A gridded dataset of consumptive water footprints, evaporation, transpiration, and associated benchmarks related to crop production in China during 2000-2018

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Authors' responses to Referee #1' s comments

We thank Referee #1 very much for such valuable comments and suggestions improving the manuscript. We learn carefully and provide preliminary responses to the comments point to point.

This study constructed a gridded dataset for crop water consumption in China. The advantages of this dataset are the separate estimation of blue and green evaporation (E), transpiration (T), the use of the local information on irrigation type per crop, and the long time series. Even though comparisons with other studies on ET look good, I have many concerns about methods that are not clear in the paper. Without this information, it is hard for me to conclude on the dataset quality and reliability. I suggest a major revision and reconsideration for publication unless the authors can address the following concerns/questions.

Major comments:

1. The aquaCrop model setting is absent.

1-A) There are different versions of AquaCrop and available on different platforms, e.g. Windows interface for FAO AquaCrop v7, v6 or before, and Python and MATLAB open source versions. Which AquaCrop version was used for this study?

Responses: Thank you for your comments and questions regarding the AquaCrop version used in our study. We apologize for not providing this information in the manuscript. We used FAO AquaCrop v6 for crop simulation because AquaCrop v7 was not yet released during the course of our study. AquaCrop v7 was developed based on AquaCrop v6 and includes some bug fixes, performance improvements, internal reorganization, as well as the addition of perennial forage crops and new calibration crops. However, these updates have minimal impact on the crops involved in our study.

Therefore, we decided to use AquaCrop v6 for the simulations. We will include this detail in the Methods section of the revised manuscript.

1-B) As I understand, publicly available AquaCrop cannot simulate perennial crops. How did the authors deal with perennial crops using AquaCrop, e.g. tea, and apple?

Responses: Thank you for your comments. In Aquacrop, the simulated plants are programmed to die at the harvest stage, indicating the completion of their life cycle. This stands in contrast to woody plants such as tea trees and apple trees, where the harvest of fruits does not result in the complete loss of the standing biomass. To accommodate the simulation of woody plants in Aquacrop, the model is used differently than the normal model set-up. Hunink and Droogers (2010, 2011) conducted simulations in Albania and Uzbekistan to assess the response of yield and water requirements of different woody plants, including apple trees, grapevines, and olive trees, to climate change. Zhuo et al. (2016a) simulated the yield and evapotranspiration of tea and apple trees in China.

Following Poppe (2016), an attempt to simulate the woody plants anyway is done by simulating only the foliage of the plants. This component is considered the annual portion of woody plants within the scope of this study. The remaining biomass, including the stem and major branches, is assumed to remain constant once the tree reaches maturity. There will also be no root development for the plant. Since yield is a direct function of biomass and harvest index, adjustments are made to the harvest index to reflect its applicability to foliage biomass only, rather than the whole biomass. Similar to other crops, the evapotranspiration of woody plants is directly associated with the canopy cover.

1-C) Using AquaCrop needs crop characteristics as input, e.g. the maximum canopy cover, canopy cover decline coefficient, canopy growth coefficient, and many others. Where did these inputs come from and what are the inputs?

Responses: Thank you for your comments. In the Annex of the Reference manual for the AquaCrop (Raes et al., 2018), crop parameters for the 12 crops covered in this study are given, including crop phenology, crop transpiration, biomass production and yield formation, and stresses, totaling 41 parameters. Furthermore, these parameters are further classified based on crop sensitivity as conservative generally applicable, conservative for a given species but can or may be cultivar specific, dependent on environment and/or management and cultivar specific.

The conservative parameters from the Annex were utilized to generate the original model input files. Vanuytrecht et al. (2014) and Zhuo et al. (2016a) pointed out that yield simulation results are sensitive to parameters such as crop planting dates, reference harvest index, crop growth stages, and maximum root depth. Hence, we obtained these parameters for this study by referring to the literature (Allen et al., 1998; Vanuytrecht et al., 2014; Chen et al., 1995; Xie et al., 2011; Zhang and Zhu, 1990; Hoekstra and Chapagain, 2006). Due to data limitations, the remaining parameters such as maximum canopy cover, canopy cover decline coefficient, canopy growth coefficient were assigned the mean values within the reference range provided in the Annex. Although this approach may overlook certain potential variations, the use of mean values generally captures the central tendency of the data.

In summary, the objective of this study is to investigate the response and variability of crop water footprints to different water supply and irrigation practices at a large regional scale. Similar to previous global and national scale studies (e.g., Liu and Yang, 2010; Mekonnen and Hoekstra, 2011; Chiarelli et al., 2020), it was neither practical nor feasible to calibrate crop parameters individually for each grid. Nevertheless, we have made every effort to ensure the reliability of the model input parameters within the constraints of the available data.

