Authors' responses to Interactive comments on "Physical versus economic water footprints in crop production: a case study for China"

Dear Referee #2,

We appreciate very much your valuable and helpful comments and suggestions concerning our manuscript. We have studied all the comments carefully and responded as followed.

Anonymous Referee #2

Summary

The manuscript evaluates the physical and economic Water Footprint of 14 crops categorised into cash and grain crops, between 2001 to 2016 over 31 provinces in China. A good background of existing studies is covered and it is shown what the added value of this study can be. However, I believe that there are some aspects that are clearly described or discussed. The methodology and discussion of the results needs to be clearly structured and expanded prior to acceptance of the paper.

Response: We are grateful for your positive comments and suggestions.

General comments

1. In the methodology, split the models used in the analysis from the equations and calculation used to for PWF and EWF. Have a separate section prior to the calculations for the data and models used in the study and then move onto the calculations of the PWF and EWF which are a results of these results. This would include the AquaCrop model, the WF calculation frame and mode of soil water dynamic balance. Also would include a description of the national statistical data used. Otherwise, it is a little difficult to follow. You should also specifically show your equations for ETb and ETg.

Response: We will add a section at the beginning of introduction of methodologies on the model used and data required, followed by the suggested logics in the revision.

The added section will be like:

"2.1 AquaCrop modeling

Crop WF per unit mass is defined by the evapotranspiration (ET) and yield (Y) over the growing period (Hoekstra et al., 2011). The AquaCrop model (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009), a water driven crop water productivity model developed by FAO, is used to simulate the daily green and blue ET and yield Y of 14 crops for each station. The AquaCrop has fewer parameters than other crop growth models and provides a better balance between simplicity, accuracy, and robustness (Steduto et al., 2009). A large number of studies have demonstrated the good performance of AquaCrop in simulating crop growth and water use under different environmental conditions (Abedinpour et al., 2012; Jin et al., 2014; Kumar et al., 2014). Also, there have been a number of studies using AquaCrop to calculate water footprints (Chukalla et al., 2015; Zhuo et al., 2016a; Zhuo et al., 2016c; Wang et al., 2019).

The dynamic soil water balance in the AquaCrop model is shown in Eq. (1):

$$S_{[t]} = S_{[t-1]} + PR_{[t]} + IRR_{[t]} + CR_{[t]} - ET_{[t]} - RO_{[t]} - DP_{[t]}, \quad (1)$$

where $S_{[t]}$ (mm) is the soil moisture content at the end of day t; $PR_{[t]}$ (mm) is the rainfall on day t; $IRR_{[t]}$ (mm) is the irrigation amount on day t; $CR_{[t]}$ (mm) is the capillary rise from groundwater; $RO_{[t]}$ (mm) is the surface runoff generated by rainfall and irrigation on day t; $DP_{[t]}$ (mm) is the amount of deep percolation on day t. $RO_{[t]}$ is obtained through the Soil Conservation Service curve-number equation (USDA, 1964; Rallison, 1980; Steenhuis et al., 1995):

$$RO_{[t]} = \frac{(PR_{[t]} - I_a)^2}{PR_{[t]} + S - I_a}, \quad (2)$$

where S (mm) is the maximum potential storage, which is a function of the soil curve number; I_a (mm) is the initial water loss before surface runoff; $DP_{[t]}$ (mm) is determined by the drainage capacity (m^3 m^{-3} day^{-1}). When the soil water content is less than or equal to the field capacity, the drainage capacity is zero (Raes et al., 2017).

