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Balancing food production within the planetary water boundary

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ABSTRACT

Freshwater use is recognized as one of the nine planetary boundaries. However, water scarcity is a local or regional phenomenon, meaning that the global boundary must be spatially downscaled to reflect differences in water availability. In China, as in most countries, irrigation is the major freshwater user, closely linking food security to the freshwater boundary. To provide evidence supporting environmentally sustainable water use in China's food production, this study explores how a grain production shift affects the national water-scarcity footprint (WSF) and the potential to reach sustainable water use limits while maintaining the current grain production level. We found that the historical breadbasket shift towards water-scarce northern regions has increased the WSF by 40% from 1980 to 2015. To operate within the boundary, national irrigation needs to be reduced by 18% in hotspot regions, with implications of a 21% loss of grain production. However, this loss can be reduced to around 8% by closing yield gaps in water-rich regions. It demonstrates the high potential of integrating crop redistribution and closing yield gaps to achieve grain production goals within freshwater boundaries. This Chinese case study can be representative of the challenges faced by many of the world's countries, where pressures on land and water resources are high and a sustainable means of increasing food supply must be found.

1. Introduction

Freshwater use has been identified as one of the nine planetary boundaries, highlighting its critical role in global sustainability (Gleeson et al., 2019; Steffen et al., 2015). It appears that current global water consumption is within the proposed planetary boundary (Steffen et al., 2015). However, as freshwater is spatially heterogeneous and often dominated by local dynamics, the global boundary must be downscaled to reflect differences in water scarcity. Currently, major parts of global freshwater withdrawals occur in water-stressed regions, indicating that the spatial water consumption pattern rather than the absolute shortage requires further assessment to reduce the pressure humanity puts on freshwater (Ridoutt and Pfister, 2010a). In China, as in most countries, irrigation of crops is responsible for the highest freshwater use (Gleick et al., 2014), closely linking food security to the freshwater boundary. It is therefore necessary to set food production goals within the downscaled planetary water boundary.

Over the past decades, China's agricultural production remarkably increased and underwent a spatial shift along with its rapidly growing economy and food demand (Liu et al., 2018; Zuo et al., 2018). Both the increase and shift of agricultural production could cause enormous water-related impacts because of the geographical mismatch between cropland and water availability (Cai et al., 2017). China's northern regions hold 65% of the total arable land but only 18% of the total water, while the water-rich southern regions often "waste" water through flood irrigation (Piao et al., 2010). Thus, China's current food production paradigm is experiencing a paradox: producing food in drier regions and transferring the food

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to wetter regions by agricultural trade (Dalin et al., 2014).

To address the water for food dilemma, strategies have been put in place on constructing massive water transfer projects (Liu et al., 2013b), saving water by internal and external virtual water trade (Dalin et al., 2014), and improving water use efficiency and land productivity (Kang et al., 2017). Undeniably, the combination of these solutions can substantially reduce the pressure on water resources. However, these strategies, which usually ignore the potential environmental impacts from water scarcity and lack a regional water use boundary, might conflict with the goal of water scarcity mitigation. For example, it was found that China's water transfer projects did not significantly mitigate water scarcity in the water-receiving regions but exacerbated water scarcity for the water-exporting regions (Zhao et al., 2015); virtual water strategies, which suggest that agricultural products should be traded from regions with high water productivity (WP) to regions with low WP (Chapagain and Hoekstra, 2008; Dalin et al., 2014), can also result in higher water scarcity as high WP can occur in a region with extreme water scarcity (Huang et al., 2014; Ridoutt and Huang, 2012). Davis et al. (2017) found that global redistribution of crops would feed an additional 825 million people while reducing the water consumption. A great potential for regional optimization was especially identified for cereals (Scherer and Pfister, 2016). However, crop redistribution at global scale is less policy relevant, because most governance takes place at the regional rather than global scale. It is therefore essential that strategies aimed at sustainable water use and food security must integrate water consumption patterns and downscaled water boundaries.

Here we quantify the water-scarcity footprint (WSF), which incorporates a water scarcity index to link water consumption to potential impacts from water scarcity (Ridoutt and Pfister, 2010b), of the main staple crops (maize, wheat and rice) under China's dramatic land-use change from 1980 to 2015. We apply the AquaCrop model (Raes et al., 2009; Steduto et al., 2009) to simulate crop yield and irrigation water consumption, which were subsequently used to calculate the crop WSF. By conducting a sensitivity analysis, we explore how the breadbasket shift affects the national WSF. We then examine the balance of both irrigation water and grain production under a downscaled planetary water boundary. In doing so, we explore whether China can reach sustainable limits while maintaining the current grain production level by closing yield gaps, i.e. by approaching potential crop yields. Our study aims to enable policies to set national agricultural water use priorities across regions by considering the environmental implications of meeting food security (a framework figure is available in Appendix A, Fig. A. 1).

2. Material and methods

2.1. Breadbasket shift

We consider three main staple grain crops (maize, wheat and rice), which account for 60% of the total cropping area, and 99% of the grain production in 2015 (NBSC (National Bureau of Statistics of China), 2016). We obtained county-level statistics for cropping area and production of each of the three crops in the years 1980, 1990, 2000 and 2015 from NBSC. To quantify the shift of cropping area and production of the crops, the share of the cropping area and production for each county in the national total cropping area and production were calculated and the relative difference between 1980 and 2015 were compared. We quantified the central tendency of the cropping area and production by mapping the location (longitude X and latitude Y) of the centroids of area and production in the examined year:

$$X_i = \frac{\sum (P_{i,c} \cdot X_{i,c})}{\sum P_{i,c}} \quad (1)$$

$$Y_i = \frac{\sum (P_{i,c} \cdot Y_{i,c})}{\sum P_{i,c}} \quad (2)$$

where $X_{i,c}$ and $Y_{i,c}$ are the longitude and latitude of the geographical centroid of county c with crop i; $P_{i,c}$ is the cropping area or production of crop i in county c. In addition to the shift quantification for each individual crop, the shift for the total area and production of the three crops were also quantified following the same method.

