Water Research 221 (2022) 118803

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Inputs for staple crop production in China drive burden shifting of water and carbon footprints transgressing part of provincial planetary boundaries

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ARTICLE INFO

Keywords:
Crop production
Agricultural inputs
Water footprint
Carbon footprint
Planetary boundary
China

ABSTRACT

Crop production is the biggest water user and key contributor to anthropogenic greenhouse gas emissions. Increasing crop yields to ensure adequate food supply under water and land scarcity is excessively dependents on intensive agricultural inputs (such as fertilizers, pesticides, agri-films, or energy), resulting in unintended environmental consequences. Supply chains bringing environmental-intensive inputs from their place of production to the croplands. However, most food-related environmental assessments ignore the environmental burden of agricultural input production, trade, and consumption. Here, we estimate spatially-detailed water (WF) and carbon footprints (CF) of wheat, maize, and rice production in China with extended system boundary from upstream raw material mining to the field. The agricultural inputs account for up to 24% and 89% of a crop's WF and CF, respectively, at the provincial level. The total local generated WF in Chinese northern provinces and CF in Shanxi and Inner Mongolia provinces for producing crops and agricultural inputs transgresses the corresponding downscaled blue water and carbon planetary boundaries. The study broadens the scope of traditional environmental impact assessments in agricultural production and sheds light on the significances to manage the linkages between the crop production and the agricultural inputs' upstream supply chains towards more efficient water use and less greenhouse gas emissions in food system.

1. Introduction

Food production accounts for 92% of human beings' water footprint (WF) (Hoekstra and Mekonnen, 2012), as well as 23–34% of anthropogenic greenhouse gas (GHG) emissions (Tubiello et al., 2013; Crippa et al., 2021). Around 41–52% of irrigation water is used at the expense of environmental flow requirements (Jägermeyr et al., 2017; Mekonnen and Hoekstra, 2020; Rosa et al., 2019). While the environmental burden of food production is global in scope, the majority of the burdens are felt at the local level. Increasing crop irrigation requirements challenge local water sustainable supplies, excessive fertilizers impair local ecosystems, and agricultural inputs such as diesel and fossil-fuel based electricity contribute to poor air quality (Tilman et al., 2001; Chen et al., 2014).

The environmental burden of food production is often attributed to the crop field (Mekonnen and Hoekstra, 2011; Goucher et al., 2017; Chen et al., 2014; Hu et al., 2020), or, increasingly, the final consumer (Xu et al., 2020; Poore and Nemecek, 2018; Dalin et al., 2017). However, the food supply chain does not begin at the farm field. Instead, the food supply chain extends backwards from the farm field to include major inputs to crop production, such as fertilizers, pesticides, and energy. These agricultural inputs, in turn, require production inputs such as coal, natural gas, sulfur, pyrite, phosphate rock and others. Supply chains connect farm fields to the inputs used in crop production, as well as the associated environmental burden of these agricultural inputs, in the same way that global supply chains connect farm fields to the final consumer.

Water and carbon footprints provide comprehensive indicators for supply chain-based environmental impact assessments. Any process of any product under the global supply chain may be accompanied by inter- and intra-national logistics, which means the inter-regional

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https://doi.org/10.1016/j.watres.2022.118803
Received 25 January 2022; Received in revised form 21 June 2022; Accepted 26 June 2022
Available online 29 June 2022

transfer of water and carbon-related environmental impacts embedded in the logistics (O'Rourke, 2014). Currently, there are a number of studies that consider the transfer of water and carbon-related environmental impacts from food consumption in the agricultural sector (Steen-Olsen et al., 2012; Yang et al., 2020; Hertwich and Peters, 2009; Zhao et al., 2015). Several studies show the crop production system boundary of environmental impact analysis including agricultural inputs and supply chains (Mungkung et al., 2019; Zhang et al., 2018; Zhai et al., 2019a, 2019b; Chen et al., 2021; Xu et al., 2020). However, they only account for the carbon footprints related to the agricultural inputs and keep the abovementioned incomplete boundary for water footprint accounting. Moreover, to the best of our knowledge, the evaluation of the burden shifts of water and carbon footprints along inter-regional logistics of agricultural inputs is still lacking.

In this study, we investigate the environmental footprint of the crop production considering, for the first time, the production, trade and consumption of agricultural inputs, in order to better understand hidden environmental tradeoffs and resultant impacts on regional environmental sustainability. We map the upstream supply chain network for crop production and its environmental burden in China circa the year 2016 using spatially detailed records of production, inter- and intra-national trade of agricultural inputs between China provinces (Fig. 1). We assess three staple crops (wheat, maize, and rice) that account for 92% of China's crop production (NBSC, 2017). We evaluate the upstream food supply chain using multiple environmental metrics, including consumptive water use (blue and green WFs), water quality (grey WF), and GHG emissions (carbon footprint, CF) at a subnational scale. The environmental burden of evaluated crops and agricultural inputs is compared to downscaled planetary boundaries for water use and GHG emissions.

2. Methods and data

2.1. System boundary

We link raw materials, processed agricultural inputs, and harvested wheat, maize, rice and through domestic and international supply chains so to capture and distinguish the direct WF (DWF) and CF (DCF) at the farm field, as well as crop indirect WF (IWF) and CF (ICF) associated with the agricultural inputs (Fig. 2). As for a region, the environmental footprint can also be divided into internal and external parts. The internal footprints refer to local water appropriation\GHG emissions within the regional boundary, whereas the external footprints are virtual water\carbon imports embedded in imported goods. In this analysis, we distinguish the external environmental footprints related to both inter- and intra-national logistics of upstream inputs at each supply chain stage, from raw material to farm field, for each province.

The supply chain of crop production consists of two primary stages, from mining to farm: the raw material-to-input product chain and the input product-to-crop chain, which represent the processes of producing and consuming agricultural inputs, respectively (Fig. 2). The latter stage has been the conventional system boundary of life cycle assessment for agricultural production. Seed, nitrogen (N) fertilizer, phosphate (P_2O_5) fertilizer, potash (K_2O) fertilizer, agricultural film, pesticide, electricity and diesel that are used for field irrigation and mechanical tillage were included in the current study.

2.2. Estimating direct WF and CF of crop production

The WF\CF of crop production consists of the direct WF\CF (DWF \DCF) and indirect WF\CF (IWF\ICF). The DWF is the traditional WF accounting scope of crop production. The blue and green DWF of each crop were calculated by dividing the blue and green evapotranspiration over the growing season by the crop yields (Zhuo et al., 2016a; Chukalla et al., 2015), while the corresponding grey DWF was defined for N and P_2O_5 fertilizer as described by Hoekstra et al. (2011).

$$DWF_b[c] = \frac{10 \times \sum_{t=1}^{gp} ET_{b[t]}}{Y[c]} \tag{1}$$

$$DWF_g[c] = \frac{10 \times \sum_{t=1}^{gp} ET_{g[t]}}{Y[c]} \tag{2}$$

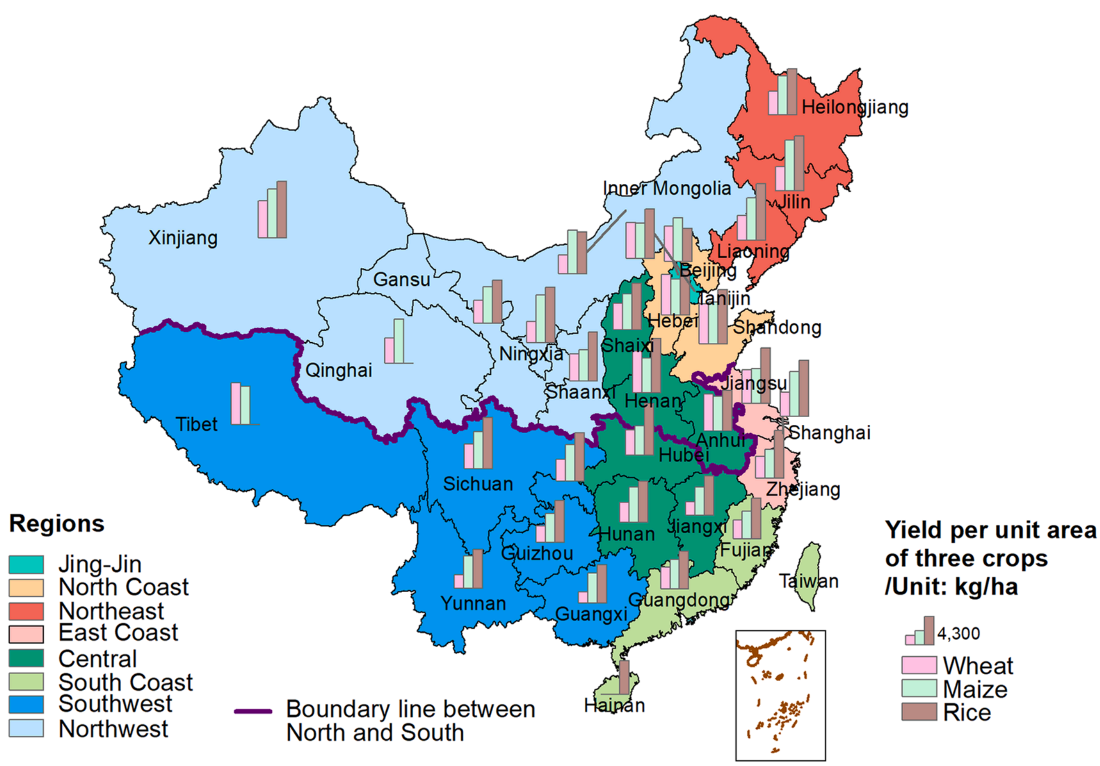

Fig. 1. *Provinces and regions of China.* The bar chart shows the yield per unit area of three considered crops in each province.

