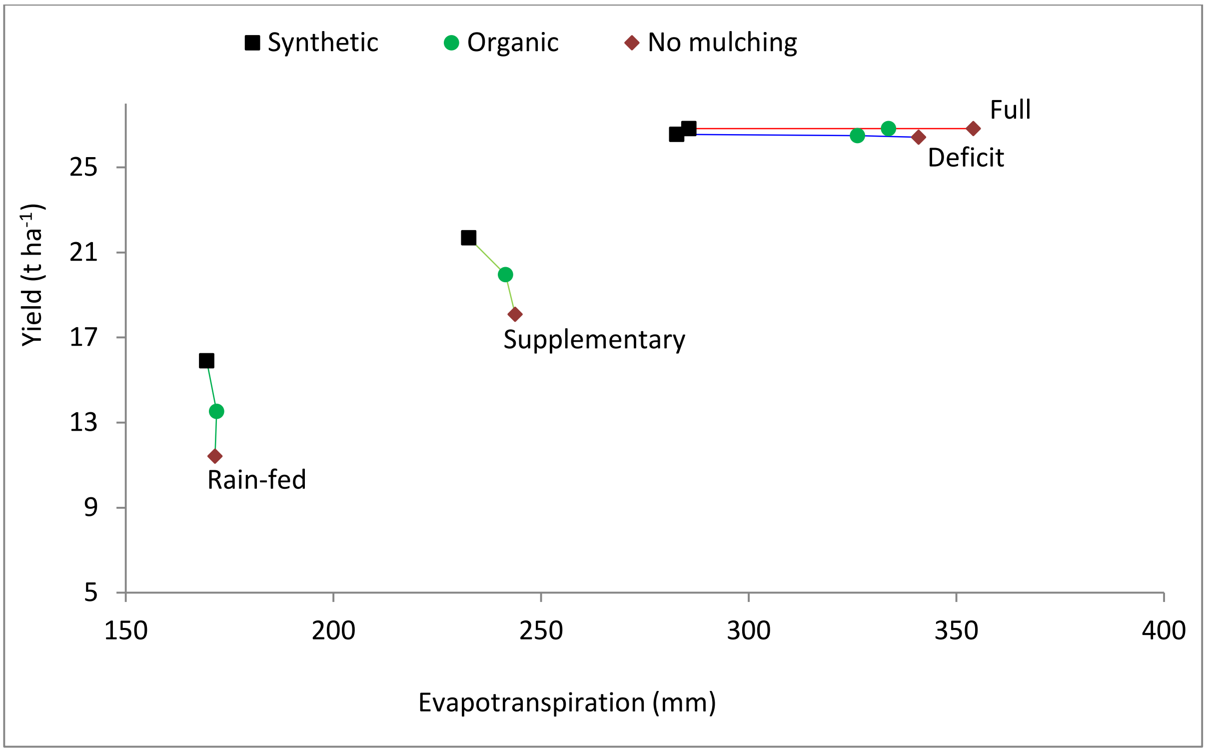


Figure 5. ET-Y plot for mulching practices at rain-fed and drip irrigated fields for the case of potato on a loam soil for a normal year in a semi-arid environment (Badajoz, Spain). The lines connect cases with one particular irrigation strategy: red, blue, light green and green denote full irrigation, deficit irrigation, supplementary irrigation and rain-fed production, respectively.