2.2. Crop yield and irrigation water consumption modelling

Crop yield and irrigation water consumption were modelled with a 5 arc-minute resolution by using the widely applied FAO AquaCrop model (http://www.fao.org/aquacrop). AquaCrop simulates the soil water balance and derives attainable yield as a function of water consumption on a daily step (Raes et al., 2009; Steduto et al., 2009). Although several crop models are available to simulate the yield response to water (Holzworth et al., 2015), many of them require an extensive number of variables and input parameters not easily available for the diverse range of crops and sites around the world. Particular features that distinguish AquaCrop from other crop models include: 1) its focus on water; 2) the relatively low number of parameters; 3) its considerable balance between accuracy, simplicity and robustness; and 4) its applicability to be used in diverse agricultural systems worldwide (Vanuytrecht et al., 2014). By conducting field experiments, the AquaCrop model was calibrated and validated for cropping systems in China (Han et al., 2019). To facilitate the use of AquaCrop for a large spatial scale, we applied a geospatial tool named GeoSim to manage AquaCrop inputs and outputs. GeoSim was previously developed as a plug-in for Quantum GIS (QGIS, https://www.qgis.org) (Thorp and Bronson, 2013) and has recently been improved to efficiently work with AquaCrop at China's national scale (Huang et al., 2019a,b).

Raster datasets (5 arc-minute) for the national distribution of maize, wheat and rice in 1980, 1990, and 2000 were obtained from the Spatial Production Allocation Model in China (SPAM-China) (Liu et al., 2013c), while the datasets in 2015 were based on SPAM-China 2010 but have been rescaled by the statistics in 2015 (Appendix A). Daily climate data from 825 meteorological stations across China from 1980 to 2015 came from the National Meteorological Information Centre (NMIC, http://data.cma.cn). Crop parameters on sowing dates, sowing density, growth stages and harvest dates were also obtained from the NMIC. Additional crop parameters such as canopy development, harvest index, and root depth were collected from our previous study and literature (Appendix A). Primary soil data applied to identify soil textures were taken from the Harmonized World Soil Database (Wieder et al., 2014). The main indicative values of soil hydraulic parameters for each soil texture and the initial soil water contents are presented in Appendix A, Table A. 6. Crop yield and water consumption under irrigation conditions were modelled by applying the option of "Determination of Net Irrigation Requirement" in AquaCrop (Appendix A). The default rain-fed condition in AquaCrop was applied to simulate the wheat and maize yield under rain-fed conditions. As almost all rice cultivation in China is irrigated (You, 2012), we did not conduct rain-fed AquaCrop modelling for rice. Due to the lack of detailed national datasets, factors, which may cause yield loss, such as nutrient deficiencies and soil salinization, were disregarded for both irrigated and rain-fed conditions. Thus, the crop yield modelled under the irrigated condition could be regarded as the potential yield.

The preparation of input data for AquaCrop modelling, and the implementation of AquaCrop by GeoSim followed our previous study (Huang et al., 2019b). Finally, crop yield and irrigation water requirement under irrigated conditions, and crop yield under rain-fed conditions with a resolution of 5 arc-minutes were obtained during 1980–2015. These data were averaged for four time series: 1980–1989, 1990–1999, 2000–2009, and 2010–2015, representing the crop yields and irrigation water requirements under irrigated conditions and rain-fed crop yields in the years 1980, 1990, 2000 and 2015.

2.3. Water-scarcity footprint calculation

The water-scarcity footprint per kg grain ($WSF_{i,g}$) was expressed in water equivalents (m^3 H_2Oe kg^{-1}) and calculated by using a water scarcity index (*WSI*), which serves as a characterization factor in impact assessment, to express the potential environmental impacts of water use (Pfister et al., 2009):

$$WSF_{i,g} = (I_{i,g} / P_{i,g}) \cdot WSI_{i,g} \tag{3}$$

where $I_{i,g}$ (m^3) and $P_{i,g}$ (kg) are the total irrigation water consumption and production for crop *i* in the grid cell *g*. The inventory of consumptive water use for crop production includes the direct water consumption associated with irrigation and the indirect water consumption, e.g., the production of farm inputs, packaging, and transportation. However, according to previous studies (Huang et al., 2014; Ridoutt and Pfister, 2010b), irrigation generally accounts for the vast majority of the total water consumption. In addition, detailed information on farm inputs matching our studied spatial and temporal resolution is not available. Therefore, only the irrigation water consumption was included for the water footprinting. Apart from irrigation, crops may also consume soil moisture (so-called green water), but it does not contribute to water scarcity, as we cannot extract it and use it for any other purpose (Ridoutt and Pfister, 2010b). $I_{i,g}$ and $P_{i,g}$ were calculated as:

$$I_{i,g} = I_{i,g,requ} \cdot A_{i,g} \cdot F_{i,g,irri} \tag{4}$$

$$P_{i,g} = Y_{i,g,irri} \cdot A_{i,g} \cdot F_{i,g,irri} + Y_{i,g,rain} \cdot A_{i,g} \cdot (1 - F_{i,g,irri}) \tag{5}$$

where $I_{i,g,requ}$ (m^3 ha^{-1}) is the irrigation water requirement for crop *i* in the grid cell *g* obtained by AquaCrop; $Y_{i,g,irri}$ (kg ha^{-1}) and $Y_{i,g,rain}$ (kg ha^{-1}) are the crop yield under irrigated and rain-fed conditions (the latter not for rice) obtained by AquaCrop; $A_{i,g}$ (ha) is the cropping area, which came from SPAM-China; $F_{i,g,irri}$ is the fraction of irrigated cropland in each grid cell, which was calculated as the ratio of the irrigated area to the total cropland area by applying the county-level statistics from NBSC (Appendix A). The $F_{i,g,irri}$ of rice in each grid cell was assumed as 100%, as almost all rice cultivation in China is irrigated (You, 2012).