1-D) What do the authors mean by calibrated AquaCrop? How did the authors calibrate AquaCrop? Section 2.3.1 does not explain the calibration on AquaCrop.

Responses: Thank you for your comments. The calibrated AquaCrop in this study was achieved by strictly screening the input parameters and keeping the simulated yields consistent with the provincial-scale statistics. In line with previous studies (Wang et al., 2019; Siebert and Doll, 2010; Mialyk et al., 2022), we attempt to represent the combined effect of advances in agricultural inputs (e.g., fertilisers, machinery, and chemical control of weeds and insects) via production scaling factors that scale simulated crop production to the annual statistics. For the ambiguous expression "calibrated AquaCrop", we will add the explanation in the manuscript.

2. Reliability in separating E and T.

2-A) Distinguishing T from ET is not traditionally in water footprint studies. One challenge is that the ratio of T to ET depends not only on crop growth, and irrigation type but also on field management, e.g. weeds, soil fertility, mulching. As for large-scale assessment, there is always lacking data for field management, thus, it is difficult to estimate T and E separately. However, total ET is more robust to field management, so lacking such data will not be a big issue for total ET. Here the authors try to explicitly distinguish E and T from ET but still have very limited ability to describe the field management in the model. In this sense, how do the authors evaluate the reliability of separating E and T?

Responses: Thank you for your comments. We acknowledge that the ratio of transpiration (T) to evapotranspiration (ET) is influenced not only by crop growth and irrigation type but also by field management factors such as weeds, soil fertility, and mulching. In this study, we specifically focused on the impact of different irrigation practices on crop water footprint, aiming to elucidate the proportion of evaporation (E) and transpiration (T) in crop water consumption under different irrigation practices.

Regarding the reliability of our research results, we will compare them with publicly available datasets and some published results from field experimental to further evaluate the robustness of the transpiration (T) to evapotranspiration (ET) ratio when considering only the difference in irrigation practices.

It is worth mentioning that the accessibility of tillage data, such as weeds, soil fertility, mulching, and others, at a large-scale fine spatial resolution presents significant challenges. Only a few studies have utilized AquaCrop modeling to simulate crop water footprints at the site scale (Chukalla et al., 2015). If there are reliable tillage data products available, we will incorporate other field management factors into the assessment of crop water consumption in future global-scale studies as per your suggestions. The above improvements will facilitate a more comprehensive evaluation of agricultural water use and clarify the relationship between transpiration (T) and evapotranspiration (ET).

Additional details regarding the aforementioned content will be included in the discussion section of the revised manuscript.

2-B) Did the authors further distinguish the color of E and T? and how?

Responses: Thank you for your comments. We distinguished the color of E and T as follows (Zhuo et al., 2016a; Chukalla et al., 2015):

$$\mathrm{ET}_{\mathrm{b}[t]} = \mathrm{IRR}_{[t]} + S_{\mathrm{b}[t-1]} - S_{\mathrm{b}[t]} - \mathrm{RO}_{[t]}\left(\frac{\mathrm{IRR}_{[t]}}{\mathrm{PR}_{[t]} + \mathrm{IRR}_{[t]}}\right) - \mathrm{DP}_{[t]}\left(\frac{S_{\mathrm{b}[t-1]}}{S_{[t-1]}}\right) \quad (1)$$

$$\mathrm{ET}_{\mathrm{g}[t]} = \mathrm{PR}_{[t]} + S_{\mathrm{g}[t-1]} - S_{\mathrm{g}[t]} - \mathrm{RO}_{[t]}\left(\frac{\mathrm{PR}_{[t]}}{\mathrm{PR}_{[t]} + \mathrm{IRR}_{[t]}}\right) - \mathrm{DP}_{[t]}\left(\frac{S_{\mathrm{g}[t-1]}}{S_{[t-1]}}\right) \quad (2)$$

$$E_{\mathrm{b}[t]} = \mathrm{E}_{[t]}\left(\frac{S_{\mathrm{b}[t-1]}}{S_{[t-1]}}\right) \quad (3)$$

$$E_{\mathrm{g}[t]} = E_{[t]}\left(\frac{S_{\mathrm{g}[t-1]}}{S_{[t-1]}}\right) \quad (4)$$

$$\mathrm{Tr}_{\mathrm{b}[t]} = \mathrm{Tr}_{[t]}\left(\frac{S_{\mathrm{b}[t-1]}}{S_{[t-1]}}\right) \quad (5)$$

$$\mathrm{Tr}_{\mathrm{g}[t]} = \mathrm{Tr}_{[t]}\left(\frac{S_{\mathrm{g}[t-1]}}{S_{[t-1]}}\right) \quad (6)$$

The green and blue components in E and Tr are 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.