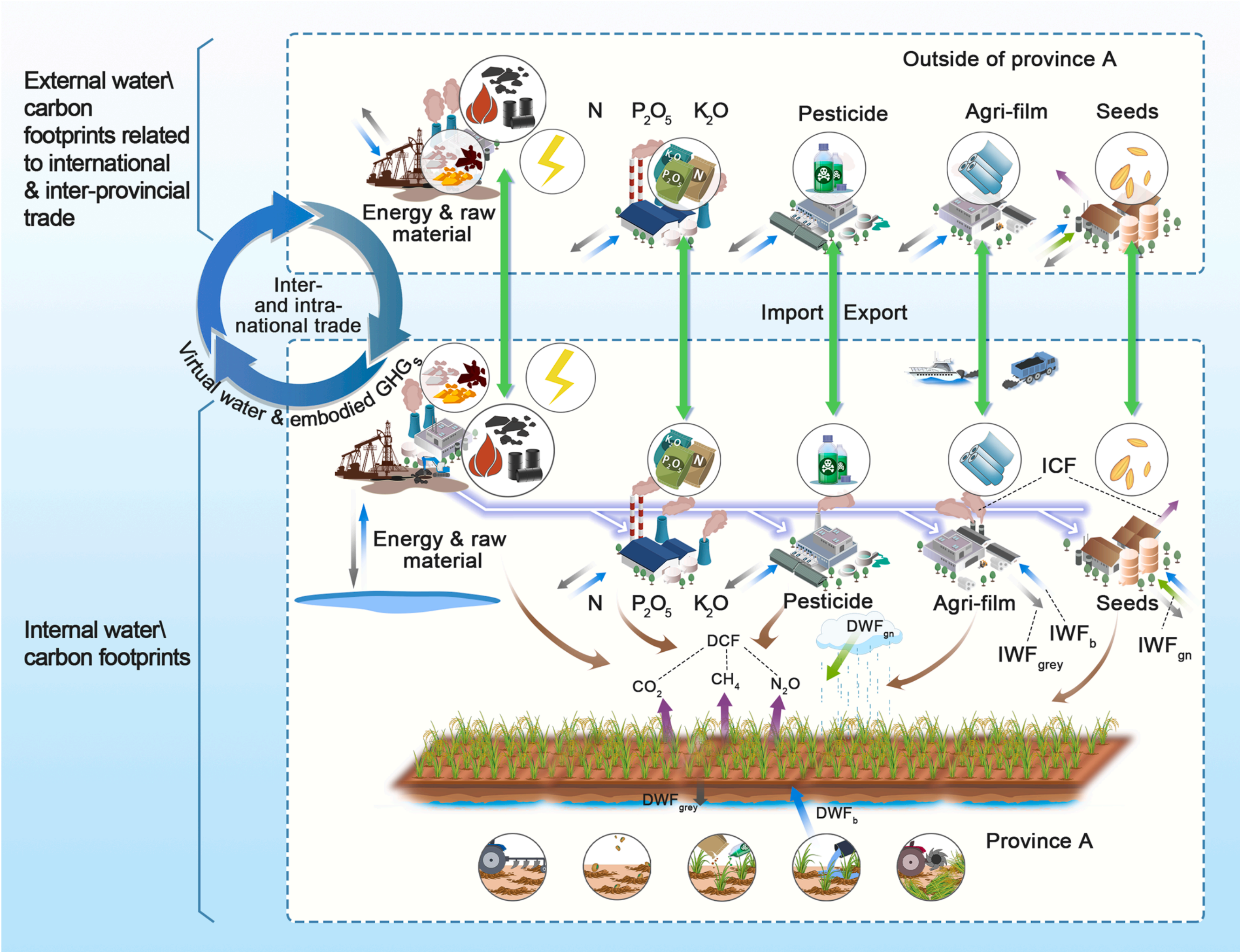

Fig. 2. *Sketch of the system boundaries from raw material to crop and associated components of supply chain-based environmental footprints for crop production at provincial level.* In the figure, IWF_b=indirect blue water footprint; IWF_{gn}=indirect green water footprint; IWF_{grey} =indirect grey water footprint; DWF_b=direct blue water footprint; DWF_{gn}=direct green water footprint; DWF_{grey} =direct grey water footprint; ICF=indirect carbon footprint; and DCF=direct carbon footprint. Internal water \carbon footprints=WF\CF related to water appropriation\GHG emissions within the province A. External water\carbon footprints =WF\CF generated during consumption of imported goods in the form of virtual water\carbon imports (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

$$DWF_{g'}[c] = \frac{\alpha \times AR}{C_{max} - C_{nat}} \times \frac{1}{Y[c]} \tag{3}$$

where $DWF_b[c]$, $DWF_g[c]$, and $DWF_{g'}[c]$ are the blue, green and grey DWF of growing unit mass of crop c, respectively, in m^3/t. gp (day) is the length of growing period. 10 is the conversion coefficient. $ET_{b[t]}$ (mm) and $ET_{g[t]}$ (mm) the daily blue and green evapotranspiration, respectively. $Y[c]$ (kg/ha) is crop yield. AR (kg/ha) is application rate of the nutrient. α the leaching-runoff fraction. C_{max} and C_{nat} are the maximum acceptable concentration and the natural concentration of the nutrient in the receiving water body, respectively. The nutrient ARs of N and P_2O_5 fertilizer are shown in Supplementary Table 1, and the values of C_{max}, C_{nat} and α are shown in Supplementary Table 2.

Applying the approach by Zhuo et al. (2016a) and Yang et al. (2021), $ET_{b[t]}$, $ET_{g[t]}$ and $Y[c]$ are simulated by the AquaCrop model for 698 meteorological stations (see Supplementary Fig. 1) and aggregated as arithmetic average for each of 31 provinces. The $ET_{b[t]}$ and $ET_{g[t]}$ are separated by tracking the soil water dynamic balances in the rootzone.

$$\begin{cases} S_{b[t]} = S_{b[t-1]} + IRR_{[t]} - RO_{[t]} \times \dfrac{IRR_{[t]}}{PR_{[t]} + IRR_{[t]}} - \left(DP_{[t]} + ET_{[t]}\right) \times \dfrac{S_{b[t-1]}}{S_{[t-1]}} \\ S_{g[t]} = S_{g[t-1]} + IRR_{[t]} - RO_{[t]} \times \dfrac{PR_{[t]}}{PR_{[t]} + IRR_{[t]}} - \left(DP_{[t]} + ET_{[t]}\right) \times \dfrac{S_{g[t-1]}}{S_{[t-1]}} \end{cases} \tag{4}$$

where $S_{b[t]}$ and $S_{g[t]}$ (mm) are the blue and green components, respectively, in 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. $RO_{[t]}$ (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. The simulated crop yield was calibrated to match provincial statistics (NBSC, 2017) (Fig. 1), in line with the calibration method in a number of existing studies (e.g., Mekonnen and Hoekstra 2011, Zhuo et al. 2016a, b, Wang et al. 2019, Zhuo et al. 2019, Yang et al. 2021, Mialyk et al. 2022).