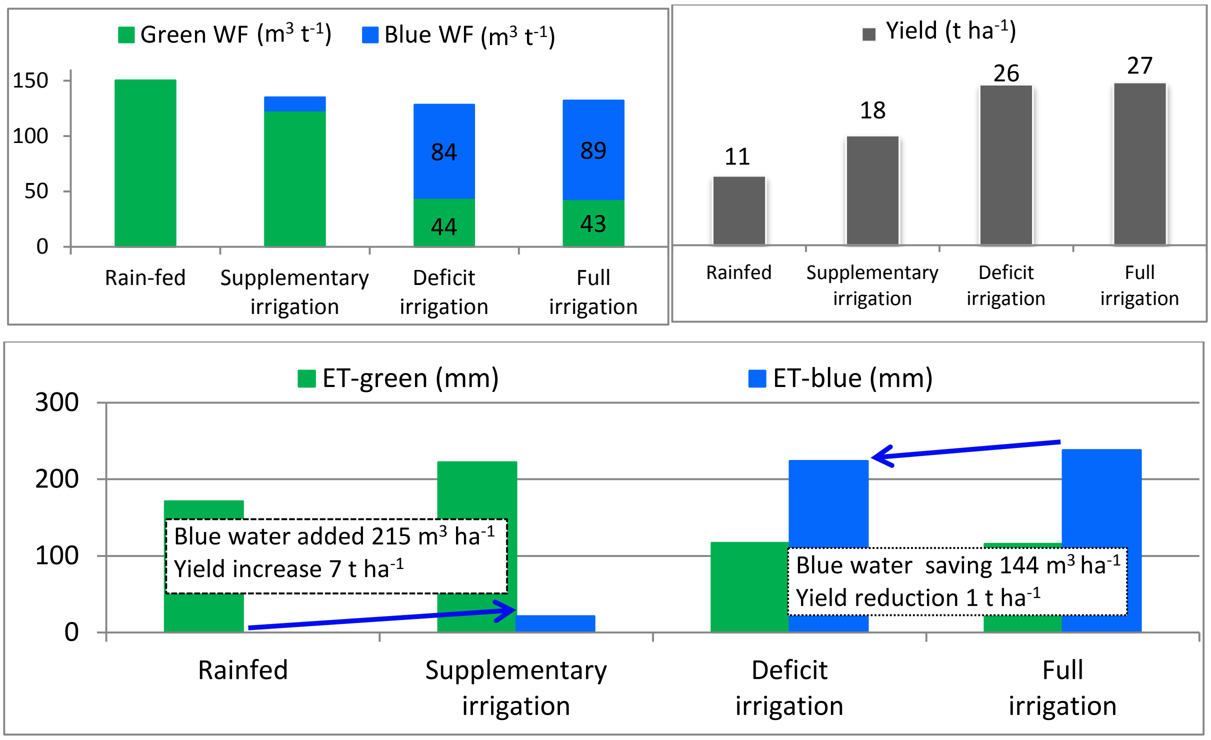


Figure 6. ET, Y and WF under different irrigation strategies for the case of potato production under drip irrigation on loam soil in a normal year in a semi-arid environment (Badajoz, Spain).

