Response to RC1

We thank the reviewer for reviewing our work. All raised points are very helpful and appreciated. Below you will find our collective responses to each part of the reviewer's comment (blue for our reply and purple for the proposed changes to the manuscript).

Summary:

The paper introduces AquaCrop-Earth@lternatives (ACEA), a global gridded crop model that was used to estimate maize WF over a longer period, splitting the WF into green, blue-irrigation, and blue-capillary rise. It's well-written and will make a valuable contribution to the literature. However, before the work is accepted, I have a few concerns that must be addressed:

Thanks for the positive evaluation of our paper.

Major comments:

- The ability to model the role of capillary rise to meeting crop water demand at a worldwide level with high spatial resolution is one of the current study's key achievements. That is something I applaud the authors for. However, I have reservations about using a simplified strategy and depending on a single static groundwater table data set that does not account for interannual change or variation during the irrigation season. Fan et al. (2013) have stated clearly that their data is based on a simple WTD that ignores local geology and is presented in its natural state, without groundwater pumping and drainage. You extrapolated this modeled data, which represents a natural condition during the modeling period, over decades. You're presuming that the WTD remains constant across decades and season to season. This assumption is not supported by scientific evidence. I have a few reservations about this strategy: 1) due to natural fluctuations in precipitation, the groundwater table varies within a year and over time; 2) depending on the intensity of groundwater pumping during the irrigation season, the groundwater level declines by as much as 20 meters or more. As a result, the blue WF from the capillary rise is only 'potential' and not actual. I recommend that you address this limitation by using data that includes interannual and seasonal groundwater level fluctuations. Alternatively, you may refer to your estimate as the potential blue WF assuming everything remains the same.

  Since we used the same monthly water table depths (WTD) from Fan et al (2013) as input for every year, there are indeed neither interannual changes in WTDs nor dynamic coupling with the crop model during the irrigation season. This is a limitation of our approach, which unfortunately cannot be avoided due to the lack of global historical data on WTD. At the same time, we would like to note that the contribution of shallow groundwater levels to maize WF is very small (~2.2 % globally with the current set-up), and thus this limitation should not affect our main conclusions. In a revised version of the manuscript, we will aim to discuss this limitation in more detail while considering your suggestion to use the word "potential" for the blue WF of capillary rise.

- The yield scaling factor is another concerning simplification. The argument is that others have done it before us, so it's fine if we do it the same way. Because of improved maize types with higher HI, yield has increased over time. The crop structure has altered from a larger plant with leaves that fall laterally to a more compact plant with leaves that grow vertically, allowing for closer planting and increased grain output. How do you explain a +56 percent increase in yield factor (S) with no influence on evapotranspiration? Please support your claim with evidence from the literature that new maize varieties have the same ET as older varieties but yield more.

This is indeed one of the major assumptions of our and several previous studies that we referred to. First, we would like to point out that according to Duvick (2005) and Lorenz et al. (2010), the harvest index (HI) is not responsible for the historical increase in maize yields as it stayed relatively constant during the last decades. Instead, the main drivers for yield increase are higher plant density (as you already mentioned), improved biotic and abiotic stress resistance, and better field management (fertilizers, chemical control of weeds and insects etc).

In ACEA, we attempt to represent the combined effect of these drivers by scaling the simulated yields to the national statistics from FAOSTAT. We only scale the yields but not the seasonal ET of maize (i.e. CWU) due to several reasons:

1. There is no strong evidence that maize CWU increased along with improvements in **maize varieties**. For example, Nagore et al. (2014) found that two new maize varieties have similar CWU as an old one in Argentina, and Xu et al. (2018) showed the only minor difference in CWU between large and small canopy maize varieties in China.

   One of the main conclusions from these studies is that differences in crop varieties may change the ratio of transpiration (T) to soil evaporation (E) but overall CWU would be only minorly affected as a decrease/increase in T is compensated by an increase/decrease in E. Both E and T consume green and blue water so we do not expect significant changes to overall green and blue CWU either.