The DCF of crop production is the sum of the GHGs emissions from cropland and from fuel burning (i.e., diesel) in mechanized farming. GHGs emissions were converted to their CO_2 equivalent (CO_2e) using 100-year global warming potentials (Fuglestvedt et al., 2003). The GHGs (i.e., CO_2) emissions per unit crop (kg CO_2e/kg crop) from fuel combustion is calculated by multiplying the direct component of the fuel's carbon emission factor (i.e., the CO_2 directly emitted during fuel combustion) by the corresponding fuel consumption. The GHGs emissions from cropland per unit crop (kg CO_2e/kg crop) is calculated by dividing the GHGs emissions (CO_2e) from farmland by the crop yield per unit area. Specifically, the GHGs emissions from farmland refer to the direct N_2O emissions and indirect N_2O emissions (i.e., volatilisation and leaching/runoff) from N fertilizer application (IPCC, 2019). For rice cultivation, the farmland GHGs emissions also include the field CH_4 emissions. The calculation formula is as follows (IPCC, 2019):

$$GHG_{field} = (N_2O_d + Nvol \times 0.01 + Nlea \times 0.011) \times \frac{44}{28} \times GWP_{N_2O} + CH_4 \times GWP_{CH_4} \tag{5}$$

where GHG_{field} (kg CO_2e/ha) is the GHGs emissions from cropland. N_2O_d (kg N/ha), $Nvol$ (kg N/ha), and $Nlea$ (kg N/ha) refer to the direct N_2O emissions, NH_3 volatilisation and, N leaching and runoff, respectively. These terms can be calculated based on the nitrogen losses model developed by Chen et al. (2014), as shown in Supplementary Section 1. The coefficients 0.01 and 0.011 indicate that 1% and 1.1% of the volatilized NH_3-N and leached NO_3-N are lost as N_2O-N, respectively (IPCC, 2006, 2019). GWP_{N_2O} and GWP_{CH_4} are the 100-year global warming potential of N_2O and CH_4 (GWP, 273 for N_2O, and 27.2 for CH_4) (IPCC, 2021), respectively, and are applied to convert these GHGs into CO_2 equivalents (CO_2e). The data on CH_4 emission from rice cultivation in different province is extracted from Guidelines for preparation of greenhouse gas inventories at the provincial level in China (NDRC, 2011).

2.3. Estimating IWF and ICF of crop production related to agricultural inputs

The IWF\ICF of crop production is the consumption of fresh water \GHG emissions from production, storage, and delivery of inputs used in crop production to the farm gate.

$$IWF[c] = \sum_i WF_{cons}[i] \times C[i] \tag{6}$$

$$ICF[c] = \sum_i CF_{cons}[i] \times C[i] \tag{7}$$

where $IWF[c]$ (m^3/t) and $ICF[c]$ (t CO_2e/t) refer to the IWF and ICF of growing crop c. $WF_{cons}[i]$ (m^3/t) and $CF_{cons}[i]$ (t CO_2e/t) is the WF and CF of unit mass of input i consumed in crop production. $C[i]$ (t/t) is the quantity of inputs i consumed to produce per tonne of crop. Estimation of $WF_{cons}[i]$ and $CF_{cons}[i]$ considers virtual water and carbon flows associated with import of inputs from other regions outside the province where the crop grows. Such virtual water and carbon imports constitute the external WF and CF, respectively for the province. We track the external blue and grey WFs as well as CF related to both international and inter-provincial imports of each considered agricultural inputs and upstream products per province. The corresponding virtual water and carbon imports of a product in a province equals to the amount of imported goods multiplied with the corresponding WF and CF, respectively, of producing unit mass of the goods in the exporting places.

For any input product i consumed in a given province x, its WF\CF (in m^3/t) can be divided into the internal and external part. The internal WF\CF ($WF_{cons,\ int}[i, x]$, m^3/t) is related to the consumption of local produced products. The external WF\CF is related to the consumption of imported goods, either from international trade or inter-provincial transfers. The calculation formula of consumption WF is as follows:

$$WF_{cons,\ int}[i,x] = \frac{WF[i,x] \times P[i,x]}{P[i,x] + I[i,y] + I[i,z]} \tag{8}$$

$$WF_{cons,\ pe}[i,yx] = \frac{\sum_y I[i,y] \times (WF[i,y] + WF_t[yx])}{P[i,x] + I[i,y] + I[i,z]} \tag{9}$$

$$WF_{cons,\ ne}[i,zx] = \frac{\sum_z I[i,z] \times (WF[i,z] + WF_t[zx])}{P[i,x] + I[i,y] + I[i,z]} \tag{10}$$

where $WF_{cons,\ int}[i,x]$ (m^3/t) refer to the internal WF of input i consumption, $WF_{cons,pe}[i,yx]$ (m^3/t) and $WF_{cons,ne}[i,zx]$ (m^3/t) refer to the external WF related to the interprovincial and international trade of input i, respectively. $WF[i,x]$ (m^3/t), $WF[i,y]$ (m^3/t) and $WF[i,z]$ (m^3/t) refer to the WF of production of input i in province x, importing province y and importing country z, respectively. In the absence of data on the WF of specific country inputs, we use the national average values instead. $P[i,x]$ (t/yr), $I[i,y]$ (t/yr) and $I[i,z]$ (t/yr) refer to the production quantity of input i in province x, imported quantity of input i by province x from exporting province y, imported quantity by province x from exporting country z, respectively. $WF_t[yx]$ (m^3/t) and $WF_t[zx]$ (m^3/t) refer to water resources consumed in the transportation process when province x imports input i from province y and country z, respectively. The calculation formula is shown in Supplementary Section 2. Amongst the various inputs of crop production, we assume that seed consumption is entirely derived from local production, so that the WF of seed consumption is equal to the WF of crop production in 2015. The CF of seed consumption adopted the estimation of Chen et al. (2014).

International and inter-provincial trade data on energy inputs (e.g., coal, crude oil and electricity) were obtained from the China Energy Statistical Yearbook (NBSC, 2016) and Gao et al. (2018). The shortest distance method was used to calculate the inter-provincial trade data for other energy and industrial inputs (Fischer et al., 2010; Yang and Zhao, 2012). That is, the corresponding volume of interprovincial input trade is calculated using the linear programming method as done in other studies (Zhuo et al., 2019), based on annual supply and demand balance of each input in each province, taking into account input movement between international and domestic provinces, and using the shortest transportation distance as a constraint.

The formula is as follows:

Minimize:

$$TC(i) = \sum_{x=1,y=1,h=1}^{x=31,y=31,h=4} (T_{int}(x,h,i) \times c(x,h) + T_{int}(h,y,i) \times c(h,y)) + \sum_{x=1,y=1}^{x=31,y=31} T_{loc}(x,y,i) \times c(x,y)$$

Subject to:

$\forall (x,y) \in [1:31]$ and $\forall h \in [1:4]$

$$\begin{cases} \sum_{x=1,y=1}^{x=31,y=31} T_{loc}(x,y,i) + \sum_{x=1,h=1}^{x=31,h=4} T_{int}(x,h,i) = P(x,i) - D(x,i), if\ P(x,i) > D(x,i) \\ \sum_{y=1,x=1}^{y=31,x=31} T_{loc}(x,y,i) + \sum_{y=1,h=1}^{y=31,h=4} T_{int}(h,y,i) = D(y,i) - P(y,i), if\ P(y,i) > D(y,i) \\ \sum_{x=1,h=1}^{x=31,h=4} T_{int}(x,h,i) = E_{int}(i) \\ \sum_{h=1,y=1}^{h=4,y=31} T_{int}(h,y,i) = I_{int}(i) \\ T_{loc}(x,y,i) \geq 0 \\ T_{int}(x,h,i) \geq 0, T_{int}(h,y,i) \geq 0 \end{cases} \tag{11}$$

Where $TC(i)$ (km/yr) refers to the total transport distance of the interprovincial trade in input i. $T_{int}(x,h,i)$ refers to the foreign export volume from province x through harbour province h. $T_{int}(h,y,i)$ (t/yr) the foreign import volume through harbour province h to province y. $T_{loc}(x,y,i)$ (t/yr) the net trade of input i from province x to province y. $c(x,h)$ $c(h,y)$ and $c(x,y)$ (km/t) the unit distances of transport between provinces. $P(x,i)$ (t/yr) the production of input i in province x. $D(x,i)$ (t/yr) the total demand of input i in province x. $E_{int}(i)$ China's total international export of input i. And $I_{int}(i)$ (t/yr) China's total international import of input i.

2.4. Estimating WF and CF of agricultural inputs production

The WF\CF of industrial input includes direct WF\CF (DWF\DCF) and indirect WF\CF (IWF\ICF), as shown in Fig. 3. Amongst them, the DWF refers to the water consumption during the input production. In general, the WF of industrial inputs does not consider the green WF. In this study, the WF of industrial input only includes blue WF and grey WF.

