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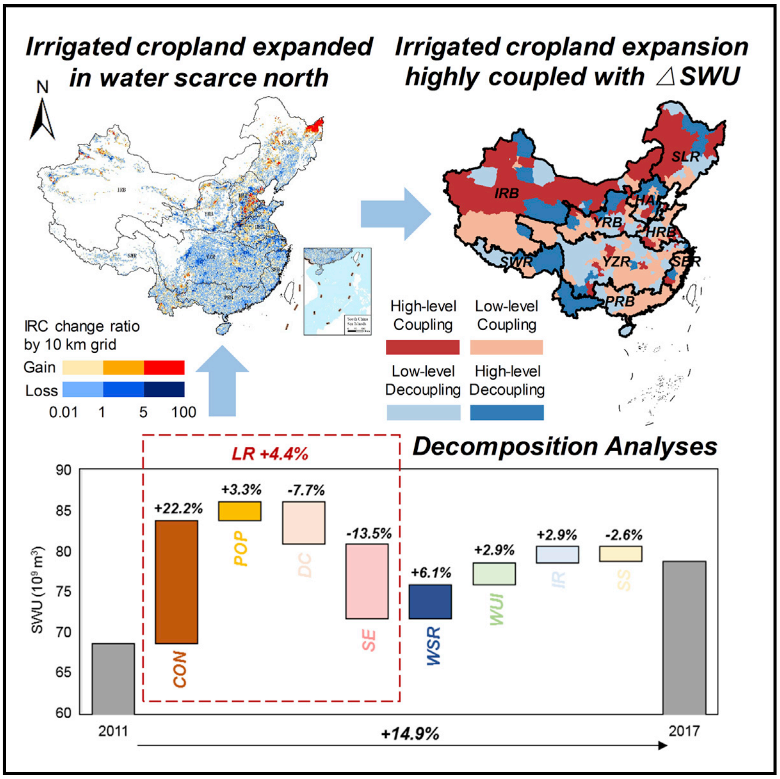
Rising agricultural water scarcity in China is driven by expansion of irrigated cropland in water scarce regions

Graphical abstract



Highlights

- Scarce irrigation water use reversed to increase since 2011 in China
- Agricultural imports and reduced water use intensity alleviated water scarcity
- Scarce irrigation water was coupled with irrigated cropland expansion in the north
- Spatial shifts of irrigated cropland drove the rising agriculture water scarcity

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In brief

This study explores the drivers of increasing agriculture water scarcity in China. Using two nationally coordinated survey datasets of land and water use at the prefecture level and spatial decomposition analysis, we show that the irrigated cropland expansion in the water-scarce north drove the rise in water scarcity after 2011. The land-water coupling analysis of this study highlights the importance of incorporating ecological impacts into the assessment of national land management policies.

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Rising agricultural water scarcity in China is driven by expansion of irrigated cropland in water scarce regions

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SCIENCE FOR SOCIETY China's ability to meet the water-related targets of the 2030 sustainable development agenda is threated by increasing agricultural water scarcity. We show that scarce irrigation water use in China rose in the last decade due to irrigated cropland expansion in the north, even if agricultural imports and reducing agricultural water use intensity reduced the volume of water used. These results showcase large impacts of current cropland compensation policies. Better-defined guidelines for the cropland requisition-compensation balance policy that fully consider water scarcity are urgently needed to avoid increasing the magnitude of associated sustainability challenges. These should be fully integrated with ecosystem conservation policy, through incorporating territorial spatial planning, to avoid serious impact of surrounding natural ecosystems.