3. Irrigation and soil moisture assumption. In Table 5, comparing the previous studies, this study has a higher water footprint. According to my experience using these datasets, they generally overestimate water consumption compared to hydrological models and recent crop models for some crops because of two reasons (maybe more): first, they assume irrigation once there is a water deficit, even though the water deficit would be tiny; second, when setting the initial soil moisture, they assumed the field capacity of the soil moisture at the beginning of each year. Both are unrealistic and will lead to overestimation of water consumption. How do the authors set irrigation rules and soil moisture in the model and did the authors have a spin-up for the model?

Responses: Thank you for your comments. In our study, we employed a supplementary irrigation strategy, similarly to the first possible reason as mentioned, whereby irrigation is applied when soil moisture falls below the plant wilting point to bring it up to field capacity. Different irrigation practices indirectly affect water consumption during the growth period due to differences in the fraction of the surface wetted.

To establish the initial soil moisture content at the beginning of the growing season, we adopted the method and assumptions proposed by Siebert and Doll (2010). Following their approach, we generated the initial soil moisture content by using the maximum soil moisture content of rainfed fallow land in the two years preceding the planting period. The initial soil moisture at the start of the growing period is assumed as green water. Such settings and assumptions have been widely applied and with acceptable uncertainties (Chiarelli et al., 2020; Hoogeveen et al., 2015).

4. Usability and quality of the benchmark

4-A) Figure 6 shows the benchmark at the grid level. However, if we have a close look at the graph, we find usually, the resolution is the provincial level, e.g. the whole province is efficient or not. This is because the calibration and scaling were on the provincial level. If it is the case, scaling factors seem to play a critical role here other than irrigation, climate, and so on. What do the authors think of the reliability of the benchmark in this case?

4-B) The whole of China was divided into two climate zones for the benchmark without considering soil type. This seems oversimplified to me. Furthermore, this dataset provides the benchmark for each year, but the idea for a benchmark is to provide a kind of efficient "reference". So, why not derive using the whole time series? Imagine one wants to use the benchmark for future analysis, which year should be selected? How do the authors suggest using their benchmark?

Responses: Thank you for your comments. To ensure completeness in addressing your questions (4A and 4B), we will provide a unified response here.

It is essential to emphasize that crop simulations in this study were conducted at a grid scale after integrating data from soil, weather, and other models. Although yield data were calibrated at the provincial level, the water footprint per unit mass of crop production (uWFCP) depends on both yield and water consumption. Figure 6 presents the benchmarks for uWFCP at different production percentiles under furrow irrigation in China by 2018. A few uWFCP benchmarks show significant regional correlations at the provincial scale due to inter-annual variations in model inputs. In fact, our previous studies examining uWFCP benchmarks for rain-fed and irrigated croplands, wet and dry years, warm and cold years, different soil types, and various climate zones have indicated that different climate zones are crucial factors influencing the uWFCP benchmarks (Zhuo et al., 2016b). Therefore, this study considered distinguishing the uWFCP benchmarks for different climate zones at the grid scale over the past 19 years. By utilizing the multi-year average of specific crop uWFCP benchmarks in guiding production practices, the influence of specific climatic conditions within the same region can be mitigated.

Minor comments:

1. In the title, "consumptive water footprints". By definition, water footprint is consumptive water use. Is consumptive redundant here? Or "consumptive water use"?

Responses: Thank you for your comments. The water footprint is a multi-dimensional indicator and divided into consumptive water footprint and degradative water footprint (Hoekstra, 2013), in which the consumptive water footprint refers to the use of both rainfall and ground-surface water (the green and blue water footprint, respectively), and the degradative water footprint refers to the water required to assimilate anthropogenic loads of pollutants to freshwater bodies (the grey water footprint). Here, consumptive water footprint refers to the blue and green water footprint crop production, excluding grey water footprint.

2. Line 95-102. The authors basically only rely on the global datasets for land use from the year 2000 and then scale to each year. Are there other better datasets that have better quality/time coverage in China?

Responses: Thank you for your comments. In our study, we employed global datasets for land use from the year 2000 as the primary data source due to its wide accessibility and compatibility with our research objectives. It is important to note that MIRCA2000 dataset and proportional scaling method have been applied in several studies within the field. As shown in section 4.1, the harvested area of specific crop obtained by the proportional scaling method show a good consistency with the published data in the same time range of the grid scale.