AquaCrop model is able to track the daily inflow and outflow at the root zone boundary. On this basis, we use the blue and green WF calculation framework by Chukalla et al. (2015) and Zhuo et al. (2016c) combined with the model of soil water dynamic balance to separate the daily blue and green ET (mm), as shown in Eqs. (3) and (4):

$$S_{b[t]} = S_{b[t-1]} + IRR_{[t]} - RO_{[t]} \times \frac{IRR_{[t]}}{PR_{[t]} + IRR_{[t]}} - (DP_{[t]} + ET_{[t]}) \times \frac{S_{b[t-1]}}{S_{[t-1]}}, \quad (3)$$

$$S_{g[t]} = S_{g[t-1]} + PR_{[t]} - RO_{[t]} \times \frac{PR_{[t]}}{PR_{[t]} + IRR_{[t]}} - (DP_{[t]} + ET_{[t]}) \times \frac{S_{g[t-1]}}{S_{[t-1]}}, \quad (4)$$

where $S_{b[t]}$ and $S_{g[t]}$ (mm) respectively represent the blue and green soil water content at the end of day t. According to Siebert and Döll (2010), the maximum soil moisture of rainfed fallow land two years before planting is taken as the initial soil moisture for simulating. At the same time, the initial soil water during the growing period is set as green water (Zhuo et al., 2016c).

The green and blue components in DP and ET were calculated per day based on the fractions of green and blue water in the total soil water content at the end of the previous day (Zhuo et al., 2016a), which are shown in Eqs. (5) and (6):

$$ET_{b[t]} = ET_{[t]} \frac{S_{b[t-1]}}{S_{[t-1]}}, \quad (5)$$

$$ET_{g[t]} = ET_{[t]} \frac{S_{g[t-1]}}{S_{[t-1]}}, \quad (6)$$

Using the normalized biomass water productivity (WP*, kg m^{-2}), which is normalized for the atmospheric carbon dioxide (CO_2) concentration, the evaporative demand of the atmosphere (ET_0) and crop classes (C3 or C4 crops), AquaCrop calculates daily aboveground biomass production (B, kg) from daily transpiration (Tr) and the corresponding daily reference evapotranspiration (ET_0) (Steduto et al., 2009):

$$B = WP^* \sum \frac{T_{r[t]}}{ET_{0[t]}} \tag{7}$$

The crop yield (harvested biomass) is the product of the above-ground biomass (B) and the adjusted reference harvest index (HI_0, %) (Raes et al., 2017).

$$Y = f_{HI} HI_0 B \tag{8}$$

where the adjustment factor(f_{HI}) reflects the water and temperature stress depending on the timing and extent during the crop cycle.

The simulated yield per crop per year per station was calibrated at provincial level, by scaling the model outputs in order to fit provincial crop yield statistics (NBSC, 2019)."

2. You also state several times that the PWF and EWP together provide a measurement to analyse the synergy between water consumption of crop production and economic value creation, can you please explain how this happens in the introduction. And also explain why it is important.

Response: The economic benefits of water use form one important pillar of fresh water distribution (Hoekstra, 2014). However, traditional studies on agricultural efficient water use focus on crop water productivity from the physical perspective, and rarely make comprehensive evaluations combining the results with an economic perspective.

As the comprehensive index to evaluate types, quantities, and efficiency of water use in the process of crop production, the WF of crop production can be expressed based on either production (PWF, m^3 kg^{-1}) or economic value (EWF, m^3 per monetary unit) (Garrido et al., 2010; Hoekstra et al., 2011), which unifies the measurement of the physical and economic levels. PWF and EWF provide insightful measurements for reducing the water resources input for harvesting crop yields and optimizing the economic benefits per unit of water consumption, respectively. Therefore, based on the quantification of PWF and EWF, we constructed the synergy evaluation index (SI) of water footprint, so that the original intention of the study -- comprehensive assessment from the perspective of both physics and economics can be implemented.

We will use the above explanation to elaborate further on the motivation for a comprehensive evaluation using both PWF and EWF in the introduction in the revised manuscript.

3. You should also define what is blue and green water. Also why is green water rainfed and both blue and green water considered in irrigated systems. This might be clear to us but may not be clear to everyone who reads your article. This can either be included in the introduction or in the methodology section.