The calculation for the grey DWF of industrial product is based on the quantitative framework of Water Footprint Assessment Manual (Hoekstra et al., 2011).

$$DWF'[i] = \frac{L \times V_p}{C_{max} - C_{nat}} \tag{12}$$

Where $DWF'[i]$ (m^3/t) is the grey DWF of a product i, L (m^3/t) is the wastewater volume per unit of the industrial product. V_p (mg/L) is the concentration of pollutants in the wastewater. Pollutants in the industrial sector take into account the main pollutants discharged during the production of agricultural inputs, such as COD, total phosphorus (TP), ammonia nitrogen and suspended matter (SS). The emission of each pollutant in each agricultural input is different, and the specific emission information is shown in Supplementary Tables 3–5. The discharge limit of water pollutants in various industries is adopted as C_{max}. In the absence of this value, we adopted the water quality level 'IV' in the China's national surface water quality standard (MEP, 2002). We adopted the corresponding water quality level 'I' in the China's national surface water quality standard as C_{nat} (MEP, 2002).

The DCF refers to the direct GHGs emissions from the production of inputs, primarily from burning fossil fuels. The DCF from fuel combustion is calculated by multiplying the direct component of the fuel's carbon emission factor (i.e., the CO_2 directly emitted during fuel combustion) by the corresponding fuel consumption.

The IWF\ICF of inputs refers to the consumption of fresh water\GHG emissions of the upstream products during the production, processing, and transportation of the upstream products needed in the production of inputs. The GHGs emissions are also converted into CO_2 equivalents

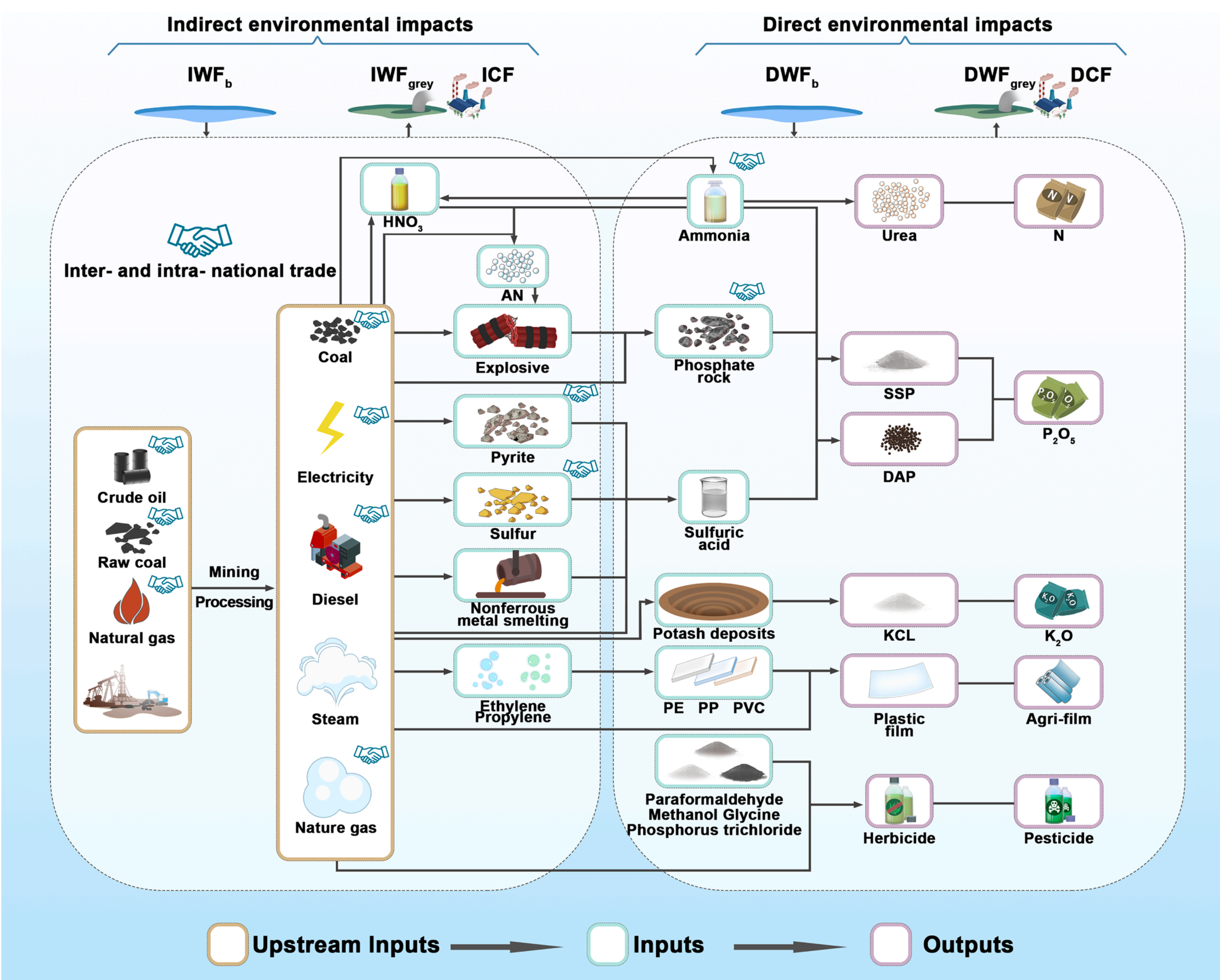

Fig. 3. *System boundary of agricultural inputs production.* Outputs in the figure refer to the agricultural inputs, and inputs and upstream inputs refer to the upstream products of agricultural inputs.

(CO_2e).

The IWF\ICF of input is the sum of the product of the quantity of upstream inputs consumed per unit of input and the WF of corresponding upstream input consumption. When the locations of production and consumption of upstream product are the same, the WF\CF of corresponding upstream input consumption equal to the WF\CF of upstream input production. The WF\CF of product consumption is calculated by the same formulas 8–10. Fig. 3 depicts the upstream products for which regional trade exists. Furthermore, the quantification of WF\CF of input must begin at the most upstream point in the input production supply chain, and the WF\CF of each upstream product production and consumption should be calculated sequentially. As can be seen from Fig. 3, the upstream of inputs supply chain is all energy inputs, so the quantification of WF\CF of crop production inputs begin with the energy WF\CF.

The primary energy courses include coal, crude oil and natural gas. The WF of the primary energy is the direct water input in mining. The blue WF data for coal, crude oil and natural gas in all Chinese provinces were obtained from Gao et al. (2018), while the national average grey WF was obtained from Ding et al. (2018). The WF of secondary energy (i.e., diesel and electricity) is the sum of the indirect WF related to the primary energy and the direct WF in production and processing. The indirect WF of secondary energy is obtained from combining the WF of primary energy consumption calculated by us with its consumption. For electricity (here refers to thermal power), its direct WF and primary energy (i.e., coal) consumption also come from Gao et al. (2018). And for the WF of crude oil processing products production, its direct WF and primary energy consumption (i.e., crude oil) are from Ding et al. (2018). WF of diesel was obtained by multiplying the WF of crude oil processing products by the value fraction and dividing it by the product fraction of the diesel produced (Hoekstra et al., 2011). The product fraction and value fraction of diesel are 0.383 and 0.398, respectively. The product fraction is based on the report of Sinopec that 0.383 t of diesel can be refined from 1 t of crude oil. The value fraction is the ratio of the market value of diesel to the aggregated market value of crude oil processing products in 2016.

The national average carbon emission factor of energy products (i.e., coal, diesel, and nature gas) and the proportion of direct emissions during combustion is derived from Li et al. (2013). The data of China's electricity is from Ren et al. (2020). The average carbon emission factor of the world's energy products is derived from IPCC (2006). In addition, considering that the CF of energy product consumption is not different amongst provinces, the ratio of internal CF and external CF of regional energy products is equal to its production and import ratio.

For a more detailed description of each input, see the Supplementary Section 3. And the material consumption inventory, wastewater discharge, and GHGs emission data required for the calculation of the WF and CF of other industrial product and their inputs are shown in Supplementary Tables 3–6.

2.5. Comparing to provincial blue water and carbon planetary boundaries

The impacts of staple crop production, agricultural input production and exports on regional sustainability are tested by comparing each province's total local generated blue WF and CFs to the corresponding local blue water and carbon planetary boundaries. The total local generated blue WF and CF of each province include the total internal blue WF\CF of crop production in the corresponding province and the locally generated blue WF\CF associated with the production of agricultural inputs for export, that is, the blue WF\CF for nonlocal crop production. Li et al. (2020) scaled down global blue water planetary boundary to 57 different sectors in 176 countries and regions in proportion to each sector's water withdrawals to the total water withdrawals. The blue water planetary boundary at the provincial level in China is calculated as the sum of the blue water planetary boundaries related to agricultural sector and the planetary boundaries of the multiple industrial sectors related to agricultural production in each province. The industrial sectors included are coal, oil, gas, minerals, petroleum and coal products, chemical and plastic products, mineral products, electricity, gas manufacture, distribution, water and transport. Hu et al. (2020) estimated China's agricultural carbon planetary boundary at 1.1 Gt CO_2e/yr by scaling the global agricultural carbon planetary boundary (5.3 Gt CO_2e/yr) according to the proportion of Chinese population. The global agricultural carbon planetary boundary is derived by combining the non-CO_2 emission planetary boundary for agriculture (4.7 Gt CO_2e/yr) reported by Springmann et al. (2018), along with CO_2 emissions from direct energy use in agriculture. CO_2 emissions from direct energy use accounted for 11–15% of the total emissions. The same downscaling method (i.e., population ratio) was used for provincial agricultural carbon planetary boundaries.