In regard to alternative datasets with potentially better quality and temporal coverage specifically for China, it is worth mentioning that existing publicly available databases have certain limitations including a limited range of crop types and intermittent time series. For instance, the SPAM dataset (IFPRI, 2019) is only publicly available for a few specific years 2000, 2005 and 2010, and interpolation is still required to fill in the gaps.

As a supplement, we present a comparison between the crop planting areas of 15 crops in the 2010 SPAM dataset and our research dataset at both the provincial and grid scales (Fig. 1 and Fig. 2). It is evident that there is a high degree of consistency between the two datasets at the provincial scale. The differences at the grid scale can be attributed to disparities in the identification of grid-level land use between the MIRCA2000 and SPAM2010 datasets.

According to Fig. 3 and Fig. 4, the planting area data for sorghum, millet, barley, and sugar beets in the GAEZ+ dataset exhibit significant deviations from the values applied in this study, both at the provincial and grid scales (Grogan et al., 2022). However, it should be emphasized that all crop planting area data in this study have been calibrated against statistical data at the provincial scale, implying an underestimation of the planting area for the mentioned crops in the GAEZ+ dataset.

Given the above analysis, we choose the MIRCA2000 database for estimating the planted areas of different crops under various water supply and irrigation practices. While we acknowledge the potential for alternative datasets, it is important to highlight that our study made a conscious decision based on the available data sources and applied rigorous methods to ensure reliability and comparability.