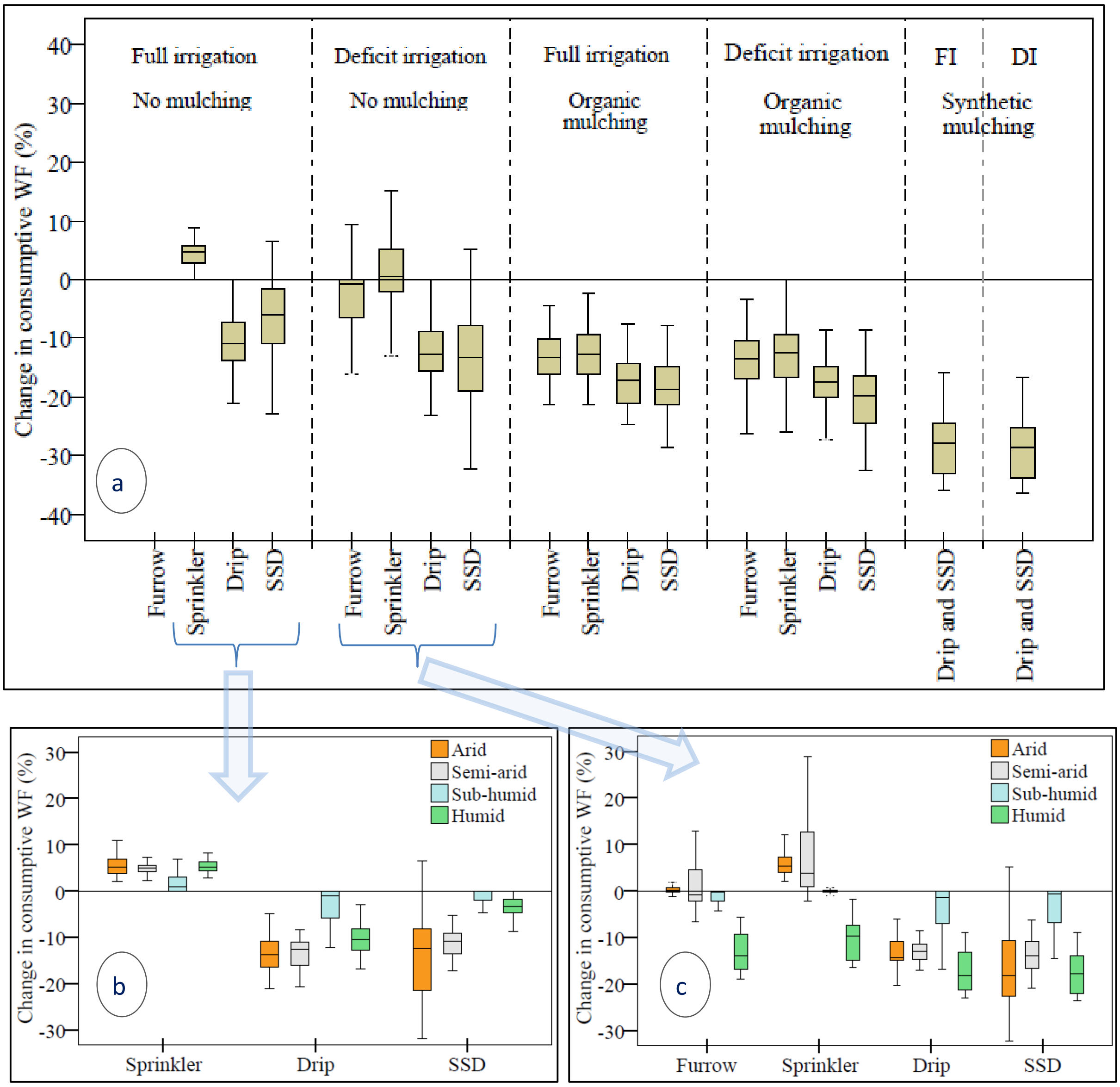


Figure 7. Change in consumptive WF from the reference for all management practices. The range for each management practice represents the variation of changes found for the various cases. The upper and lower ends of the whiskers are the largest and smallest changes found. 50% of the cases fall within the range represented by the upper and lower value of the box. The line within the box represents the change in the median case. Figure **(a)** gives an overview for all management practices; Figures **(b)** and **(c)** zoom in for the practices of full and deficit irrigation, respectively, without mulching, showing specific WF changes per type of environment. SSD stands for subsurface drip, FI for full irrigation, DI for deficit irrigation, NoML for mulching practice, OML for organic mulching and SML for synthetic mulching.