SUMMARY

Increasing agricultural water scarcity is threatening food security and ecosystem sustainability in China. Previous studies showed a deceleration in the growth of irrigation water use in China due to reducing water use intensities of irrigation. However, a finer-scale analysis at the prefecture level is urgently needed to account for the impacts of land management policies and the impact of international food trade in water stress mitigation. Here, we address these gaps and demonstrate that the scarce irrigation water use trend reversed to rising after 2011 through shifting to irrigated cropland, even if grain import reduced water stress at the national scale, and we highlight the specificity of relationships between scarce water use and irrigated cropland change at both the river-basin and prefecture scales. These results call for an urgent re-evaluation of the implementation guidelines of China's Land Requisition-Compensation Balance policy on scarce irrigation water use.

INTRODUCTION

Freshwater use is one of nine planetary boundaries, which is based on allowable human blue water consumptive use.[1,2] Although freshwater use does not exceed its planetary boundary threshold from a global perspective at present,[3] increasing risk exists in terms of the regional water crisis and scarcity.[2,4] Agriculture is the largest user of freshwater by far,[5] which consumes 70%–86% of available water resources in the world[6,7] and is the largest contributor to the rising level of regional water scarcity.[8,9] Rising water scarcity brings increasing risk to agricultural production and ecosystem services.[10] It has been acknowledged that such factors as uneven distribution of global freshwater resources,[11] unsustainable irrigation utilization,[12] over-exploitation of groundwater, and marginal land expansion for food security[13] have exacerbated ecological degradation in water-scarce areas. As a result, the academic community has not only discoursed on sustainable, equitable, and efficient water use/allocation by volumetric-oriented water footprints[6,14] but also focused on the environmental impacts of water consumption and the resultant water scarcity.[15,16] Two indicators in the Sustainable Development Goals (SDGs) thus were developed, 6.4.1 on water efficiency and 6.4.2 on water stress, to facilitate reduction in water scarcity.[17]

As one of the most water-scarce countries in the world,[18] China's water consumption for irrigation increased by 17% from 1987 to 2010.[19] Moreover, recent research indicates that 66% of China's irrigation water consumption was defined as unsustainable water use, where water consumption exceeded local renewable water availability.[12] The spatial distribution of China's water resources is extremely uneven,[20] and the spatial mismatch in water and arable land availability[21] has significantly contributed to the regional water scarcity. Although the growth rate of irrigation water use has slowed down due to the reduced water use intensities of irrigation,[22] the understanding of the trends and drivers of China's unsustainable irrigation water use remains limited.[23]

In order to feed 1.4 billion people, China has made great efforts to protect its cropland from competitive uses.[24,25] A very important policy effort was the Land Requisition-Compensation Balance policy,[13] which regulates "how much cultivated land is expropriated and how much is compensated" by the policy. The force of urbanization and industrialization constrained by this policy has led to a pattern shift of cropland from south-east to north-west China, where the ecosystem is more vulnerable. Accordingly, environmental sustainability issues induced by such a shift has aroused wide concern, in addition to the concern that the loss of high quality cropland was compensated by poor-quality land in less accessible areas.[13,26] However, a systematic assessment on the environmental impact of this stringent land protection policy in general and its impact on irrigation water resources is largely missing.

The existing literature has explored the major drivers of the increasing amount of water use and found that the socioeconomic developments are increasingly becoming the largest driver in many regions of the world.[27] The improvement in water accessibility has driven up water use intensity (WUI) of domestic economies and will lead to additional surface-water deficits in the near future.[23] The demand-side drivers include growing population[28,29] and income level,[30] increases in per capita food demands, and rising standards of living.[31] While the existing studies have shown that the economic structure and sectoral technological factors, production scale effect, water saving technology, and plantation structure in the case of agriculture have driven water use,[32,33] the trade globalization has created a linkage among different countries that could reshape the patterns of water use and ecosystem impact via the form of virtual water flows.[34] On the one hand, importing water-intensive food products may help to reduce water stress in water-scarce countries[35] and sub-national regions.[36,37] On the other hand, exporting highly water-intensive products exacerbates domestic water stress. As a result, the international food trade has gradually become a crucial factor affecting water stress, but the role of trade in water-stress mitigation in a certain region is ambiguous,[38] especially for sub-national regions/prefectures of China, which has been a net crop importer since 2004.[12]