In this study, the total local generated blue WF and CF associated with staple crop production for each province is the sum of blue WF\CF for local and nonlocal crop production within each province. Formula is as follows:

$$WF_b[x] = \sum_c \sum_y WF_{b,int}[c,x] \times P[c,x] + WF_{b,pe}[c,xy] \times P[c,y] \tag{13}$$

$$CF[x] = \sum_c \sum_y CF_{int}[c,x] \times P[c,x] + CF_{pe}[c,xy] \times P[c,y] \tag{14}$$

where $WF_b[x]$ (m^3/yr) and $CF[x]$ (t CO_2e/yr) refer to the total local generated blue WF and CF related to wheat, maize and rice production in province x, respectively. $WF_{b,int}[c,x]$ (m^3/t) and $CF_{int}[c,x]$ (t CO_2e/t) refer to the internal blue WF and CF of crop c production in province x, respectively. $WF_{b,pe}[c,xy]$ and $CF_{pe}[c,xy]$ (t CO_2e/t) (m^3/t) refers to the blue water consumption and GHGs emissions of province x for per unit crop c production in province y. $P[c,x]$ (t/yr) refer to the production quantity of crop c in province x. $P[c,y]$ (t/yr) refer to the production quantity of crop c in province y.

2.6. Data availability

The meteorological data on daily precipitation and maximum and minimum temperature in 2016 required for the AquaCrop model were acquired from the China Meteorological Data Service center (http://data.cma.cn/en). Data on the planting area and crop yields for each province was obtained from the China Statistical Yearbook 2017 (NBSC, 2017). In simulating the soil water balances by the AquaCrop model, the soil texture data were retrieved from ISRIC database (Dijkshoorn et al., 2008). The soil water content data was from Batjes (2012).

Most of the material consumption inventory, wastewater discharge, and GHGs emission data required for the calculation of the WF and CF of industrial product and their inputs were derived from national statistics, national standards, industrial reports, and the academic literature (see Supplementary Tables 3–6). The consumption of N, P_2O_5, K_2O per crop was calculated by dividing the crop specific fertilizer application rate by crop yield. The quantity of seed, pesticides, and electricity consumed per unit of crop was obtained from Compilation of the National Agricultural Costs and Returns 2016 (NDRC, 2017). The quantity of pesticides, diesel and electricity consumed was calculated from corresponding product price per unit of crop obtained from Compilation of the National Agricultural Costs and Returns 2016 (NDRC, 2017). Provinces lacking data were supplemented by those of neighbouring provinces. The data describing the production of agricultural inputs (e.g., fertilizers, energy, etc.) and their geographical locations were derived from the List of State Energy Conservation Supervision Enterprises of Major Industries in 2018 published by the MIIT (2018) and the Baidu Map (https://map.baidu.com/), respectively. Data on shipping distance related to international trade is obtained from website (https://sea-distances.org).

In trade estimation of agricultural inputs, national data on the supply and demand balance of inputs are mostly derived from industry reports.

In the absence of national demand data, we use the apparent consumption of inputs, that is, output plus imports minus exports. The output, import and export of agricultural inputs at the national level were obtained from Yearbook of Chinese Chemical Industry (CNCIC, 2016) and China Industry Information Network (http://www.chyxx.com/). Demand data for provincial inputs are obtained by aggregating downstream industries demand of agricultural inputs in each province. The latter can be obtained by downscaling the consumption of downstream industries at the national level in proportion to the province's contribution to the national total output of downstream industries. The provincial output and national consumption data of downstream related products of agricultural inputs required for trade flow simulation were obtained from Yearbook of Chinese Chemical Industry (CNCIC, 2016) and the data centres of Longzhong Information Technology Co. Ltd (https://www.oilchem.net) and China Industry Information Network (http://www.chyxx.com/).

3. Results

3.1. Environmental footprints of the crop production supply chain

The national average blue WF of wheat, maize and rice production is 445, 220 and 327 m^3/t, respectively, whereas the national average CF is 0.77, 0.62, and 1.33 t CO_2e/t, respectively. Note that wheat and rice's blue WFs are significantly higher than maize because of their higher irrigation water requirements. While rice's CF is nearly double that of maize and wheat with the unique component resulted from the CH_4 emission from paddy fields. The total blue WF of crop production is 185.27 Gm^3/yr. The total CF is 543.45 Mt CO_2e/yr.

The blue WF and CF of staple crop production within China exhibit significant heterogeneities between provinces and crops (Fig. 4). The blue WF is generally higher for crops grown in the northern provinces due to the comparatively dry climate and intensive irrigation (Wang et al., 2019). High-value regions of CF were concentrated in East Coast, South Coast, as well as a few northern regions (such as Beijing, Tianjin, Inner Mongolia and Shaanxi). The contribution of agricultural inputs to a crop's total blue WF, which is represented by the ratio of IWF to WF, is relatively small at the national level (6%, 2% and 2% for wheat, maize, and rice, respectively). Different farm and industrial production processes across places can lead to a visible weight of IWF (Fig. 4a). Eight provinces have the rate of blue IWF of wheat exceeding 10%. The biggest blue IWF of wheat is 24% of wheat's total blue WF in Fujian provinces. For maize, the biggest rate of blue IWF is 16% in Yunnan province. For rice, the biggest rate of blue IWF is 5% in Ningxia provinces. Compared with maize and rice, wheat has a higher proportion of blue IWF in total blue WF because of the higher blue WF and application rates of wheat seeds (Supplementary Table 7). Seed, N fertilizer, and P_2O_5 fertilizer production account for the majority of the blue IWFs in most provinces (Fig. 5a). In some northern provinces, the contribution of P_2O_5 fertilizer is similar to that of N fertilizer in the blue IWF of three crops. The contribution of pesticides to the blue IWF of rice exceeds that of P_2O_5 fertilizer in provinces in the East Coast and Hunan province (Fig. 5a). In this main text, we focus on the blue WF. Results related to the analysis of the grey WF and green WF can be seen in the