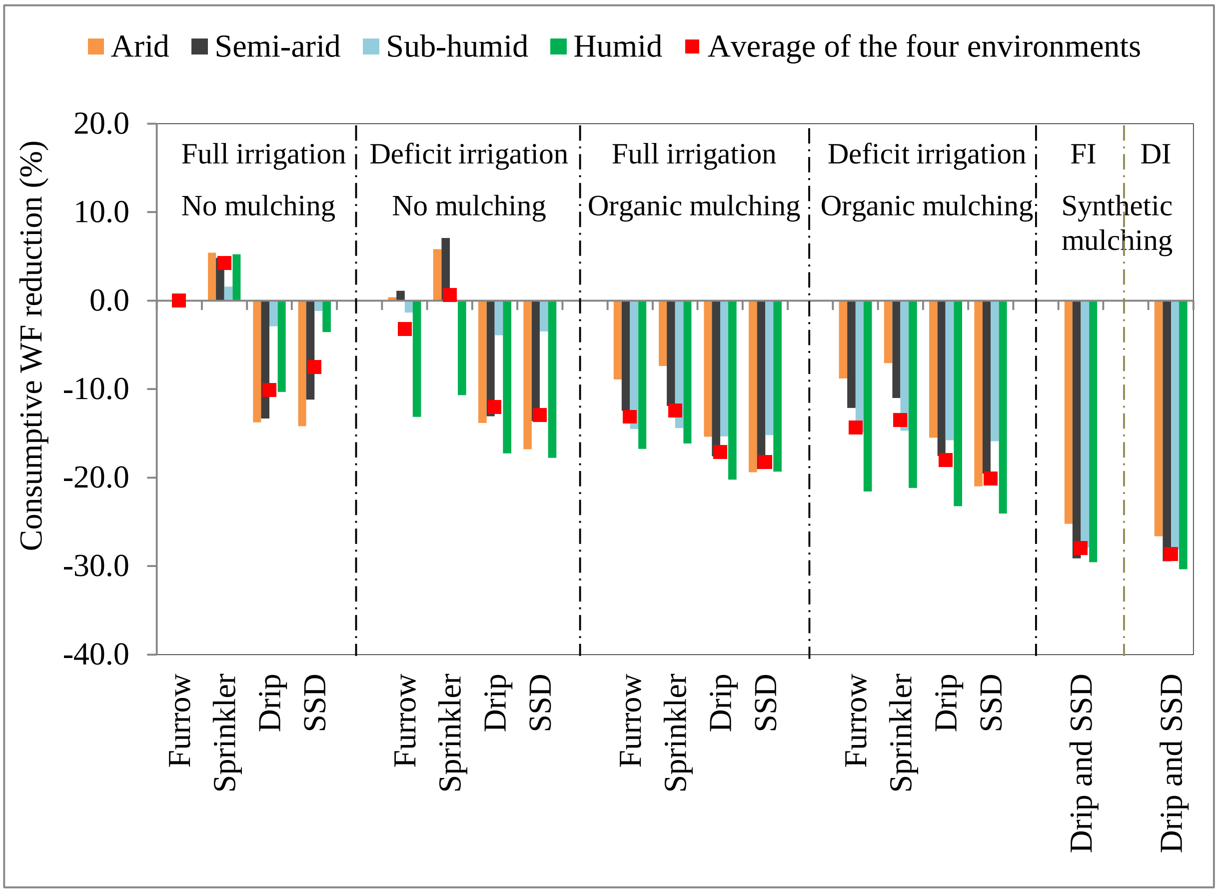


Figure 8. Average change in consumptive WF from the reference for all management practices, specified for the four types of environment. The horizontal red lines represent averages for the four environments. SSD stands for subsurface drip, FI for full irrigation, DI for deficit irrigation, NoML for mulching practice, OML for organic mulching and SML for synthetic mulching.