The WSI relates to the ratio of water consumption to water availability, ranging between 0.01 and 1 (Pfister et al., 2009). A WSI of 0.5 indicates the expert judgment of the threshold between moderate and severe water scarcity (Pfister et al., 2009). The calculation of WSIs were based on previous studies which have calculated the global WSIs as consumption-weighted average of monthly WSIs (Pfister and Bayer, 2014; Scherer and Pfister, 2016). We recalculated and updated the WSIs for the decades of 1980–1989, 1990–1999, 2000–2009, and 2010–2015 with a resolution of 5 arc-minutes to match our studied temporal and spatial resolution (Appendix A).

The *WSFs* per kg grain at grid level were aggregated to production-weighted county-level $WSF_{i,c}$ (m^3 H_2Oe kg^{-1}) for each crop by the following equation:

$$WSF_{i,c} = \sum (WSF_{i,g} \cdot P_{i,g}) \Big/ \sum P_{i,g} \tag{6}$$

The total $WSF_{i,c,tota}$ (m^3 H_2Oe) of crop *i* in the county *c* was calculated based on the actual production as:

$$WSF_{i,c,tota} = WSF_{i,c} \cdot P_{i,c,actu} \tag{7}$$

where the $P_{i,c,actu}$ (kg) was the actual crop production in the county *c*, obtained from NBSC. The total WSF of the three crops in each county were calculated as the sum of the WSF for each crop in the county.

2.4. Sensitivity analysis

To separate the impact of the crop production shift on national water scarcity from other factors, we conducted a sensitivity analysis by changing one-factor-at-a-time (OFAT) (Thornton, 1993). The OFAT method was adjusted to perturb each parameter (i.e. driver of the WSF) one-at-a-time to the value in 2015, while all other parameters were held fixed at their initial value in 1980. The parameter perturbations for the sensitivity analysis are were conducted as follows: P1—change in the national total production of the three crops from 1980 to 2015; P2—change in the WSF per kg for each crop in each county from 1980 to 2015; P3—change in the national crop mix from 1980 to 2015; and P4—change in the production centroid per crop from 1980 to 2015. The details of the sensitivity analysis are available in Appendix A. The national WSFs under each parameter perturbation were calculated following the methods presented under section 2.3.

2.5. Downscaled planetary water boundary and current gap

The original planetary water boundary concept was defined as the global rate of blue water consumption (Steffen et al., 2015). To reflect the spatial heterogeneity in regional water scarcity reflected by both water consumption and water availability, we downscale the planetary water boundary by applying the above-mentioned water scarcity index (WSI) (Appendix A, Fig. A. 2). We define the sustainable water boundary in an area with grain cultivation as the water consumption level at which the WSI would be 0.5, indicating a water scarcity threshold between moderate and severe (Pfister et al., 2009).

To assess the current gap between the target water consumption at the downscaled water boundary and the water consumption in 2015, we conducted the following calculations. First, we calculated the monthly water consumption ($WC_{c,m,actu}$, m^3) by all water users (i.e. agricultural, industrial and domestic sectors) in county *c* in 2015 by summing rescaled grid-level data. The grid-level data were obtained from the global datasets, which were used to calculate the WSIs in 2000–2009 (see section 2.3). These were then rescaled to 2015 based on basin statistics (CMWR, 2000–2015). Second, we calculated the monthly target water consumption at grid-level by setting the WSI to 0.5, and aggregated the values again to the county-level ($WC_{c,m,targ}$, m^3) by summation. Third, the ratio (R_c) of the difference between the $WC_{c,m,targ}$ and $WC_{c,m,actu}$ to the $WC_{c,m,actu}$ at county-level was calculated as:

$$R_c = \min_{m \in months} (WC_{c,m,targ} - WC_{c,m,actu}) / WC_{c,m,actu} \tag{8}$$

The consideration of the minimum ratio among the twelve months in a year aims to always reach the sustainability target even in the month with the most extreme water-scarce situation.

2.6. Irrigation and production balance

To assess whether China can maintain its current grain production level while achieving a downscaled water boundary, we quantify the amount of national irrigation and grain production by the current cropping land. We calculated the average irrigation water consumption per kilogram of crop i ($I_{i,c,kg}$, $m^3\ kg^{-1}$) in each county based on the county-level sums of grid irrigation water consumption and crop production obtained from the AquaCrop modelling (see section 2.3). The actual irrigation water consumption ($I_{i,c,actu}$, m^3) for crop i in each county was calculated as:

$$I_{i,c,actu} = I_{i,c,kg} \cdot P_{i,c,actu} \tag{9}$$

Then the difference ($I_{i,c,diff}$, m^3) between the actual and target irrigation water consumption for each crop at county-level was calculated by applying the R_c:

$$I_{i,c,diff} = I_{i,c,actu} \cdot R_c \tag{10}$$

Here we assumed that to reduce the water consumption for a sustainable water use boundary (WSI = 0.5), all the water users should share the same responsibility. Thus, R_c was applied for each crop. A negative $I_{i,c,diff}$ indicates the county needs to reduce the irrigation water consumption to meet the boundary, while a positive value indicates the county has a certain potential to increase irrigation.