2. To address the effect of increased **plant density**, we carried out sensitivity analysis and found that it does not lead to significant changes in CWU. We illustrate this by simulating maize production in one of the cells in northern Italy during 1986-2016 with three plant density values (see table below):

Plant density [plants ha^{-1}]	Average yield [t ha^{-1} y^{-1}]		Average CWU green [mm y^{-1}]		Average CWU blue [mm y^{-1}]	Average WF [m^3 t^{-1} y^{-1}]	
	rainfed	irrigated	rainfed	irrigated	irrigated	rainfed	irrigated
50000	7.2	13.5	343.5	309	187.6	477.1	367.9
75000	7.2	14	341.7	308.3	194.1	474.6	358.9
100000	7.4	14.3	341.4	310.6	195.7	461.4	354.1

As you can see from the table, CWU values barely change with an increase in plant density. Thus, the difference in maize WFs comes from an increase in yields rather than in CWUs. Also, Barbieri et al. (2012) concluded that a change in maize row spacing does not affect CWU. Hence, having the same plant density value for the whole simulation period worldwide seems to be a reasonable assumption (in our paper we assumed 75 000 plants ha^{-1} as it is the most common value in literature).

3. As for the **fertilizer application** rates, Rudnick et al. (2017) showed that nitrogen inputs might increase maize CWU up to 13 % compared to no nitrogen input. Also, the authors demonstrated that CWU does not show the consistent direction of changes with different nitrogen application rates (from 84 to 252 kg ha^{-1}) but they were always in a range of -10 % to +10 %. In our study, we have to assume no nutrient stress (i.e. optimal nutrient supply) as AquaCrop cannot simulate the nutrient cycle. This might lead to the overestimation of CWU in the grid cells with no fertilizer application. However, we expect no significant impact on global maize WFs. First, because the potential overestimation of CWU by even 13 % is still minor compared to the effect of yield scaling. Second, because fertilizer application is a common practice among the big maize producers, and thus we think it is safe to assume that the (production-weighted) global average maize WFs would be hardly affected.

To sum up, the literature seems to indicate that historical changes in crop varieties and field management only minorly affect green and blue maize CWU compared to crop yields. Therefore, we conclude that using the yield scaling factors is sufficient to represent historical dynamics in maize WFs at the global level. We will further substantiate our assumptions in the Methods and Discussion chapters according to the mentioned above reasoning. Also, we will add a comparison of our maize ET estimates to the existing literature which, in case of minor differences, would again indicate that scaling of ET is not needed.

Literature:

- D. N. Duvick, 'The Contribution of Breeding to Yield Advances in maize (Zea mays L.)', in Advances in Agronomy, vol. 86, Elsevier, 2005, pp. 83–145. doi: 10.1016/S0065-2113(05)86002-X
- A. J. Lorenz, T. J. Gustafson, J. G. Coors, and N. de Leon, 'Breeding Maize for a Bioeconomy: A Literature Survey Examining Harvest Index and Stover Yield and Their Relationship to Grain Yield', Crop Sci., vol. 50, no. 1, pp. 1–12, Jan. 2010, doi: 10.2135/cropsci2009.02.0086.
- M. L. Nagore, L. Echarte, F. H. Andrade, and A. Della Maggiora, 'Crop evapotranspiration in Argentinean maize hybrids released in different decades', Field Crops Research, vol. 155, pp. 23–29, Jan. 2014, doi: 10.1016/j.fcr.2013.09.026.
- G. Xu et al., 'A lysimeter study for the effects of different canopy sizes on evapotranspiration and crop coefficient of summer maize', Agricultural Water Management, vol. 208, pp. 1–6, Sep. 2018, doi: 10.1016/j.agwat.2018.04.
- P. Barbieri, L. Echarte, A. Della Maggiora, V. O. Sadras, H. Echeverria, and F. H. Andrade, 'Maize Evapotranspiration and Water-Use Efficiency in Response to Row Spacing', Agronomy Journal, vol. 104, no. 4, pp. 939–944, Jul. 2012, doi: 10.2134/agronj2012.0014.