Response: Blue water is surface and ground water, whereas green water is defined as the water kept in the unsaturated soil layer and precipitation, which is eventually transferred into canopy evapotranspiration (Falkenmark and Rockström, 2006). The consumptive WF of crop production can be divided into blue and green WFs (Hoekstra et al., 2011). The blue WF refers to the consumption of surface water and groundwater. In agriculture, the blue WF measures irrigation water consumption. Green WF refers to the consumption of rainwater (Hoekstra et al., 2011). Therefore, only green water is consumed at rainfed field.

We will add corresponding information to the revised introduction.

4. I do not really understand why you used the actual yield in your calculations instead of the modelled yield. You used the modelled yield for alpha but not for the actual yield which only effects your EWF for irrigated areas. Is there a reason for this? Also, maybe it would be a good idea to also calculate this using the modelled yield and compare with the results you obtain using the statistics or actual yield?

Response: We are very sorry to raise both your and Referee #1's confusion because of our unclear expression.

The current calculation of water footprint is based on both the modeled ET and yield. Being consistent with the existing calibration method which has been widely applied (Mekonnen and Hoekstra, 2011; Zhuo et al., 2016b, 2016c, 2019; Wang et al., 2019), the modeled crop yield was calibrated at provincial level according to the statistics (NBSC, 2019). Within a province, we calibrated the average level of the modeled yields among station points to match the provincial statistics. Therefore, we kept the spatial variation in crop yields, so that in associated water footprints simulated by AquaCrop model.

We will add the above explanation to the revised manuscript.

5. What is GeoDa? I have looked it up but I would suggest that you also describe this in your models section that I suggested you incorporate into your methodology.

Response: Thank you very much for your valuable suggestions.

GeoDa is a free software program intended to serve as a user-friendly and graphical introduction to spatial analysis. It includes functionality ranging from simple mapping to exploratory data analysis, the visualization of global and local spatial autocorrelation, and spatial regression. A key feature of GeoDa is an interactive environment that combines maps with statistical graphics, using the technology of dynamically linked windows. In terms of the range of spatial statistical techniques included, GeoDa is most alike to the collection of functions developed in the open-source R environment. (Anselin et al., 2006).

We will add the above description of GeoDa to methodology in the revised manuscript.

6. More explanation is required in the results or in the discussion regarding what the results mean and not just the statement of the numbers. Why is the SI lower in one province, what significance does having H-H clustering in several provinces mean to the area? What does it mean if there is a decrease in agglomeration over time? What impact does this have? You need to go into the impacts of your numbers and trends so that the reader can get some information from the paper. These are just some questions but you should do this for all your results.

Response: Thank you very much for your valuable suggestions. We will carefully check all the results accordingly and improve the interpretation by deeper analysis on reasons behind the shown numbers.

For example, for the first question in the comment, we find that SI values negative mostly in northwest China for grain crops, whereas positive in southeast coastal provinces in China. The main reason behind is that the drier Northwest, where grows wheat and maize, have both high water intensity and low crop prices. While the water-abundant and economically developed southeast coastal provinces grow rice with a lower PWF and higher prices. In the revision, we will show in detail all the revised parts by addressing all the questions listed in the comments, in responses to comments.

7. In table 8, you are comparing EWF in 'Wheat in Morocco', 'Wheat in Tunisia', 'Winter wheat in China' and 'Spring wheat in China'. Considering the large differences in the regions/countries, is this possible to compare? Please also make note these comparisons are not in the same regions and make sure you include the assumptions you make in these comparisons.

Response: Yes, we realize that the current writing is not clear in related to Table 8. There was no existing EWF values for the same region. We wish to show the available values on EWF of crops, while for countries other than China. In the revised paper, we will clarify the statements in text and discuss the reasons behind the differences in EWF values among the countries.

8. The main goal of this paper is the SI, but I am still unclear on this index. I think this index needs to be explained in greater detail in the methodology as well as the interpretation and impact of this index in the subsequent results and discussion sections needs further improvement. This is the innovation of your paper so this needs to be more clear.