The change of crop production ($P_{i,c,diff}$, kg) associated with the difference of the irrigation water consumption was calculated as:

$$P_{i,c,diff} = I_{i,c,diff} \Big/ I_{i,c,kg} \tag{11}$$

By analogy with $I_{i,c,diff}$, a negative $P_{i,c,diff}$ indicates the county needs to reduce the grain production while a positive value indicates the county has a certain potential to increase production. However, here the potential for the grain production increase is the extreme potential, which was based on only considering the factor of irrigation water availability. The real production might be constrained by the crop yield and available cropping area. Thus, we further assessed the possible potential for the counties which have room for extra irrigation water to increase the crop production. We assumed that there was no agricultural expansion in the water-rich counties so that the potential for increasing the grain production would fully be attributed to closing yield gaps. Previous studies showed that current farm yields tend to stagnate when reaching around 80% (75–85%) of the potential yield (Lobell et al., 2009; Van Wart et al., 2013). Consequently, we assessed the potential increase ($P_{i,c,pote}$, kg) of the crop production at county-level by applying a 75% and 80% potential yield:

$$P_{i,c,pote} = \sum \left(Y_{i,g,irri} \cdot A_{i,g} \cdot 75\%\right) - P_{i,c,actu} \tag{12}$$

$$P_{i,c,pote} = \sum \left(Y_{i,g,irri} \cdot A_{i,g} \cdot 80\%\right) - P_{i,c,actu} \tag{13}$$

where the potential yield ($Y_{i,g,irri}$, kg ha^{-1}) was the yield obtained by AquaCrop modelling under the irrigated condition (see section 2.2). Then the constrained potential ($P_{i,c,cons}$, kg) for a water-rich county to increase crop production was determined by:

$$P_{i,c,cons} = \min\left(P_{i,c,diff}, P_{i,c,pote}\right) \tag{14}$$

The actual irrigation ($I_{i,c,actu}$), target irrigation ($I_{i,c,diff}$), actual production ($P_{i,c,actu}$), and target production ($P_{i,c,diff}$ and $P_{i,c,cons}$) at county-level were aggregated at China's agro-ecological zone (AEZ) level for the analysis of the regional balance of water consumption and crop production. The total I_{actu}, I_{diff}, P_{actu}, P_{diff} and P_{cons} of the three crops at county- or AEZ-level were calculated as the sum of the corresponding indicator for each crop at county- or AEZ-level.

3. Results

3.1. Breadbasket shifts towards the northeast

The cropping area of grain crops (maize, wheat and rice) in China increased by 21% while the total production increased by 130% from 1980 to 2015 (Appendix A, Table A. 1). The area of maize almost doubled and the maize production increased by 339%. Although there was a slight decrease in the wheat (8%) and rice (9%) area, the total production of the two crops increased 127% and 45%, respectively, because of the growing yields.

From 1980 to 2015, the northern regions including Huang-Huai-Hai, the north plateau, northeast and northwest experienced an increase in shares of both cropping area (16%) (Fig. 1a) and production (26%) (Fig. 1b). Accordingly, the southern regions decreased their area and production shares by 16% and 26%, respectively. The spatial change of area and production share varies among crops (Appendix A, Fig. A. 3). The main relative increase for both maize area and production happened in the northeast (10% for both), north plateau (6% for both), and northwest (2% for area and 4% for production). Wheat production concentration in Huang-Huai-Hai gradually increased since 1980, accounting for 63% of the national wheat area and 72% of the production in 2015. Remarkable spatial changes of rice happened in the northeast where the share of both area and production increased from 2% to 12%. The southern regions including the south, the middle-lower reaches of Yangtze basin, Jiangnan and Sichuan basin experienced a relative decrease in both rice area (12%) and production (14%).

The spatial shift of China's breadbasket is further reflected by the shift of centroids for total cropping area and total production (Fig. 1c). The area centroid shifted from the south of the Huang-Huai-Hai in 1980 towards its northeast in 2015. The production centroid showed a similar trend, shifting northeastward, but over a longer distance from the middle-lower reaches of Yangtze basin to Huang-Huai-Hai. Both area and production centroids of maize shifted from the middle-west of Huang-Huai-Hai in 1980 towards its northeast in 2015 (Appendix A, Fig. A. 4a). The centroids of wheat area and production were located in the southwest of Huang-Huai-Hai and shifted towards different directions (Appendix A, Fig. A. 4b). The area shifted towards the southeast, while the production centroid shifted towards the northeast. The centroids for both area and production of rice from 1980 to 2015 were located in the middle-lower reaches of Yangtze basin, and shifted from its south towards its northeast (Appendix A, Fig. A. 4c).

3.2. Increase in water-scarcity footprint

China's national water-scarcity footprint (WSF) for grain production was 6.0×10^{10} m^3 H_2Oe in 2015 (Fig. 2a), which was 2.6 times higher than in 1980. Compared with 1980, the WSFs of all the sub-regions have increased. The counties with higher WSFs were found in the regions with higher water scarcity, higher production, or a combination of both, such as Huang-Huai-Hai (accounting for 28% of the total), the middle-lower reaches of Yangtze basin (24%), the northwest (17%) and northeast (16%) (Fig. 2b). The regions with a higher increase in the WSF from 1980 to 2015 were found where the WSFs in 2015 were much higher than the counties' average. Thus, the major contributors to the increase were also Huang-Huai-Hai (accounting for 25% of the increase), the middle-lower reaches of Yangtze basin (21%), the northeast (21%) and northwest (18%).