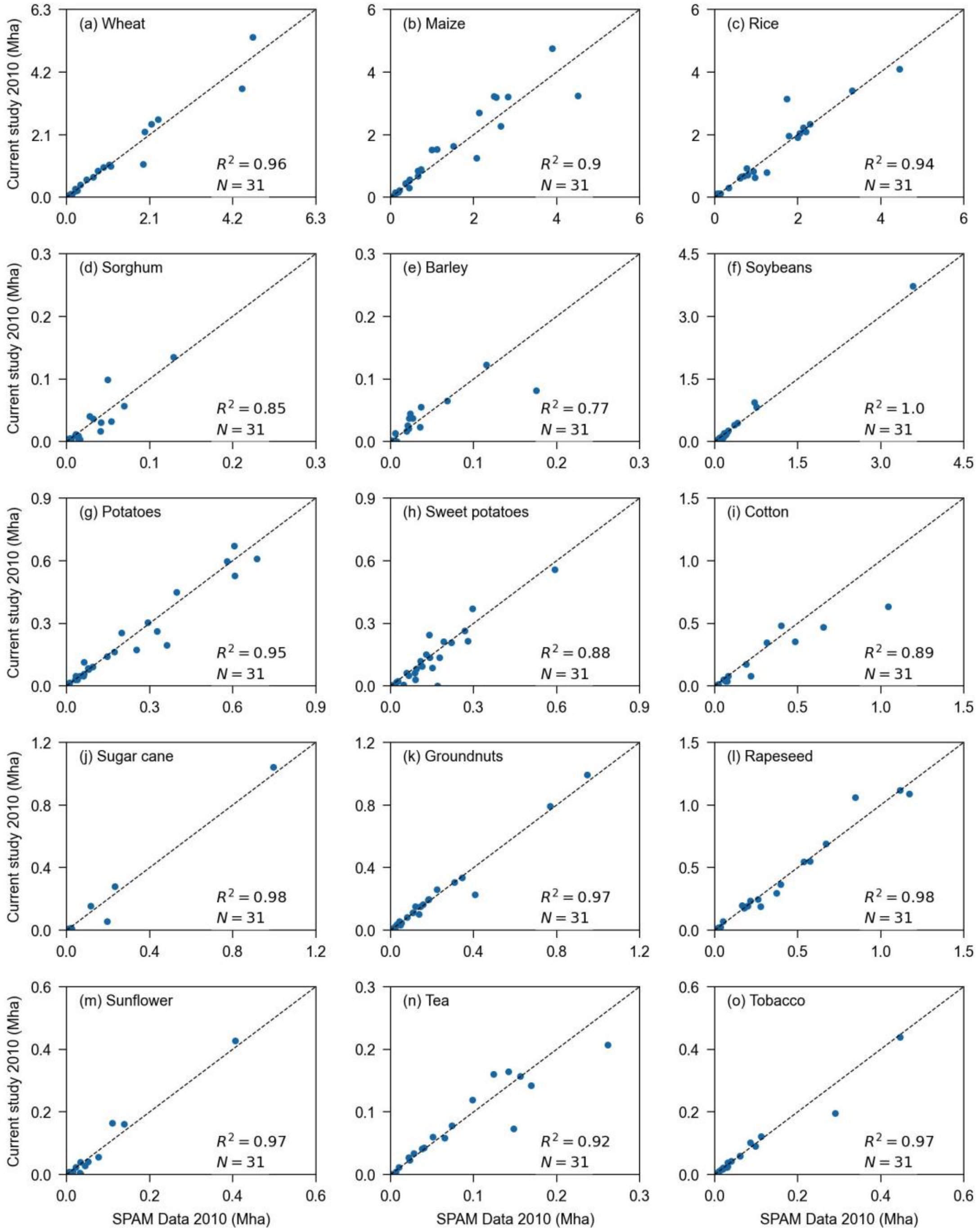

Figure 1. Comparison of the current provincial area representing land coverage with the MapSPAM2010 datasets.

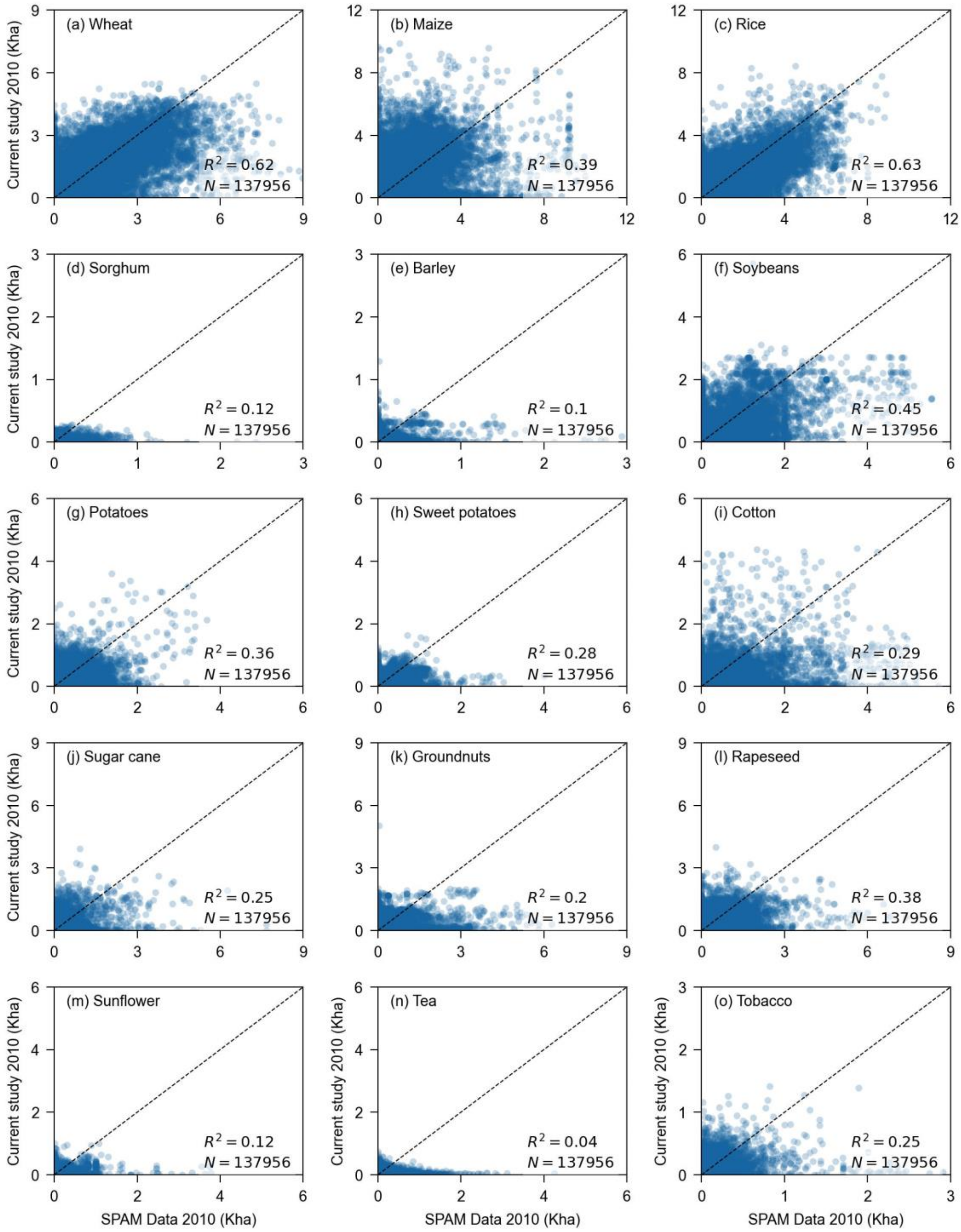

Figure 2. Comparison of the current gridded area representing land coverage with the MapSPAM2010 datasets.