Response: As we respond to Referee #1's similar comments, the synergy evaluation index (SI) in the current study is the measure of the synergy levels between the PWF and EWF of crops, by summing up their corresponding difference between the water footprint and the base value divided by the range (the maximum minus the minimum) of the water footprint. Here, we adopt the weighted national average level water footprint value as the reference for comparison. The synergy (both the PWF and EWF are lower than the national averages), trade-off (one is higher than the national average while the other is lower), or lose-lose (both are higher than the national averages) situation can be identified.

For the two provinces with high SI values, they were both in an advantageous position, while the one with a higher SI values performed better in terms of synergy between PWF and EWF.

We will improve the interpretation on the SI in the methodology and clarify the impact of this index in the subsequent results and discussion sections in the revised manuscript.

9. You need to be careful with some English terminology such as 'contradiction'. I do not believe that is what you meant in several places where you use it.

Response: We are very sorry for the incorrect wording. As we respond to the similar comment by Referee #1, we will check carefully through the text and correct the word "contradiction" into "trade-off" or "lose-lose" accordingly.

Specific comments

P3L79 – Change 'which are respectively calculated from the daily green ($ET_{g[t]}$, mm) and blue evapotranspiration ($ET_{b[t]}$, mm)' to which are respectively calculated from the blue evapotranspiration ($ET_{b[t]}$, mm) and daily green evapotranspiration ($ET_{g[t]}$, mm)' as you use respectively and then change the order or green and blue.

Response: We will correct the sentence in the revision.

P5L131 – you should define what economic benefit unit is.

Response: The economic benefit unit refers to crop price in the current study. We will clarify the terminology in the revision.

P7L184 – move the data section before your methods.

Response: We will revise accordingly.

P7L175 – You state 'Obviously, -2 <= SI <= 2'. Why is this obvious? Please explain and clarify in text.

Response: The synergy evaluation index (SI) is the sum of the difference between the water footprint and the base value divided by the range (the maximum minus the minimum) of the water footprint. Here, we adopt the national average level water footprint value as the reference of comparison. The SI is calculated as follows:

$$SI_{i,j,c} = \frac{\overline{PWF_{j,c}} - PWF_{i,j,c}}{PWF_{j,c,max} - PWF_{j,c,min}} + \frac{\overline{EWF_{j,c}} - EWF_{i,j,c}}{EWF_{j,c,max} - EWF_{j,c,min}}$$ (18 in the original manuscript)

where $SI_{i,j,c}$ is the synergy evaluation index of PWF and EWF of crop c at province i in year j, $\overline{PWF_{j,c}}$(m^3 kg^{-1}) and $\overline{EWF_{j,c}}$(m^3 USD^{-1}) are the averages at the national level in year j. Obviously, the absolute value of the difference between the WF and their corresponding national average level cannot exceed the maximum minus minimum values. Therefore, the absolute value of SI cannot exceed 2.

We will clarify in the text in the revision.

P8L191 – I would refer to your figure 1.

Response: We will revise accordingly.

References

Abedinpour, M., Sarangi, A., Rajput, T. B. S., Singh, M., Pathak, H., and Ahmad, T.: Performance evaluation of AquaCrop model for maize crop in a semi-arid environment, Agricultural Water Management, 110, 55-66,https://doi.org/10.1016/j.agwat.2012.04.001, 2012.

Anselin, L., Syabri, I., and Kho, Y.: GeoDa: An introduction to spatial data analysis, Geographical Analysis, 38, 5-22,https://doi.org/10.1111/j.0016-7363.2005.00671.x, 2006.

Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y.: Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching, Hydrology and Earth System Sciences, 19, 4877-4891,https://doi.org/10.5194/hess-19-4877-2015, 2015.

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-Asce, 132, 129-132,https://doi.org/10.1061/(asce)0733-9496(2006)132:3(129), 2006.

Garrido, A., Llamas, R., Varela-Ortega, C., Novo, P., Rodríguez-Casado, R., and Aldaya, M. M.: Water Footprint and Virtual Water Trade in Spain: Policy Implications, Springer, New York, USA, 2010.

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.: Water scarcity challenges to business, Nature Climate Change, 4, 318-320,https://doi.org/10.1038/nclimate2214, 2014.