For each individual crop, the national WSFs increased (Appendix

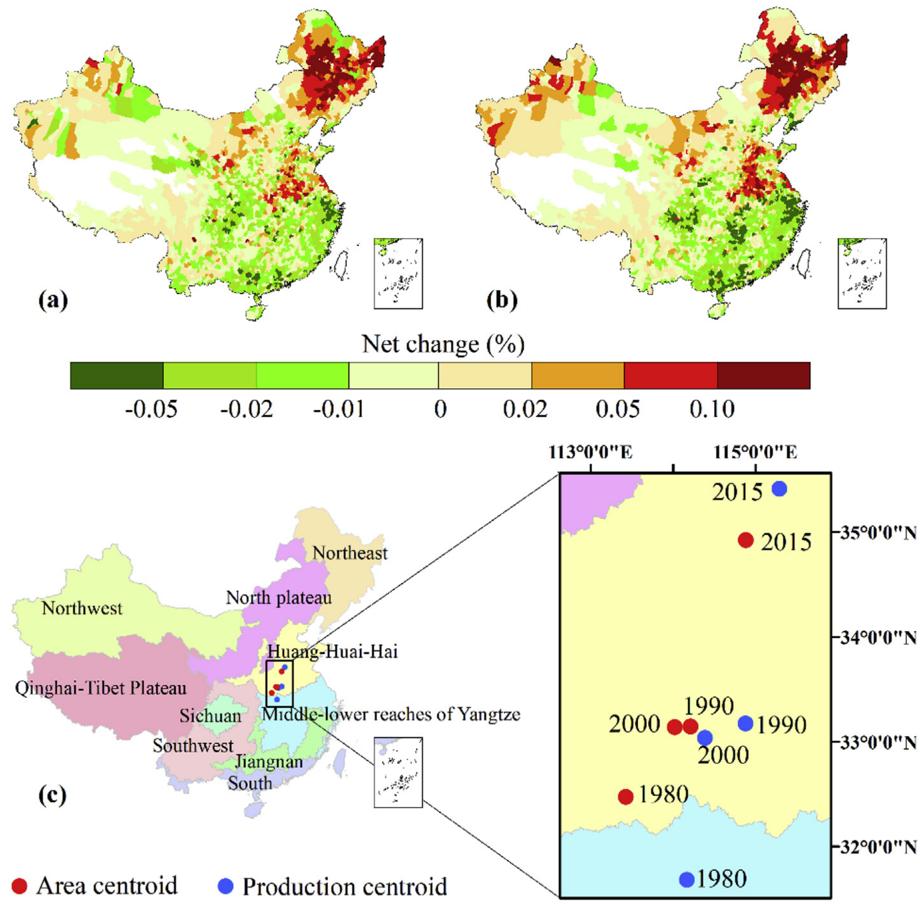

Fig. 1. Shift of cropping area and production for the three main staple crops. (a) is the net change of the cropping area, (b) is the net change of production, and (c) shows the shift of the cropping area and production centroids. The colours in (c) represent China's first-order agro-ecological zones (AEZs) (Liu and Chen, 2005). White indicates no data or no crop. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

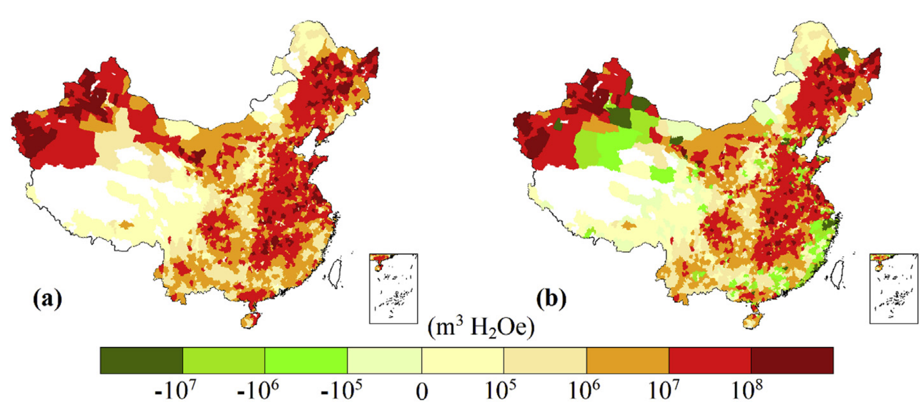

Fig. 2. Water-scarcity footprint (WSF) of the three crops (a) in 2015 and (b) the net change between 1980 and 2015. White indicates no data or no crop.

A, Fig. A. 5). The WSFs of maize in all the sub-regions have increased and the total increase was 9.7×10^9 m^3 H_2Oe in 2015, which was 4.6 times that in 1980. The main contributors to the increase were the northwest (51%), northeast (16%), north plateau (15%) and Huang-Huai-Hai (13%). Both the total WSFs of wheat and rice in 2015 have increased 2.3 times compared with 1980. The main increases for wheat occurred in Huang-Huai-Hai (73%) and the northwest (20%), while some southern regions, such as Jiangnan and the south, experienced a decrease. The WSFs of rice in all the regions have increased, and the main contributors were the middle-lower reaches of Yangtze basin (40%), the northeast (35%) and Sichuan basin (10%).

Based on four parameter perturbations (P1–4) in the sensitivity analysis (Fig. 3), we found that, apart from the change in the crop mix (P3), the increase of production (P1), the increase of the WSF per kg crop (P2) and the shift of the production centroid (P4) significantly contributed to the increase of the total WSF from 1980 to 2015. The increase of the total WSF (increase by 130%) under P1 kept pace with the increase of production and was the highest among all the parameter perturbations. The total WSF under P2