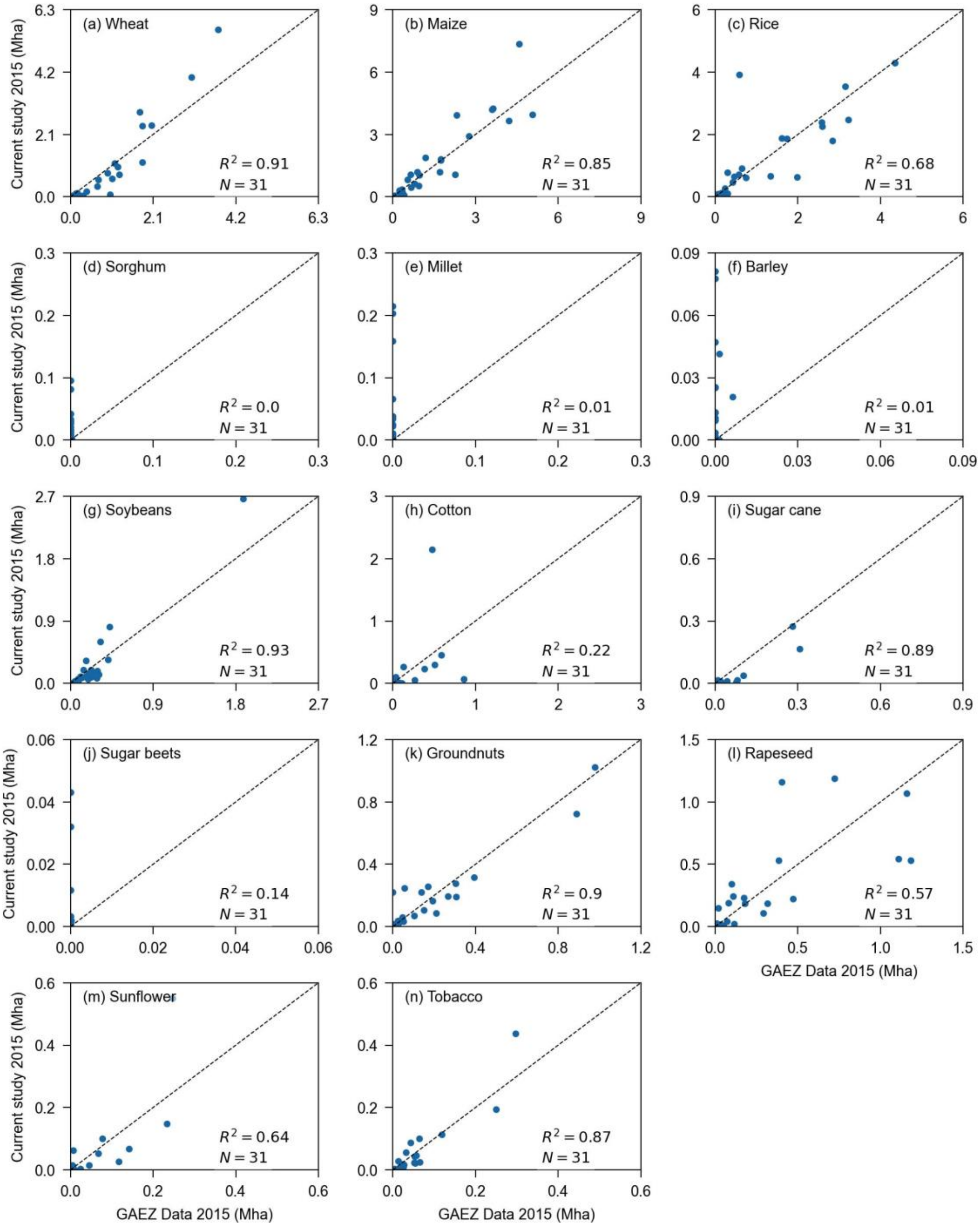

Figure 3. Comparison of the current provincial area representing land coverage with the GAEZ+2015 datasets.