Hsiao, T. C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., and Fereres, E.: AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize, Agronomy Journal, 101, 448-459,https://doi.org/10.2134/agronj2008.0218s, 2009.

Jin, X., Feng, H., Zhu, X., Li, Z., Song, S., Song, X., Yang, G., Xu, X., and Guo, W.: Assessment of the AquaCrop Model for Use in Simulation of Irrigated Winter Wheat Canopy Cover, Biomass, and Grain Yield in the North China Plain, Plos One, 9,https://doi.org/10.1371/journal.pone.0086938, 2014.

Kumar, P., Sarangi, A., Singh, D. K., and Parihar, S. S.: EVALUATION OF AQUACROP MODEL IN PREDICTING WHEAT YIELD AND WATER PRODUCTIVITY UNDER IRRIGATED SALINE REGIMES, Irrigation and Drainage, 63, 474-487,https://doi.org/10.1002/ird.1841, 2014.

Mekonnen, M. M., and Hoekstra, A. Y.: The green, blue and grey water footprint of crops and derived crop products, Hydrology and Earth System Sciences, 15, 1577-1600,https://doi.org/10.5194/hess-15-1577-2011, 2011.

National Data. National Bureau of Statistics, Beijing, China: http://data.stats.gov.cn/english/easyquery.htm?cn=E0103, 2019.

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, Agronomy Journal, 101, 438-447,https://doi.org/10.2134/agronj2008.0140s, 2009.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E.: Reference manual for AquaCrop version 6.0 - Chapter 3, Food and Agriculture Organization, Rome, Italy, 2017.

Rallison, R. E.: Origin and evolution of the SCS runoff equation. In: Symposium on Watershed Management, pp. 912–924, 1980.

Siebert, S., and Döll, P.: Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation, Journal of Hydrology, 384, 198-217,https://doi.org/10.1016/j.jhydrol.2009.07.031, 2010.

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, Agronomy Journal, 101, 426-437,https://doi.org/10.2134/agronj2008.0139s, 2009.

Steenhuis, T. S., Winchell, M., Rossing, J., Zollweg, J. A., and Walter, M. F.: SCS RUNOFF EQUATION REVISITED FOR VARIABLE-SOURCE RUNOFF AREAS, Journal of Irrigation and Drainage Engineering-Asce, 121, 234-238,https://doi.org/10.1061/(asce)0733-9437(1995)121:3(234), 1995.

USDA: Estimation of direct runoff from storm rainfall. National Engineering Handbook, Washington DC, USA. Section 4 Hydrology, Chapter 4: 1-24, 1964.

Wang, W., Zhuo, L., Li, M., Liu, Y., and Wu, P.: The effect of development in water-saving irrigation techniques on spatial-temporal variations in crop water footprint and benchmarking, Journal of Hydrology, 577,https://doi.org/10.1016/j.jhydrol.2019.123916, 2019.

Zhuo, L., Mekonnen, M. M., and Hoekstra, A. Y.: Benchmark levels for the consumptive water footprint of crop production for different environmental conditions: a case study for winter wheat in China, Hydrology and Earth System Sciences, 20, 4547-4559,https://doi.org/10.5194/hess-20-4547-2016, 2016a.

Zhuo, L., Mekonnen, M. M., and Hoekstra, A. Y.: The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: A study for China (1978-2008), Water Res, 94, 73-85,https://doi.org/10.1016/j.watres.2016.02.037, 2016b.

Zhuo, L., Mekonnen, M. M., Hoekstra, A. Y., and Wada, Y.: Inter- and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River basin (1961–2009), Advances in Water Resources, 87, 29-41,https://doi.org/10.1016/j.advwatres.2015.11.002, 2016c.

Zhuo, L., Liu, Y., Yang, H., Hoekstra, A. Y., Liu, W., Cao, X., Wang, M., and Wu, P.: Water for maize for pigs for pork: An analysis of inter-provincial trade in China, Water Research, 166,https://doi.org/10.1016/j.watres.2019.115074, 2019.