In the relationship between major influencing factors and water footprint change as revealed by the existing studies,[22,39,40] land-use change has played an explicit or implicit role in quantifying the major parts of water consumption and water pressure. However, land-use changes in these studies have mainly focused on the conversion between different types of land use,[41] being unable to account for the impact of changes in irrigation practices and the distribution of irrigated cropland due to data constraints. High-resolution remote-sensing data have been regarded as the best available data for land-use changes; nevertheless, for water use and water scarcity analysis, remote-sensing data often need to be scaled up to the administrative level (usually the national or provincial level) for matching with socio-economic variables.

Due to the spatial mismatch between water and cropland endowments across different regions in China,[18] changes in regional water use caused by spatial pattern shifts of cultivated land will also have differentiated ecosystem impacts across space. Ridoutt and Pfister thereby suggested incorporating water stress characterization factors into the modified impact-oriented water footprint methodology.[42] Compared to traditional volumetric-oriented water use accounting, scarce water can distinguish different ecosystems impacts from the same volume of water use[16,37] and show "water-deprivation impact potential" across different locations.[43] Water scarcity arises in locations where there is insufficient water to simultaneously support both human and ecosystem water needs. It can be further characterized as green, blue, and economic water scarcity depending on analytical focus.[9] High land productivity typically relies on intensive irrigation and the associated water consumption.[35] An expansion of irrigated cropland, due to the growing demand for water-intensive crops, in places where water is scarce will directly lead to negative ecosystem impacts from water-resource depletion. Although existing studies have indeed confirmed that the expansion of irrigated cropland will increase the demand for irrigation water in China at the national level[44] and the major-river-basin level, such as Hai River Basin[45] and Songliao River Basin,[46] an analysis with finer resolution at the sub-provincial level is critical to understand the impact of China's Land Requisition-Compensation Balance policy.

This study addresses the above-identified knowledge gaps through achieving three objectives. Firstly, we combine the irrigation water requirements estimated by the GIS-based Environmental Policy Integrated Climate (GEPIC) model and the Water Stress Index (WSI) to investigate the trends of scarce water use and their changes at the prefecture-level from 2004 to 2017, which fills an important niche by analyzing the trends of scarce irrigation water use and its ecosystem impacts at the scale of small administrative units called prefectures, thanks to a unique nationwide survey dataset of land use in China. Secondly, we apply the logarithmic mean divisia index (LMDI) decomposition technique to detect the drivers at the same prefecture level. We further employ the irrigation information in the unique land use dataset to do coupling/decoupling analysis between irrigated cropland expansion and water scarcity across prefectures, which is the finest resolution so far in revealing the impact of land-use changes on water scarcity in China. Thirdly, we use the "land-water" nexus evidence found in this study to explore implication for upgrading the current land-use policy. Here, we find that the trend of scarce irrigation water use reversed to rising after 2011 through shifting to irrigated cropland though grain import is curbing water stress in China. Our

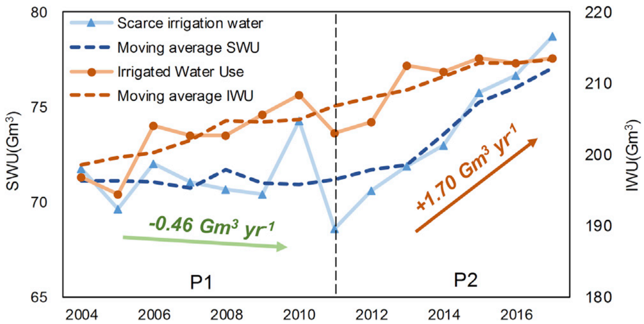


Figure 1. Trends of crop irrigation water use (IWU) and scarce irrigation water use (SWU) from 2004 to 2017