- D. R. Rudnick, S. Irmak, K. Djaman, and V. Sharma, 'Impact of irrigation and nitrogen fertilizer rate on soil water trends and maize evapotranspiration during the vegetative and reproductive periods', Agricultural Water Management, vol. 191, pp. 77–84, Sep. 2017, doi: 10.1016/j.agwat.2017.06.007.

Specific comments:

Introduction: Some of the notes have mischaracterized the earlier studies:

- Line 44-45- point 1: True, the cited studies did not take into account thermal stress, but they did take into account water stress. Have you looked at the impact of thermal and water stress on crop output separately? Please clearly show the influence of thermal and water stress on crop production as well as the WF (m3/t) as you stated this is one of your additions to the worldwide WF study. You can include a map in the SI.

  We realize we need to explain this point better in the paper. The cited papers indeed consider the effect of soil water deficit by reducing the amount of actual daily ET and/or adjusting final crop yield. However, this approach neglects the dynamic feedbacks between crop development and water deficit. In previous studies, crop water requirements (CWR) during each day of the season are based on reference ET and a crop factor, which is a pre-described input not affected by the model. This means that when water stress occurs there is no feedback that actually affects crop phenology and CWR in the remainder of the growing season.

  In AquaCrop (as well as in ACEA), water stress has multiple negative impacts on the crop (to name a few: canopy cover reduction, pollination failure, stomatal closure, restricted root development, harvest index reduction). The impacts not only affect the specific date when the water stress occurs but also subsequent days. For instance, water stress reduces canopy expansion, which directly affects the crop biomass and transpiration on subsequent days. Therefore, the approach in the cited papers can be considered rather simplistic compared to AquaCrop. We acknowledge that our statement in the paper is not so clear so we will change it according to the above-mentioned explanation.

  As for the separation of water and heat stresses, we cannot look at them separately in the current simulation setup of ACEA. The only way to do this is to perform separate simulations of maize production with and without heat and water stresses, which can provide valuable insights to model sensitivity and to the impacts of those stresses on crop WFs. Unfortunately, this is not the focus of our paper, but we agree that this topic should be addressed in future research.

- Line 54: " To our knowledge, global crop WFs have never been studied with GGCMs". This is not They may have not used the term WF but there are some global studies - look EPIC (Liu et al. 2007, Liu and Yang 2010, Liu et al. 2009, Liu et al. 2016) and LPJmL (Fader et al. 2010, Rost et al. 2008).

  Thanks for providing these references. We will add some of them to the Introduction and revise our statement.

- Line 61-63: true AquaCrop requires different input files for each site, which adds to the processing time and effort. However, I disagree with your assertion that it increases model complexity and computational load without providing evidence. One effort to make input and output processing easier is the AquaCrop-GIS created by Lorite et al. (2013). Others have written their own script to handle a huge number of simulations' input and output.

  We indeed do not provide the performance indicators of ACEA since the simulation process was not executed in one batch. However, we can provide approximate indicators of the first part of the simulation and compare it with Lorite et al. (2013). The authors provided the following numbers: 1 hour for simulation of 27 cells x 4 models x 60 years (= **6480 years (runs) per simulation hour**). In ACEA, for the first part of the simulation, it took around 5.5 h for 12000 cells x 2 scenarios x 34 years (=396000 years per 5.5 h, which is **72000 runs per simulation hour**). Consequently, ACEA might be 11 times faster than AquaCrop-GIS. Also, ACEA does not need to create separate input files for each grid cell (as AquaCrop-GIS does). Even though our statement still holds, we will rephrase it since there is not enough performance data to make a fair comparison with AquaCrop-GIS.

<u>Method section</u>:

- Line 131-134: Please define the scenarios s1 to s6

  They are already defined in lines 86-88. We will add letter **s** to the scenario numbers in those lines to make it more clear.