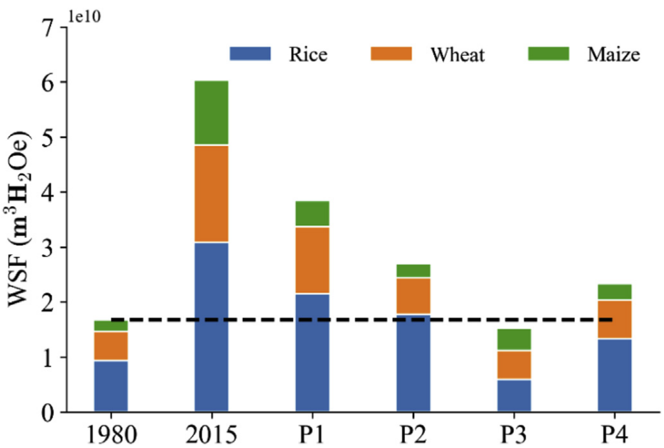

Fig. 3. Sensitivity analysis of the water-scarcity footprint (WSF). P1: change in the total production; P2: change in the WSF per kg for each crop and county; P3: change in the crop mix for the county as a whole; and P4: change in the production centroid per crop.

was also much higher than that in 1980 (increase by 60%), because of higher WSF per kg grain (Appendix A, Table A. 2). The shift of the production centroid has increased the total WSF by 40%. While most southern regions reduced their WSFs, the main increase happened in the northeast (65%), the northwest (23%), and Huang-Huai-Hai (20%) (Appendix A, Table A. 3). Rice, wheat and maize contributed to the total increase by 62%, 24% and 14%, respectively. The increase of rice's WSF was mainly caused by its production increase in the northeast, which was responsible for 104% of the total increase of rice's WSF (note that it is >100% because the WSF decreased elsewhere) (Appendix A, Table A. 3). The other northern regions including Huang-Huai-Hai, the north plateau and northwest together contributed to 14% and the southern regions accounted for −18%. The increase of wheat production in Huang-Huai-Hai and the northwest accounted for 87% and 18% of the total increase of wheat's WSF, respectively (Appendix A, Table A. 3). Most southern regions decreased their wheat's WSFs except for a small increase (3%) in the middle-lower reaches of Yangtze basin. For maize, the production increase in the northwest, north plateau and northeast accounted for 118%, 7% and 2% of the total increase in the WSF, while its decrease in Huang-Huai-Hai was responsible for −25% of the total increase (Appendix A, Table A. 3). In an overall picture, the shift of rice to the northeast, wheat to Huang-Huai-Hai, and maize to the northwest were the main causes for the increase of the total WSF, accounting for 65%, 21% and 16%, respectively. This illustrates that the current distribution of grain crops has become substantially less sustainable than in 1980, which has exacerbated China's water scarcity.

3.3. Potential to meet the downscaled planetary water boundary

To reach a sustainable limit, which was determined by a water scarcity index (WSI) of 0.5, China must reduce the irrigation water consumption in hotspot regions by 2.4×10^{10} m^3, which is 18% of the national irrigation for the three crops in 2015 (Fig. 4a and Appendix A, Table A. 4). The major hotspot regions were in Huang-Huai-Hai, the northwest, and northeast, which required 46%, 31% and 7% of the total irrigation reduction target, respectively. For each individual crop (Appendix A, Fig. A. 6 and Table A.4): the northwest, Huang-Huai-Hai, and north plateau required 63%, 20%, and 11% of the total irrigation reduction target for maize, respectively; Huang-Huai-Hai and the northwest contributed to 74% and 24% of that for wheat; the northeast, the middle-lower reaches of Yangtze basin, and Huang-Huai-Hai were responsible for 27%, 20%, and 17% of that for rice. The water-rich regions, which had relatively lower WSIs (<0.5), had a potential to increase irrigation by 2.2×10^{12} m^3, which is far more than the reduction target for the hotspot regions (Appendix A, Table A. 4). These regions are mainly located in the south but also in the northeast, accounting for 78% and 19% of the total potential increase of irrigation water. Consequently, there is no absolute national irrigation water shortage for grain production within the water boundary.

The reduction of irrigation in the hotspot regions implies that the associated grain production would also be decreased. Based on the current crop yields, the total grain loss in the hotspot regions was estimated as 1.3×10^{11} kg, 21% of national production in 2015 (Fig. 4b and Appendix A, Table A.4). The national production of wheat, maize and rice would be reduced by 34%, 27% and 6%, respectively (Appendix A, Fig. A. 6 and Table A. 4). However, the potential increase of irrigation in water-rich regions makes it also possible to increase grain production there. By considering both the irrigation water availability and crop yield potential, we find that the possible increase of grain production in water-rich regions can compensate 56–65% of the loss when yield gaps are closed to 75–80% of the potential yield (Fig. 5 and Appendix A, Table A. 4). Thus, the total grain loss would be reduced from 21% to only 8–9% of the national grain production in 2015. Closing the yield gap for rice in water-rich regions can compensate 95% of the rice loss in water-scarce regions considering a 75% potential yield, and rice production can be fully compensated when a 80% potential yield is reached. For wheat, closing yield gaps compensated 30–34% of the loss, while for maize it was 67–76%.

4. Discussion

4.1. Limitations

The results of this study were based on several models and data sources, subject to a range of uncertainties. Firstly, due to a lack of detailed national datasets, such as actual irrigation practices, soil fertility and salinity matching the studied temporal and spatial resolution, we simulated crop yield and water consumption by assuming that there is no stress from water (under irrigation), nutrient deficiencies and soil salinization, and then rescaled water consumption with actual crop production. This may overestimate or underestimate the results because the relationship between crop yield and water consumption is not necessarily linear. Although the sensitivity analysis has been conducted to separate the impact of the breadbasket shift on the total WSF, the relative impact expressed by percentage rather than the absolute value is therefore more meaningful. Secondly, there was a lack of consistent datasets. Consequently, we simulated the crop irrigation water consumption and yield with AquaCrop using Chinese datasets, while estimating the WSIs by using several global datasets. Thirdly, we set the sustainable water use boundary at a WSI of 0.5, which is based on the data from 2010 to 2015. However, for future work, the value of 0.5 should be further assessed according to different regional water use goals and the indicator should be updated to account for changes in temperature and precipitation. Fourthly, a broader perspective including socio-economic barriers and other environmental issues were beyond the scope. For example, dietary preferences, cultural traditions, and more complex logistics through further transportation may limit the application of crop redistribution. In addition, the sole focus on water scarcity does not consider the frequent trade-offs with other environmental issues (e.g., global warming and land degradation). Therefore, future work may investigate local irrigation water management and other farm practices, and apply more consistent data sources to provide more