The light blue line represents the trend of original scarce water use, and the dark blue dash line represents the five-year moving average of scarce water use. The light red line represents the trend of original irrigation water use, and the dark red dash line represents the five-year moving average of irrigation water use. The piecewise linear regression with national SWU from 2004 to 2017 (R^2 = 0.973; $p < 0.001$) confirms the statistically significant turning point in 2011.

decomposition analysis reveals the presence of low-level versus high-level coupling and low-level versus high-level decoupling relationships between scarce water use and irrigated cropland change at both the river-basin and prefecture scales. This finding complements the existing literature showing that the growth of irrigation water use has decelerated due to the reduced water-use intensities of irrigation, and it provides evidence for the need to evaluate the impact of China's Land Requisition-Compensation Balance policy on scarce irrigation water use.

RESULTS

China's rising demand for scarce agriculture water use

Demand for scarce crop irrigation water use (SWU) experienced a fluctuated decrease before 2011 with a decreasing rate of -0.46×10^9 m^3y^{-1} and then a rapid increase with a speed of 1.70×10^9 m^3y^{-1} (Figure 1). In order to further detect the driving factors of scarce irrigation water changes and the impact of irrigated cropland changes, our analysis is divided into two time periods, 2004–2011 (P1) and 2011–2017 (P2). The starting year, 2004, marks the onset of net grain import era of China and the turning point of 2011 denotes the reverse of China's scarce water-use trend from decreasing to increasing after the year. These two periods also overlay with China's 11th (2006–2010) and 12th (2011–2015) 5-year development plan. In the two study periods, the national-level use of scarce water changed by −0.6% and +2.5%, respectively. It should be noted that 2010 was an unusual year for changes in scarce water because of a historic drought in the southwestern provinces according to the Annual Report of the National Water Resources Statistics, which led to a prominent increase in irrigation water use in the year.

From 2004 to 2011, China's SWU decreased by 4.5%, and SWU in both northern and southern regions was decreasing at the rates of −3.2% and −12.9%, respectively (Figure 2). The SWU in all river basins in the south decreased except Southwest River Basin with an increase by 2.7%. By sharp contrast, the SWU in all river basins in the north increased except Inland River Basin with a decrease by a large margin at 14.1%, which directly drove a decrease of SWU in aggregation across the north regions. In the period of 2011–2017, the trend of China's SWU reversed to increase by 14.9%. The river basins in the north showed a prominent increase rate of 18.8% in the study period, while river basins in the south remained decreasing by 14.0%. Specially, the increase of SWU in the Inland River Basin (+4.1 10^9 m^3, +25.0%), the Yellow River Basin (+1.7 10^9 m^3, +17.2%), and the Huai River Basin (+5.3 10^9 m^3, +26.5%) largely led to the growth of China's SWU during this period (Figure 2).

Drivers of SWU

Figure 3A shows that from 2004 to 2011, the growth in total land requirement (LR) as driven by increase in food consumption and population growth led to an increase in SWU by 17.4%. By contrast, changes in water use intensity (ΔWUI), water scarce ratio (ΔWSR), and irrigation ratio (ΔIR) led to the decrease in SWU. The calculation formulae of ΔWUI, ΔWSR, and ΔIR are presented in Equations 8–10 in the experimental procedures. In more detail, ΔWUI contributed −13.8% to the total change in SWU during P1 (Figure 3A), of which −7.3 percentage points was attributed to ΔWUI of wheat and −4.7 to that of maize; ΔWSR contributed −6.0% (Figure 3A), of which −2.1 percentage points was attributed to maize and −2.0 to rice (Figure 4A); and ΔIR contributed −3.5% to the total change in SWU during P1. Figure 3A also shows that the change in self-sufficient ratio (ΔSS) contributed +1.4% to the total SWU change during P1.