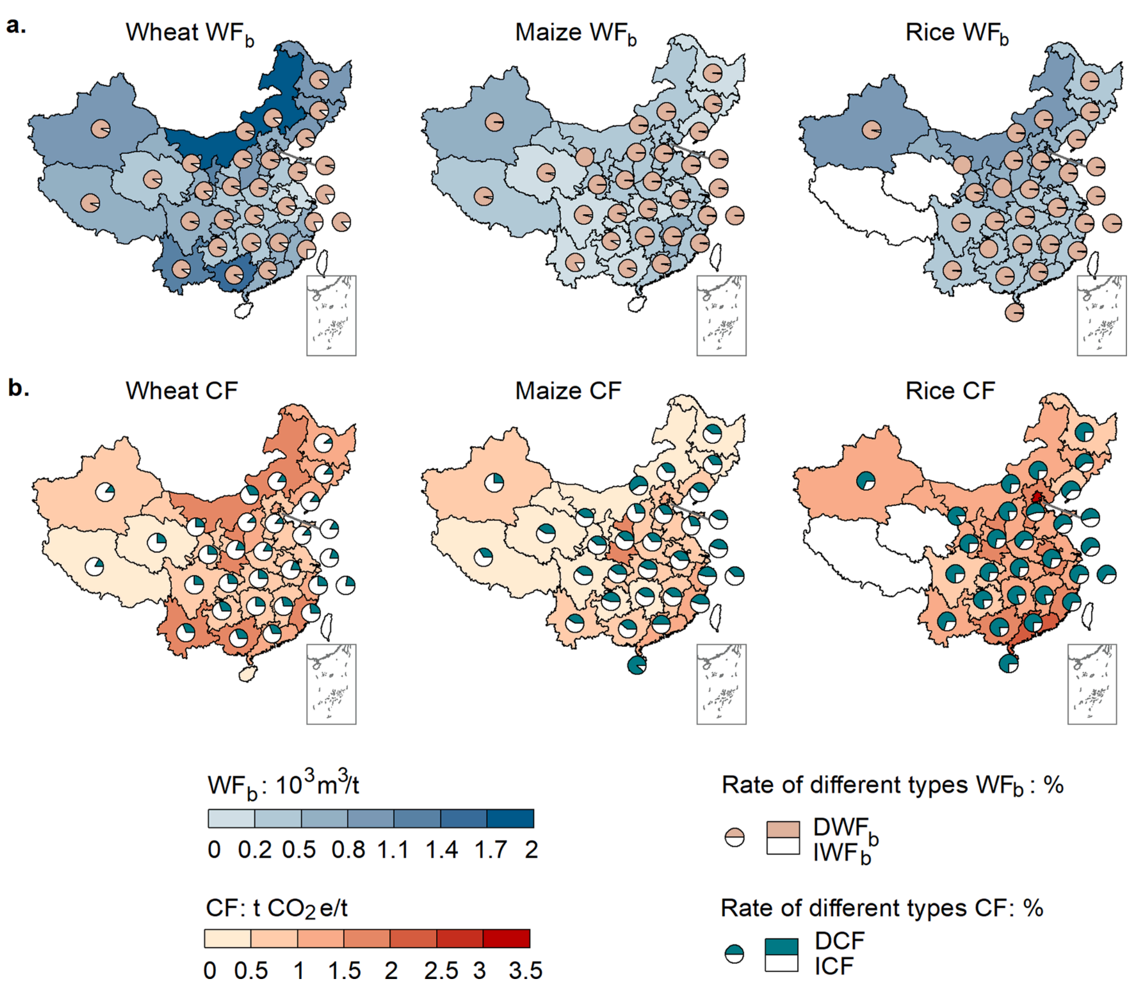

Fig. 4. The blue WF and CF of staple crop production in China (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

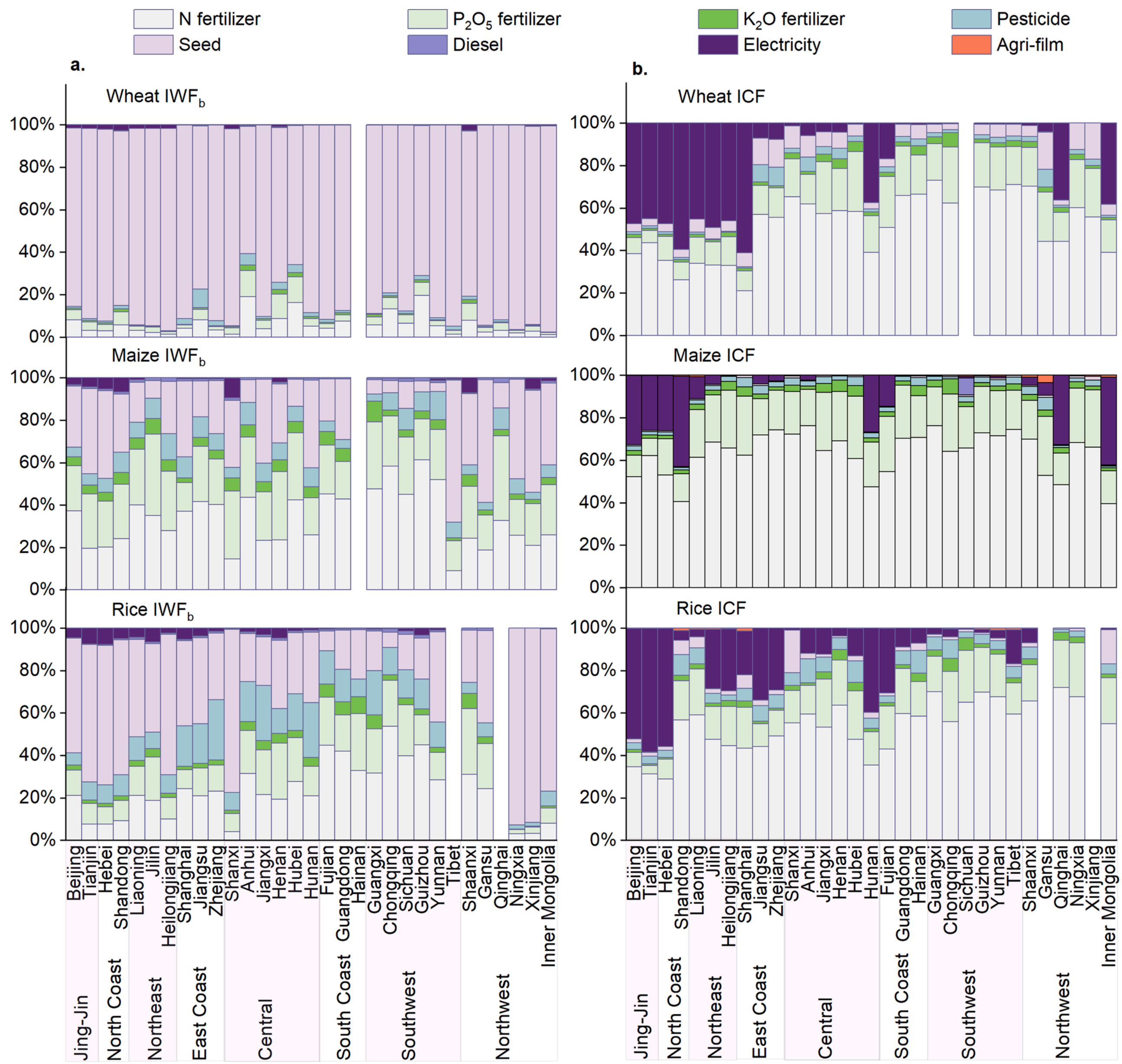

Fig. 5. Spatial distribution of composition for blue IWF and ICF (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Supplementary Results.

The DCF in the field, especially CH_4 emissions, dominate rice's CF, which ranges from 54% to 84% across provinces. In contrast, the rate of ICF to CF for wheat and maize production ranges from 40% to 89% at provincial level (Fig. 4b). Except for some provinces in the Jing-Jin, North Coast, and Northeast where thermal power generation is the dominant contributor to the ICF, the supply chain of N fertilizer contributes the bulk of provinces' crop ICFs (Fig. 5b).

3.2. Environmental burden shifting

Interprovincial and international agricultural supply chains allow some of the environmental burden of food production to be shifted from where the crop is grown. Although over 95% of China's staple crops' WF occurs at the farm field (i.e., DWF), much of the CF of wheat and maize production occurs upstream within the agricultural supply chain (i.e., ICF), particularly for crops grown in eastern China (Fig. 6a, b). The external CF of all the three crops is largely embodied in inter-provincial trade of N fertilizer and upstream electricity inputs. For example, more than 70% of external CF of all the three crops in Guangdong and Gansu provinces are driven by the production and interprovincial trade of N fertilizer (Supplementary Fig. 2–3). In other cases, such as the Hubei, Sichuan and Inner Mongolia provinces, a province's external CF are mainly driven by the interprovincial trade of upstream inputs for local N fertilizer production (Supplementary Fig. 2–3). Moreover, at the national level, electricity inputs contribute 39% of the CF of N fertiliser production (Supplementary Fig. 4), demonstrating the large but hidden role fossil fuel-based electricity has in agricultural production's environmental footprint.

Fig. 6d shows the inter-provincial virtual carbon flows of considered agricultural inputs. Virtual carbon generally flows from the west to east China, matching the locations of fossil fuel-based energy production and consumption. The CF of inputs (such as fertilizers, agri-films, and pesticides) used to supply major grain-producing areas is largely transferred from their upstream energy and power producing areas. China's current power structure is still dominated by coal-based thermal power