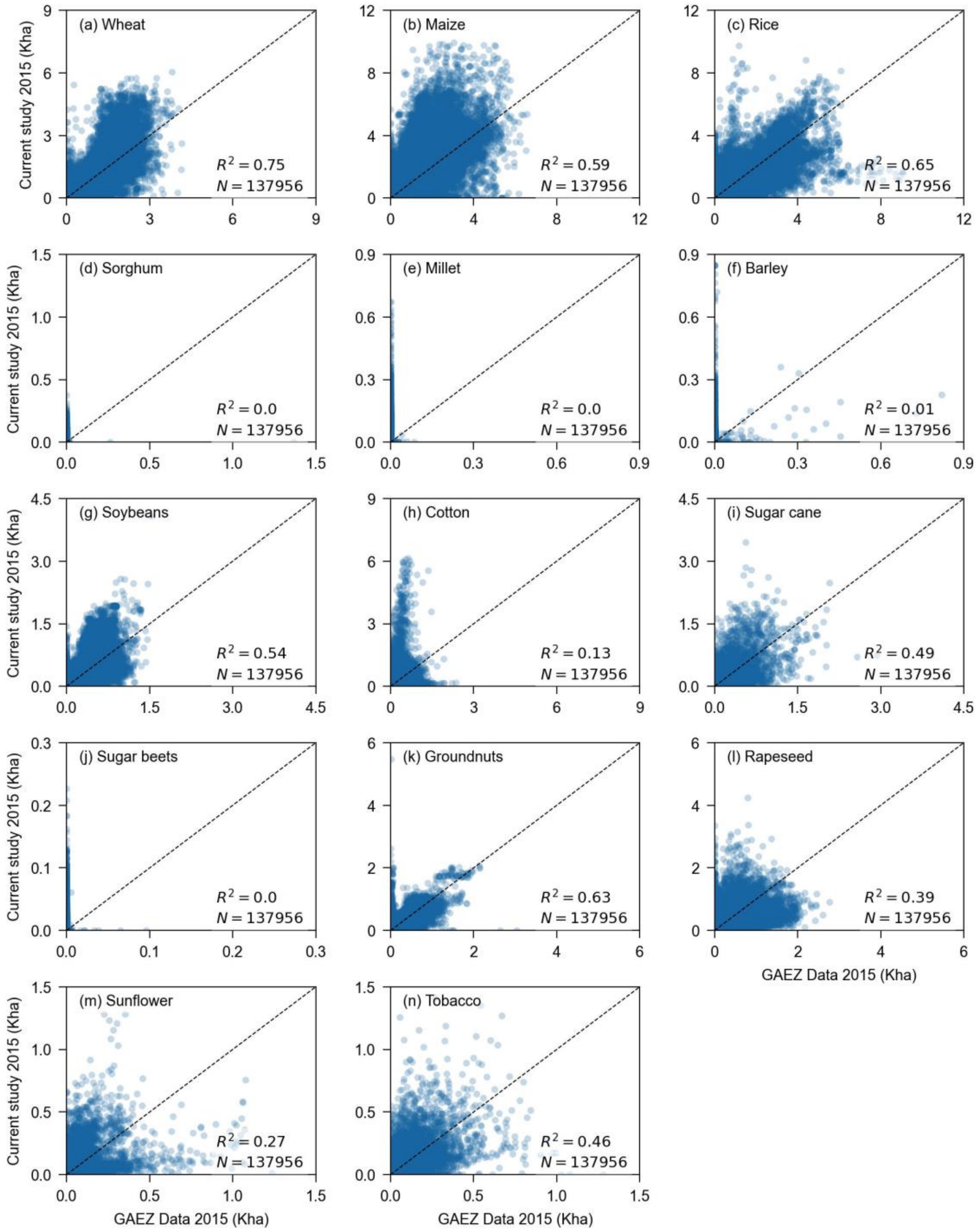

Figure 4. Comparison of the current gridded area representing land coverage with the GAEZ+2015 datasets.

3. What is CC in Equation 11? Canopy cover?

Responses: Thank you for your comments. Sorry for not explaining this variable in the text. In the revised manuscript, we will add this part, where CC is canopy cover (m^2 m^{-2}).

4. I didn’t see the causal relationship between the number in lines 222-228 and why it is important to distinguish irrigation type. Lines 263-269 do explain some.

Responses: Thank you for your comments. In this paragraph, our research findings underscore the substantial increase in WFCP by 0.8 and 25 times under sprinkler and micro-irrigation, respectively, while a decreasing trend is observed under furrow irrigation. Considering the positive correlation between WFCP and the cultivated area under different water supply and irrigation practices, the above results reflect the preference for sprinkler and micro-irrigation over furrow irrigation on existing and freshly reclaimed farmland.