During 2011–2017, the roles of ΔWSR, ΔWUI, and ΔIR were reversed and all of them contributed to the rapid increase in SWU. Among factors determining LR, the improvement in the supply efficiency (SE), which was mainly driven by increase of land productivity, was most noticeable with a contribution of −13.5% to the total change in SWU and drove down the contribution share of land requirement to +4.4%. The role of SS was also reversed to contributing −2.6% to the change in SWU due to significant increase in China's crop imports (Figure 3A). ΔWSR contributed 6.1% of the increase in SWU, mainly due to the increased water consumption in water-scarce areas of China, especially rice, which contributed 3.3% of the increase (Figure 4B). According to the statistical analysis of this study, water consumption increased by 17.0% in the areas where the WSI was above 0.5. The increasing effects from ΔWSR indicate a shift in the spatial distribution of crop production to water scarcer places. ΔWUI contributed 4.0% of the increase, mainly due to the increased irrigation WUI of maize and wheat (Figure 4B). ΔIR contributed 2.9% of the increase, mainly due to an increase in the share of irrigated land in the total.

For the whole study period of 2004–2017 and at the national level, crop consumption (CON) and population (POP) growth were the most important factors influencing SWU growth, contributing 46.7% and 6.7%, respectively. ΔWSR, ΔIR, and ΔWUI contributed to the overall decrease of SWU, but their effects were gradually weakened, which also resulted in the increase of SWU in P2. ΔSE and ΔDC were the main factors contributing to the reduction of SWU (−17.9% and −13.8%, respectively) and the reduction effect had gradually increased. Figure 3B further visualizes the comparative temporal characteristics of these driving factors.

