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.

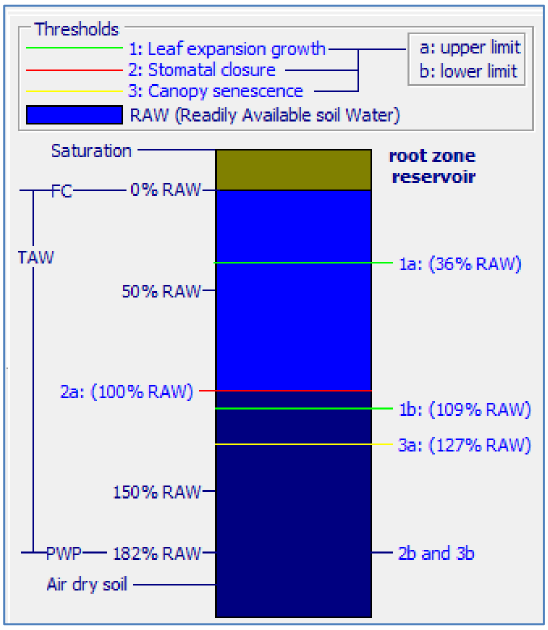

Fig: the three thresholds in water stress for potato: leaf expansion growth, stomata closure and canopy senescence.

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 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.

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