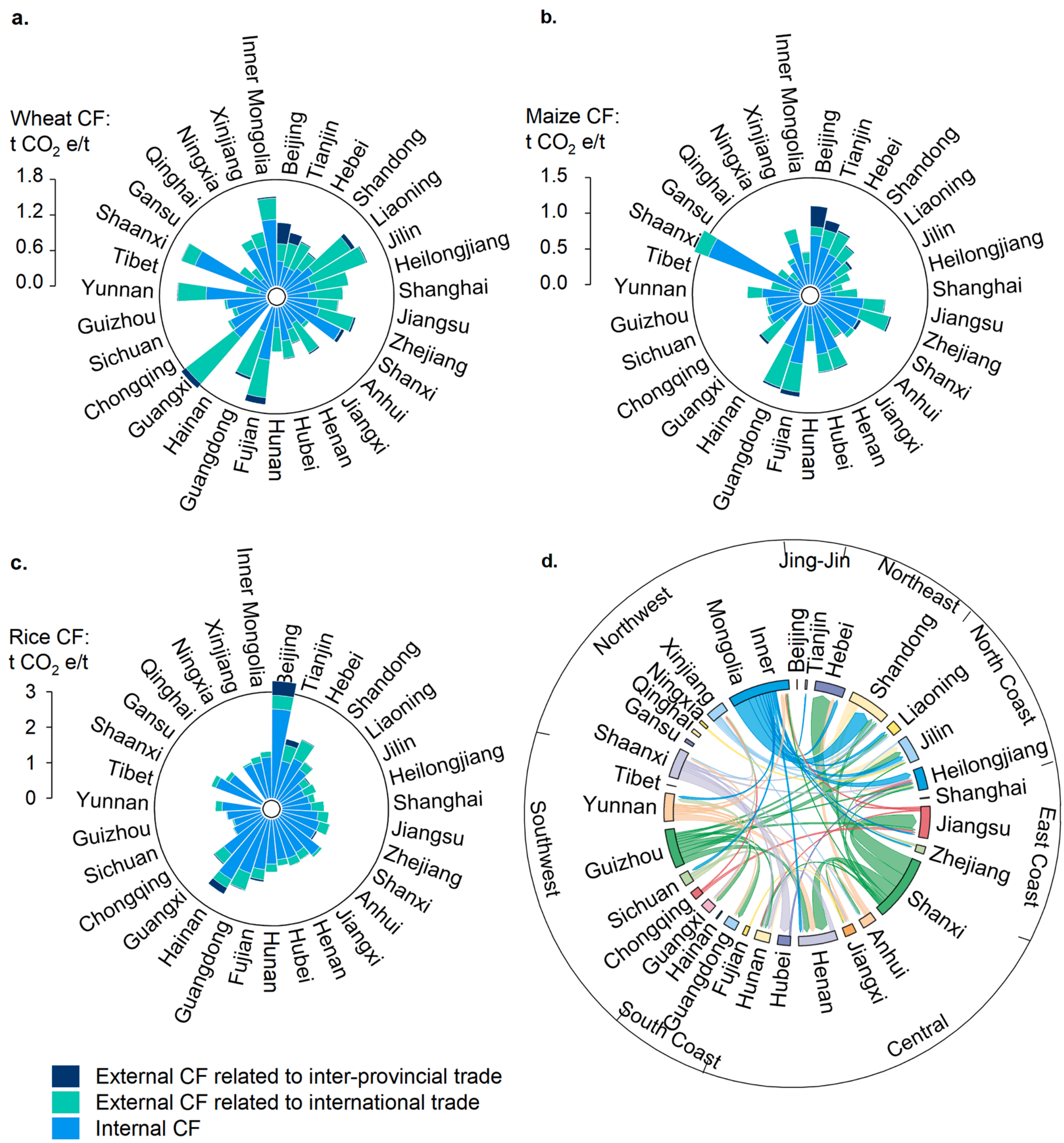

Fig. 6. *Greenhouse gas shifting in supplying crop production inputs*. Fig. 6a–c show the contributions of international and inter-provincial trade in three crop production inputs to the CF of crop production. The external CF of three crops mainly came from the inter-provincial trade of supply chain input product. And the external CF related to international trade was mainly concentrated in Jing-Jin, Coast and their surrounding provinces. Fig. 6d shows inter-provincial virtual carbon flows of inputs for crop production (Unit: Mt CO_2e/yr). The ribbon end in direct contact with the coloured bands show the province where GHGs are emitted, while the ribbon end that does not touch the outer band represents the province as a virtual carbon importer through traded agricultural inputs.

generation (Supplementary Table 8). Shanxi and Inner Mongolia, as the main producing areas of coal-driven electricity, are the largest net CF exporters, accounting for 23% (30 Mt CO_2e/yr) and 18% (24 Mt CO_2e/yr) of the total exports, respectively. The virtual carbon flows from Shanxi to Hebei (the 4th largest wheat producing area), Jiangsu (the 4th largest rice producing area) and Henan (the 1st largest wheat producing area), and from Inner Mongolia to Shandong (the 2nd largest wheat and 3rd largest maize production base in the country) accounted for 23% (31 Mt CO_2e/yr) of the national total. The corresponding inter-provincial virtual water flows are shown in Supplementary Fig. 5.

Rural farmlands shift environmental pressures associated with food production to urban areas through supply chain. Previous studies defined the boundaries of the food production system as farm to fork (Marston et al., 2015), largely ignoring the food system components before the farm field. Naturally, these studies conclude that urban areas displace the environmental burden of their food demand to rural areas that grow their food. However, by tracking available production locations of agricultural inputs across the country and matching them with national land use data with a spatial resolution of 30 m for 2015 obtained from the Resource and Environment Data Cloud Platform (https://www.resdc.cn/), we find that environmental burden shifting between urban and rural areas is not unilateral. All agricultural inputs except P_2O_5 fertilizer are predominately produced in urban areas and contribute to local air pollution (Supplementary Fig. 6).

3.3. Transgressing part of provincial water and carbon planetary boundaries

China's staple crop production is violating regional water and carbon planetary boundaries. The total local generated blue WF and CF associated with staple crop production for each province are compared to corresponding downscaled planetary boundaries (Li et al., 2020; Hu et al., 2020) (Fig. 7). At the national level, the total local generated blue WF (185.1 Gm^3/yr) of staple crops appears sustainable since less than a third (30%) of the national blue water planetary boundary is utilized. However, here we highlight that the sustainability of crop production varies significantly within the country (Fig. 7a). Wide-spread wheat and maize production drive the crop-related blue WF in six relatively water-scarce northern provinces (Tianjin, Hebei, Shandong, Henan, Ningxia and Shanxi Provinces) to exceed their local blue water planetary boundaries. Amongst them, the blue WF in Ningxia is five times higher than its blue water planetary boundary.

Compared with the national carbon planetary boundary, total CF (535 Mt CO_2e/yr) of staple food crops within the country seems sustainable at 49% of national PBs of carbon emission, but it changes into an adverse story when downscaling to provincial levels. Shanxi and Inner Mongolia, the two major power generation bases, have CFs related to staple crop production reaching 133% and 174% of the local carbon planetary boundary, respectively (Fig. 7b). And the CFs of crop production in six provinces (Heilongjiang, Jiangxi, Hunan, Guizhou, Shaanxi, Xinjiang) has reached more than 60% of the carbon planetary boundaries. In China, 45% of the CF related to staple crop production is concentrated in seven provinces. Shanxi accounts for the largest CF (~39 Mt CO_2e/yr) due to its heavy dependency on fossil fuel-based energy. This is followed by Henan (39 Mt CO_2e/yr) and Anhui provinces (35 Mt CO_2e/yr), mainly due to the scale of local staple crop cultivation. More than two-thirds of total CF in four provinces (Shanxi, Inner Mongolia, Guizhou and Qinghai, respectively) is associated with the nonlocal crop production, thus demonstrating how nonlocal demands can shape environmental outcomes, often in a negative way.

4. Discussion

4.1. Agricultural inputs and supply chains are crucial

By evaluating environmental impacts associated with the agriculture inputs and supply chain upstream before the farm field, we find that the agricultural inputs in the supply chain of crop production account for up to 24% and 89% of a crop's WF and CF, respectively, at the provincial level in China. Interprovincial virtual blue water and carbon flows embedded in the trade of agricultural inputs reached 889 Mm^3 and 134 Mt CO_2e, respectively. At the same time, production of agricultural inputs for export directly leads to unsustainable carbon emissions in Shanxi, Inner Mongolia and Guizhou provinces. Given the larger environmental impact, the crop supply chain should not be ignored.

Moreover, the current study shows that the upstream partners responsible for the supply and processing of raw materials and energy for inputs are also accountable for improving water efficiency and mitigating GHGs emissions from crop production, in addition to the agricultural sector itself. At the national level, industrial products accounted for 73% and 54% of the blue IWFs of maize and rice respectively, and more than 95% of the three crops' ICFs (Fig. 5). Unfortunately, the current water resources and GHGs emissions managements are in silos. Cooperation across different sectors, especially between the chemical industry and agriculture, should be strengthened.