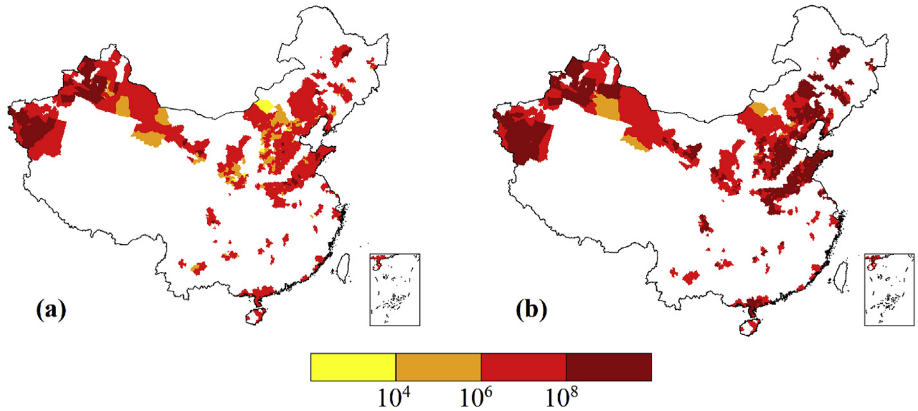

Fig. 4. Targets for (a) irrigation water (m^3) and (b) grain production (kg) reduction in hotspot regions to achieve a downscaled planetary water boundary (WSI = 0.5). White indicates no data, no crop, or no need for a reduction.

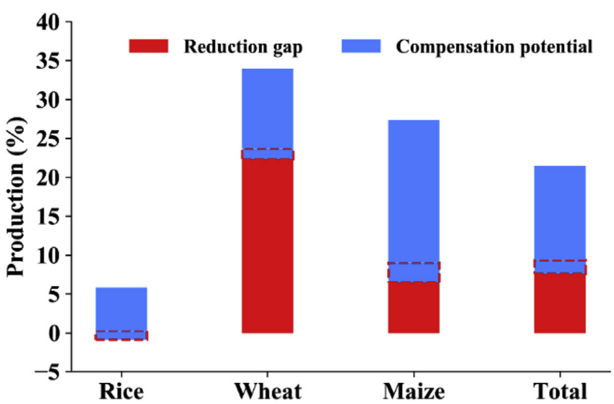

Fig. 5. Loss of grain production (whole bars) to meet the downscaled planetary water boundary in hotspot regions and potential for compensation (blue bars) by closing yield gaps in water-rich regions. The red dashed frames indicate the additional compensation potential by closing the yield gaps from 75% to 80% of the potential yield. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

detailed evidence for decision-making. In addition, crop redistribution for water scarcity mitigation must carefully consider life cycle socio-economic and other environmental factors.

4.2. Implications

The planetary boundaries concept has received wide attention by both scientists and policymakers (Dearing et al., 2014; 9Gleeson et al., 2019). However, the planetary boundary framework for freshwater use generally provides a global benchmark of blue water consumption. As most governance takes place at the regional rather than global scale, and freshwater is spatially heterogeneous, it is necessary to downscale the planetary water boundary at the regional scale (Dearing et al., 2014; Gleeson et al., 2019; Ridoutt and Pfister, 2010a). In addition, the absolute benchmark does not consider the water scarcity background reflected by both water consumption and water availability. To apply an indicator consistent with the water-scarcity footprint, we downscaled the planetary water boundary by targeting a water scarcity index (WSI) of 0.5, which better aligns regional water consumption with availability. We further examined the potential for China to achieve grain production goals within the downscaled water boundary. As agriculture is the major driver for water use (Gleick et al., 2014), the conjunction of food production and a downscaled planetary water boundary illustrates the broader value of the safe and just operating space approach for sustainable development.

To satisfy the growing demand, China's grain production is expected to continue to increase (Lv, 2013). To keep pace, grain production will require unprecedented amounts of irrigation water (Dalin et al., 2015; Kang et al., 2017; Piao et al., 2010). As shown by the sensitivity analysis (Fig. 3, P1), increasing production will result in an increase in the WSF and it seems unlikely that national water scarcity can be resolved by constraining production. The national WSF could be decreased by reducing the WSF per kg grain (Fig. 3, P2). However, the WSF is related to numerous factors including climate, management practice and so on, which are subject to uncertainties, and the related solutions face a wide range of economic and other obstacles (Wada et al., 2014). As the WSF per kg varies among crops, optimizing the crop mix can be another option. Based on our analysis (Fig. 3, P3), the national crop mix in 2015 was more sustainable than in 1980, as the share of maize with a lower WSF per kg increased, while the share of rice with a higher WSF per kg decreased (Appendix A, Table A. 2). To further optimize the crop mix also seems unlikely as there are constraining economic and demand-related factors.