<u>Result section</u>:

- You talked about the different regions' relative reductions in WF, yet you didn't even mention the vast red shaded areas in Figure 6. How can you account for the rise in WF in those dark red areas? You listed some countries where the WF has increased on lines 281-283, but you didn't explain why. Please discuss your findings and try to explain why some locations have seen an increase in WF.

  Due to prolonged water and/or heat stresses, some rainfed areas experience years with very small accumulated biomass (and hence yields). As a result, there are relatively big fluctuations in maize yields in areas such as Kenya, Zimbabwe, Nigeria, and North-East China.

  If the yield is very small, the crop WF is very large and any fluctuations in the yield have a large effect on WF. These fluctuations can result in WF peaks of 10000 – 30000 $m^3 t^{-1} y^{-1}$ in some cells which lead to high CV values as you can see in Fig. 9. At the same time, some areas have a decreasing trend in crop yields overall. For example, in Zimbabwe we can see both big fluctuations and decreasing crop yields (see the figure below). This leads to higher average WF values during 2012-2016 compared to 1986-1990 (i.e. maize WF increases in Fig. 6).

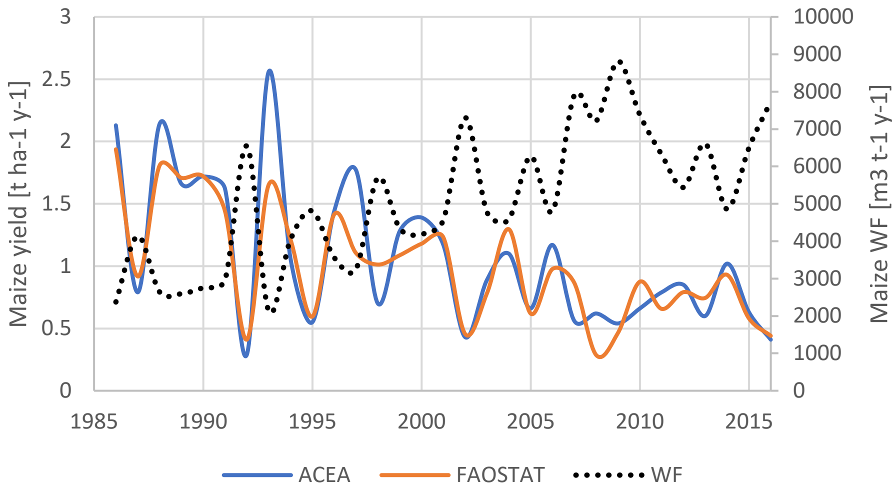

Figure: Average historical maize unit water footprint and yields (simulated in ACEA in blue, provided by FAOSTAT in orange) in Zimbabwe

Different dynamics can be observed in North Korea where maize yields have dropped dramatically since the mid-1990s (the period known as "*The North Korean famine*") and still have not recovered (FAOSTAT, 2021) resulting in higher maize WFs in 2012-2016. We will add more explanations to the manuscript in accordance with the above-mentioned text.

References

Fader, M., Rost, S., Müller, C., Bondeau, A. and Gerten, D. (2010) Virtual water content of temperate cereals and maize: Present and potential future patterns. Journal of Hydrology In Press, Corrected Proof.

Liu, J., Williams, J.R., Zehnder, A.J.B. and Yang, H. (2007) GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems 94(2), 478-493.

Liu, J. and Yang, H. (2010) Spatially explicit assessment of global consumptive water uses in cropland: Green and blue water. Journal of Hydrology 384(3-4), 187-197.

Liu, J., Zehnder, A.J.B. and Yang, H. (2009) Global consumptive water use for crop production: The importance of green water and virtual water. Water Resources Research 45(5), n/a-n/a.

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Lorite, I. J., García-Vila, M., Santos, C., Ruiz-Ramos, M., and Fereres, E.: AquaData and AquaGIS: Two computer utilities for temporal and spatial simulations of water-limited yield with AquaCrop, Computers and Electronics in Agriculture, 96, 227–237, https://doi.org/10.1016/j.compag.2013.05.010, 2013.