4.2. Practical implementations and suggestions

Improving the food system within sustainable limits will require a multifaceted approach that considers all actors within the supply chain network. To be more specific, at the farm field well-known measures to

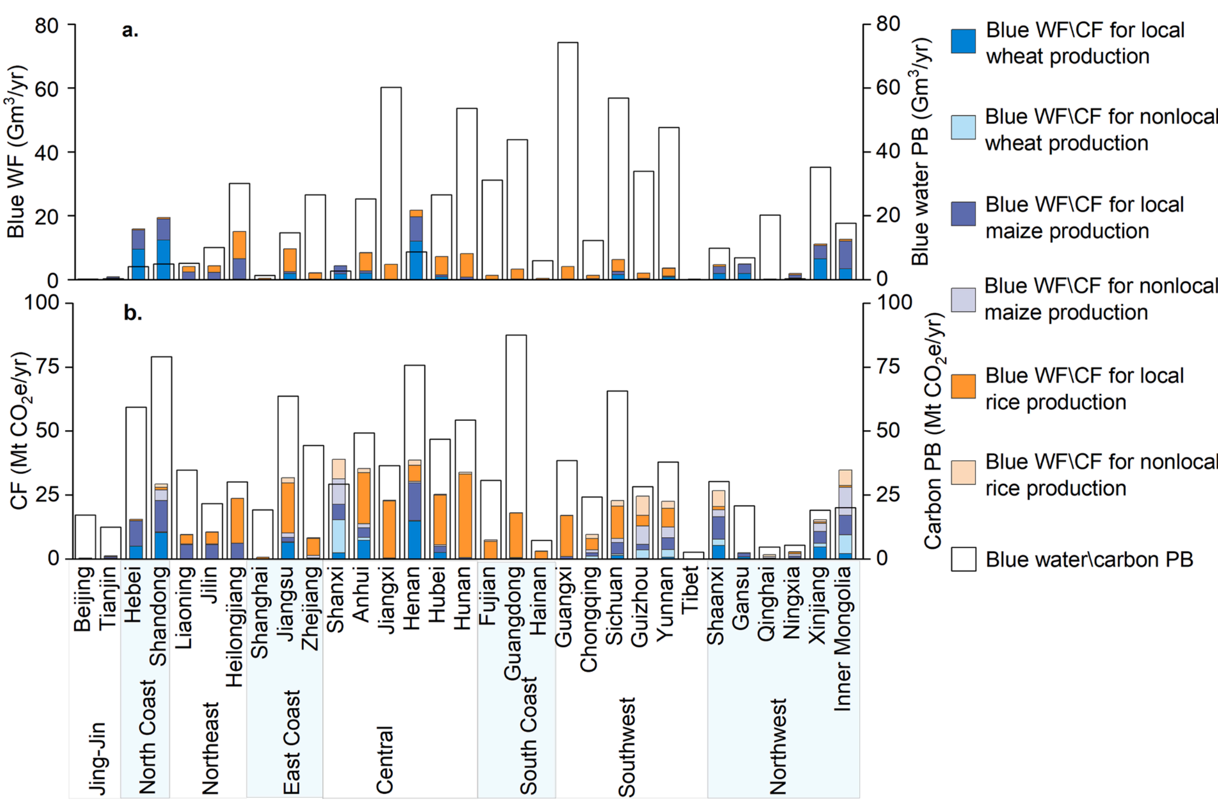

Fig. 7. Provincial blue water (a) and carbon footprint (b) versus associated local planetary boundaries (PBs) in Chinese provinces (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

improve water use efficiency, reduce nutrient runoff, and mitigate GHGs emissions could be more widely employed. For example, rainwater harvesting, mulching, no-till farming, high-efficiency irrigation systems, and laser field-levelling can be used to decrease the use of scarce blue water (Wang et al., 2018; Wang and Shangguan, 2015). Precision agriculture technology can minimize fertilizer applications, thereby reducing water pollution and GHG emissions. Adding biochar and nitrification inhibitor to soils, applying N fertilizer deeper to reduce N_2O emission from N fertilizer application (Hu et al., 2013), carbon sequestration within the soil (Chen et al., 2021), and optimizing irrigation applications to reduce CH_4 emissions from rice fields (Guo et al., 2017) are additional strategies to reduce the environmental footprint of food production without limiting production. Water and carbon markets and caps could spur innovation across the entire food sector, as well create new opportunities and investments from other sectors. For the chemical industry supply agricultural inputs, more water-saving and low-carbon production materials and process designs should be encouraged. A shift toward clean renewable energy sources, such as wind and solar power, will significantly reduce the WF and CF of the food system (Bogdanov et al., 2019). In addition, we need to be alert to the fragility of international trade networks, which are vulnerable to climate change, natural disasters, economic development and international relations (Puma et al., 2015).

Bringing the food system within sustainable limits is made more challenging due to broader concerns beyond the environment. Our results show regions like Shanxi and Inner Mongolia depend on environmentally damaging mining, heavy industry, energy production, and agriculture to lift their economy and the livelihoods of their people. Thus, despite the considerable environmental damage attributable to the food system in these provinces, it will likely not be tenable to limit their production or exports to more sustainable levels. An alternative approach to limiting production and exports is to focus investments in clean energy, improving manufacturing efficiencies, and precision agriculture within these regions. Investments aimed at addressing the supply chain stages and locations where the greatest environmental damage occurs – as detailed in this study – can improve both environmental concerns and economic competitiveness.

Greater information sharing and transparency within the food industry, including best practices, disclosure of water uses and GHG emissions, and industry specific CF and WF benchmarks (Marston et al., 2020), can help shift the entire food system toward a smaller environmental footprint. Consumer preferences may help incentivize the food industry to move in this direction, though it remains unclear the degree to which market forces can shift the food system toward a more environmentally sustainable outcome (Potter et al., 2021). Instead, government coordination, investments, incentives, and regulations may prove more effective.

4.3. Limitations and uncertainties

There are limitations to be in caution. A lack of detailed facility-level data required us to simplify the diversity of industrial product varieties and production processes across China. We assumed widely used varieties, production processes, and energy consumption types, such as urea for N fertilizer, reverse flotation for K_2O fertilizer production, and coal-based thermal power generation. In addition, our study focuses on one year, 2016. Thus, the current analysis did not capture inter-annual variability in WFs and CFs due to the impact of year-to-year changes in agricultural production, meteorological conditions, industrial and energy sector structure, trade patterns, and national policies. Due to the lack of a database of available seed WF showing spatial differences, we treat the seed as field crops, which may underestimate the IWF of crops. Although there may be underestimates, it is not expected to change the key conclusion that the crop IWF is nonnegligible. It is still highly recommended to take specific field measurements of WF of seedlings for smaller scale assessments.

Compared to previous studies (Chen et al., 2021), the current shown national average CF of rice and wheat is 5% and 4% lower, respectively, while that of maize is 24% higher, which is related to the study's system boundary and the carbon emission factor of each stage of the supply chain. Straw burning and manure compost are not considered in this study, but the GHGs emission of seeds are. We also consider regional differences in carbon emission factors of crop production supply chain inputs. In addition, we used the nitrogen loss model to calculate the N_2O emissions caused by N fertilizer application in the field. Most studies have found a strong exponential relationship between N loss and input (Chen et al., 2014; Cui et al., 2013). Calculating N_2O emissions using the common IPCC methodology will have a big impact on the results in areas of overfertilisation, particularly in China. Therefore, we believe that the current results are relatively more reasonable.

The national average WF of the three crops estimated in the current study is much higher than that of Mekonnen and Hoekstra (2011) and Zhang et al. (2018), which is mainly due to our high grey WFs. Two reasons explain this phenomenon. The one is the broader system boundaries. Our study considered the indirect water pollution caused by inputs throughout their life cycle, while other studies only considered grey DWF caused by the application of N and P_2O_5 fertilizer. The second is the difference between our maximum allowable and natural nitrogen concentration (c_{max} - c_{nat} in Formula 3) used a more stringent assumption of 0.8 mg/L, while Mekonnen and Hoekstra was 10 mg/L.

5. Conclusion

This study systematically analyses the linkages between the final consumption of agricultural production and the upstream sectors, as well as the resulting inter-regional transfer of environmental impacts and regional sustainability, by looking at the supply chain of staple crop production from upstream to downstream in a geographically refined manner. The study broadens the scope of traditional agricultural production impact assessments, and the same assessment methods can also be applied to many other countries, sectors and products facing similar sustainability challenges. At the same time, because agriculture is the primary water user and carbon emitter, such assessments are essential to ensure regional food security and sustainable development in the face of rising global trade, water scarcity and strict carbon neutrality targets.

CRediT authorship contribution statement

Bianbian Feng: Investigation, Data curation, Formal analysis, Writing – review & editing. **La Zhuo:** Investigation, Writing – review & editing. **Mesfin M. Mekonnen:** Investigation, Writing – review & editing. **Landon T. Marston:** Investigation, Writing – review & editing. **Xi Yang:** Data curation. **Zenghui Xu:** Writing – review & editing. **Yilin Liu:** Data curation. **Wei Wang:** Data curation. **Zhibin Li:** Formal analysis, Writing – review & editing. **Meng Li:** Formal analysis, Writing – review & editing. **Xiangxiang Ji:** Writing – review & editing. **Pute Wu:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The study is financially supported by the Program for Cultivating

Outstanding Talents on Agriculture, Ministry of Agriculture and Rural Affairs, People's Republic of China [13210321], and the National Youth Talents Plan.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2022.118803.

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