Given the large scale of crop cultivation in China, such a significant shift in irrigation practices will have important implications: (i) it will affect the quantification of national crop water consumption; (ii) it will create market opportunities and drive technological innovation in the irrigation infrastructure construction industry.

Therefore, different from the comparison of uWFCP in lines 263-269, this paragraph strives to elucidate the significant impact of considering different irrigation practices at the national level from the perspective of WFCP. In the revised manuscript, we will provide additional explanations for this section.

5. In the paper, e.g. line 240, the authors discussed the monthly blue and green water consumption but is not available in the dataset. Some items are available monthly and some annually. What are the criteria to decide which data is open to the public or not? And the dataset lacks projected coordinate system information.

Responses: Thank you for your comments. The current online database only comprises monthly-scale data on WFCP under various water supply and irrigation practices. Monthly-scale data for blue and green water footprint will be uploaded to the online database in a timely manner once our ongoing work is published. If necessary, we can share the unpublished data with you. The online database adopts the "WGS 84" projection coordinate system, and we will supplement it with further explanations.

6. Line 245-247, why sprinkler irrigation has the highest value? Because of crop type?

Responses: Thank you for your comments. The spatial distribution of WFCP under different water supply and irrigation practices is expressed in units of mm mon^{-1} (monthly scale) and mm yr^{-1} (annual scale), representing the water consumption per unit planted area at monthly and annual scales. As described in section 2.2.3, Different irrigation practices indirectly affect water consumption during the growth period due to differences in the fraction of the surface wetted (f_w). The f_w-values used for furrow, sprinkler, and micro-irrigation were 80%, 100%, and 40%, respectively. The fraction of the surface wetted influences the soil evaporation coefficient (K_e), resulting in increased water consumption during the crop growing period (Equations 6 and 7). Hence, crops under sprinkler irrigation exhibit the highest water consumption.

As mentioned in our previous study (Wang et al., 2019), conventional water-saving irrigation methods primarily focus on increasing water use efficiency in the field and reducing water losses during delivery. For instance, sprinkler irrigation can effectively reduce water demand by 46% compared to furrow irrigation (Xue and Ren, 2016). However, when it comes to reducing the water footprint of crop production, sprinkler irrigation is not an efficient solution. On the one hand, although furrow irrigation is less efficient with higher percolation and runoff fluxes compared to sprinkler irrigation, these fluxes return to the catchment and are not considered as actual water consumption (Hoekstra et al., 2011; Grafton et al., 2018). On the other hand, sprinkler irrigation results in a larger ET due to the large surface-wetting rate for an equal yield.

7. Line 298-300, can the authors explain why the benchmarks of some crops are higher in arid zones and others are higher in humid zones?

Responses: Thank you for your comments. The benchmarks of crops under rainfed cultivation are higher than those under irrigation cultivation. The benchmarks of crops under different irrigation practices vary according to climatic zones and crop types. Several factors contribute to these results. Firstly, crops grown in arid zone rely more on irrigation due to limited rainfall and experience higher evapotranspiration, resulting in higher uWFCP compared to humid zone. Secondly, crops such as cotton have higher benchmarks in humid zone due to their yield are significantly lower than those extensively cultivated in arid zone. Importantly, the uWFCP benchmarks of the same crop vary depending on different irrigation practices and climatic zones. Based on the findings of this study, agricultural practitioners can guide production practices from the perspectives of irrigation practices and climatic zones.

8. in GAEZ+2015 and MapSPAM2010, they also have other crops, did the authors include them in the comparison? And GAEZ+2015 is developed for the year 2015 and MapSPAM2010 is developed for the year 2010, why not use the corresponding years other than the average between 2001 and 2008?

Responses: Thank you for your comments. The publicly available crop planting area data in GAEZ+ dataset is limited to the year 2015, whereas the SPAM dataset covers data for the years 2000, 2005, and 2010. In the main text, we have presented the comparison of major crop planting areas with the GAEZ+2015 and MapSPAM2010 datasets. The comparative results of other crop areas have been discussed and explained earlier in the minor comments 2.

Technical corrections

1. Table 3 doesn't seem consistent with the text. I only checked for rice. In Table 3, the total water consumption of rice is 81847+58979+4629+5540=150995 M m3 and in the text, it is 143 G m3.

Responses: Thank you for your comments. Sorry for this expression error. The 143 G m^3 in the text refers to the multi-year average of WFCP from 2000 to 2018, while the table only presented the WFCP for the year 2018. we will provide additional clarifications in the revised manuscript.

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