Here we find that the breadbasket shift caused a significant impact on China's water scarcity (Fig. 3, P4). A breadbasket shift can be affected by numerous factors such as land-use policy, technological progress, and ecological and environmental factors (Verburg et al., 2000; Zuo et al., 2018). Particularly, urbanization and climate change were identified as important drivers for the spatial shift of China's grain production (Li et al., 2016, 2015). Previous studies on China's land-use change mainly focused on the impact on agricultural productivity (Jin et al., 2015; Yan et al., 2009). Few studies investigated environmental sustainability and gave contradictory results, complicating decision-making. For example, Zuo et al. (2018) reported that land-use change contributed a very small proportion to the increase of environmental impacts including water consumption in terms of national average irrigation water use intensity (IWI, irrigation water consumption per kcal). They recommended to prioritize reducing the IWI in regions with high IWI. As demonstrated in our previous studies (Ridoutt and Huang, 2012), such volumetric indicators frequently deliver results that are in conflict with the goal of water scarcity mitigation. The study by Zhang et al. (2016a) accounts for the contribution of water consumption to local water scarcity and confirms that the crop distribution and associated water use pattern differs for a scenario with the aim to maximize water savings as opposed to a scenario which accounts for water security. As such, it is in line with our study, which claims that it makes a difference if a volumetric or an impact-oriented indicator is used. By applying the impact-oriented WSF indicator to reflect the environmental relevance, we found that land-use change and the associated grain production shifts have substantially exacerbated China's water scarcity. This demonstrates that the pressure which land-use change puts on China's freshwater arises from the current patterns of water consumption, which often occurs in highly water-scarce regions.

Efforts to reduce the WSF caused by crop production should be guided by the WSF (per kg): the higher WSF (per kg) the more urgent action is needed. We identify that the most promising strategy for China's grain production would be optimizing the current water use patterns by redistributing the national cropping system. It is found that to reach the downscaled boundary (WSI = 0.5), there is no national water shortage and the potential for food balance depends on the production potential in water-rich regions. Many studies have demonstrated that the yield gaps of wheat, maize and rice are large in China where smallholder farming dominates the agricultural landscape (e.g., Deng et al., 2019; Meng et al., 2013; Sun et al., 2019). Numerous factors (e.g., crop variety, plant density and tillage management) contributing to yield gaps were identified, and there are many areas where inputs are already high or excessive, yet yield is substantially below the potential level (Zhang et al., 2016b). Knowledge and technologies are available in China for high-yield and high-efficiency practices (Chen et al., 2014; Zhang et al., 2016b). The challenge is to equip smallholders with them to achieve greater performance. Successful cases have already been conducted. For example, via a platform named Science and Technology Backyard (STB), which involves agricultural scientists living in villages among farmers, advancing participatory innovation and technology transfer, the five-year average yield of crops increased from 67.9% of the attainable level to 97% among leading farmers, and from 62.8% to 79.6% countywide (Zhang et al., 2016b). It demonstrated the possibility to increase China's grain production by closing yield gaps. This study found that the grain loss in hotspot regions can be reduced to only 8% of the national production when reaching an 80% attainable yield level. Our analysis was based on the current cropping area for each crop to avoid cropland expansion. Wheat in water-rich regions shows a lower potential (30–34%) to compensate the loss in hotspot regions, as it is constrained by the limited cropping area. For such a case, it also needs to explore the harvest area gap, i.e. the potential of using the physical area more times by increasing the cropping frequency (Yu et al., 2017). It is reported that the attainable harvest gap in China ranges from 14 to 36 million ha (relative to the total 160 million ha), which are mainly located in the water-rich southern regions (Yu et al., 2017). Thus, closing harvest gaps in the water-rich regions, such as growing wheat in fallow fields in the winter, might be another promising strategy.

We identified that national redistribution of crops is the most promising strategy to alleviate China's regional water scarcity. Its implemented in China seems feasible, considering China's increasing awareness of the environmental impacts from agricultural production and related policies. For example, a Winter Fallow Policy, which aims to reduce groundwater extraction for wheat irrigation, is currently implemented in some water-scarce regions in the North China Plain. Our study provides detailed spatiotemporal information to support this kind of policy-making. Our findings do not conflict with existing technologies and knowledge offering benefits for water scarcity mitigation. However, priorities regarding technological improvements (e.g., the application of highly efficient irrigation systems and drought-tolerant crop varieties) and policy implementation should be given to the hotspot regions to satisfy the more urgent needs and obtain a higher positive impact. In addition to the measures from the production perspective, there are also numerous options from the consumption side for China to ensure its food security while meeting sustainable water limits, such as reducing food waste (Liu et al., 2013a) and shifting to a sustainable diet (Sabaté and Soret, 2014). Integrating socio-economic and environmental aspects is critical in achieving China's sustainable development of agriculture.

5. Conclusions

Humanity faces the twin challenge of achieving food security while minimizing its environmental impacts. Here we take China's shifting breadbasket as a case study to address the water-food nexus. We demonstrate that China's historical shift of grain production has exacerbated national water scarcity and illustrate the potential to achieve grain production goals within freshwater boundaries. The results obtained in this study lead to several strategic implications for China's grain production. First, the spatial water consumption pattern rather than the absolute shortage requires more political attention. There is no absolute national irrigation water shortage for China's grain production within the water boundary. The pressure which land-use change puts on China's freshwater arises from the current pattern of water consumption, which often occurs in highly water-scarce regions. Second, China must reverse its grain production shift towards water-scarce regions. There is high potential to balance national grain production by just closing yield gaps in water-rich regions while meeting a downscaled water boundary. Third, national crop redistribution can also be combined with existing technologies and knowledge offering benefits for water scarcity mitigation. However, priorities should be given to the hotspot regions to satisfy the more urgent needs and obtain a higher positive impact. Last but not least, it is critical to integrate socio-economic and environmental aspects in achieving China's sustainable development of agriculture. By integrating food production and a water boundary, we illustrate the broader value of the safe and just operating space approach for sustainable development.

Author contributions

J.H., B.G.R., J.L.H., F.C., and L.S. designed the study. K.L., K.R.T., and X.H.W performed the AquaCrop modelling. J.H., L.S., Z.X.S., and X.G.Y. performed the data analysis. J.H., B.G.R., and L.S. wrote the paper.

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Appendix A. Supplementary data

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