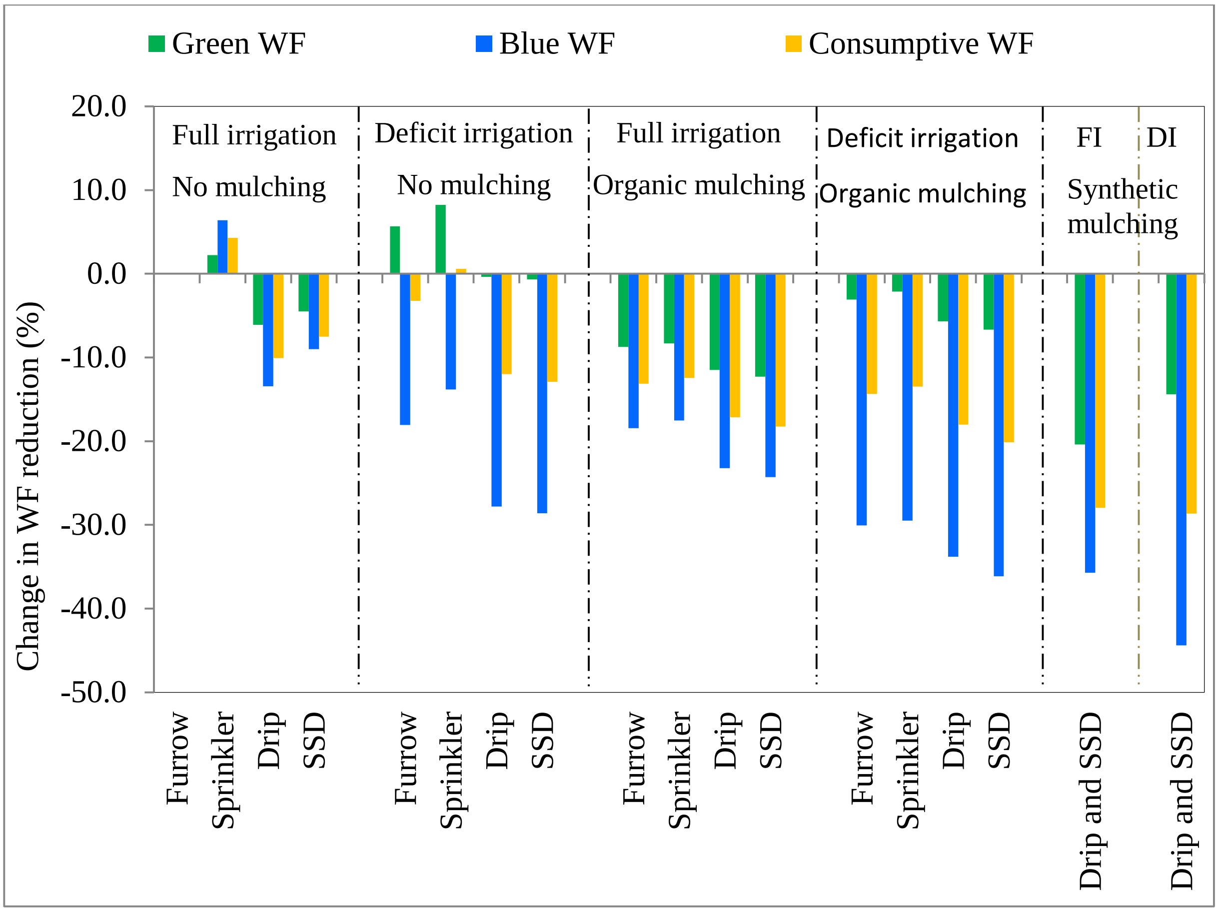


Figure 9. Average change in green, blue and total consumptive WF from the reference for all management practices. SSD stands for subsurface drip, FI for full irrigation, DI for deficit irrigation, NoML for mulching practice, OML for organic mulching and SML for synthetic mulching.

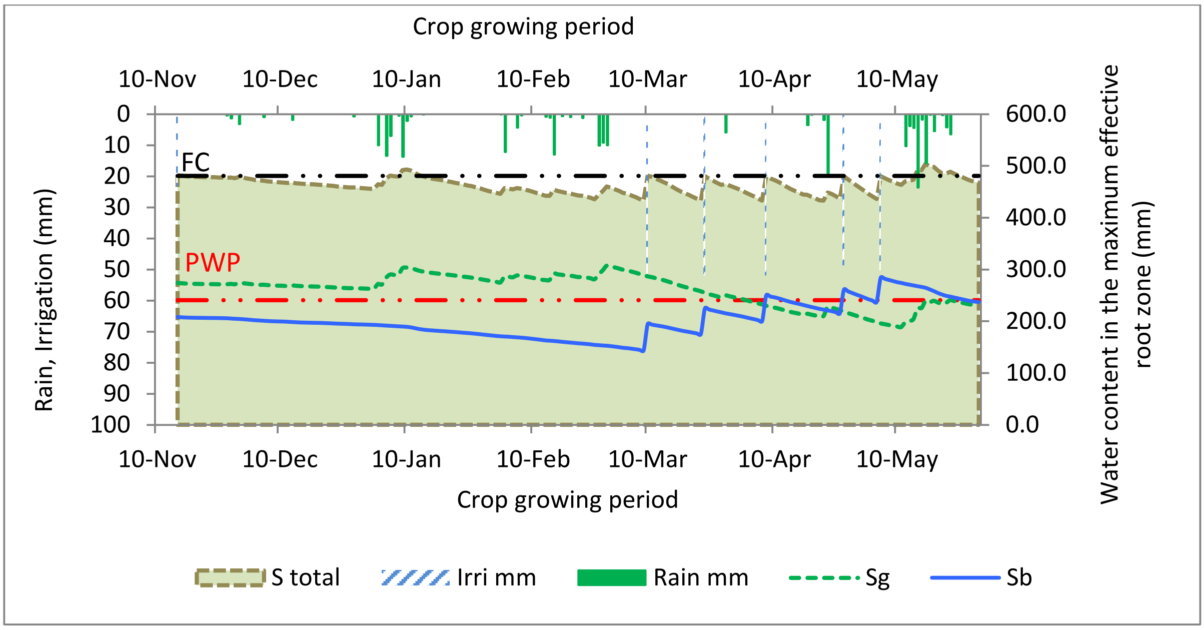


Figure A1. The development of the green (S_g) and blue (S_b) soil water content over the growing period for the case of maize on a loam soil and a normal year at Badajoz in Spain. The symbol S represents total soil moisture, Irri irrigation, FC field capacity, and PWP permanent wilting point.