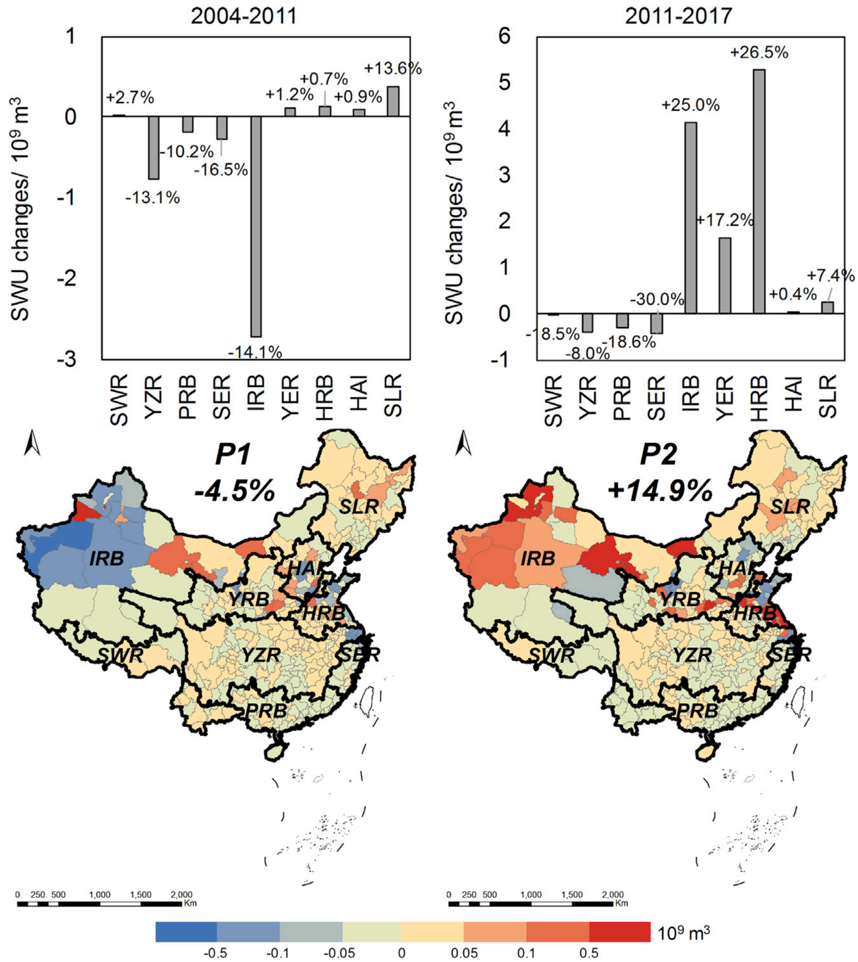


Figure 2. Spatiotemporal change of demand for SWU

SWR, Southwest River Basin; YZR, Yangtze River Basin; PRB, Pearl River Basin; SER, Southeast River Basin; IRB, inland River Basin; YER, Yellow River Basin; HRB, Huai River Basin; HAI, Hai River Basin; SLR, Songliao River Basin. SWR, YZR, PRB, and SER are river basins in the south while IRB, YER, HRB, HAI, and SLR are river basins in the north of China. See Section S1 in the supplemental information for details.

Spatial shifts of drivers for SWU

In order to detect the spatial details of major driving factors, this study decomposed SWU into five factors, including water-use intensity, irrigated ratio, production structure, production efficiency, and population in the two phases, P1 and P2, at the prefecture level. It should be noted that due to the difference in decomposition model and spatial scales, the aggregated effect of the same factor could show different effects in comparison with those in Figures 3 and 4 at the national level.

In P1, the 4.5% decline of total SWU can be mainly attributed to the SWU decline in the northern Inland River Basin (−3.8 percentage points) (Figure 5). At the national aggregation, ΔPI (production intensity), ΔWUI (water use intensity), and ΔPS (production structure) largely drove the decline of SWU, contributing −26.1%, −12.1%, and −11.3% of total decrease, respectively. Of the ΔPI's −26.1% contribution share to the change in SWU, drop of ΔPI in Huai River Basin and Yellow River Basin contributed −11.9 and −4.6 percentage points, respectively. The contribution shares of ΔWUI and ΔPS were dominated by their effects in Inland River Basin (ΔWUI, −9.0%) and Huai River Basin (ΔPS, −7.2%). By contrast, ΔIR (irrigation ratio) contributed 39.4% increase of SWU, the increasing ΔIR mainly distributed in Huai River Basin (+14.5%), Yellow River Basin (+5.6%), and Hai River Basin (+5.6%) (Figure 5).

P2 witnessed a reverse from decrease to rapid increase in the SWU. From geographical aspect, the increase rate of 14.9% in this phase was mainly driven by Huai River Basin (7.7 percentage points) and Inland River Basin (6.0 percentage points). ΔWUI and ΔIR are two dominant drivers of the rising SWU with contribution shares of 12.0% and 4.6%, respectively. ΔWUI, as the largest increasing factor, was mainly contributed from Huai River Basin (+7.8%) and Yellow River Basin (+3.1%) (Figure 5). The increasing IR in Inland River Basin also contributed 2.8% of the total SWU increase. The increase of ΔPOP (population) contributed 3.2% to the SWU growth with significant spatial variations. The population changes in most river basins contributed to the growth of SWU, except the Songliao River Basin, where population was decreasing.

ΔWUI and ΔIR proved to be crucial factors affecting the change of SWU at the river-basin level. These two land-induced factors are mainly affected by the expansion of irrigated cropland, via both reclaiming new irrigated land and converting dryland to irrigated land. In this regard, the unique land-use survey data we employed for this study are indispensable because the dataset provided the best available information on the development of irrigation and irrigated cropland.

Coupling of irrigated croplands change and SWU change

The detailed land-use survey data show that in P2, during which the SWU reversed to increase (Figure 6A; see Note S2 for rasterization of national land survey data), river basins in the south experienced a decreasing trend of irrigated cropland mostly due to ecological forest planting, with the percentage of grain to green conversion area accounting for 50.0%, 35.5%, 42.4% of the total decrease for Southeast River Basin, Yangtze River Basin, and Pearl River Basin. Urbanization was also a major factor for irrigated cropland loss in Huai River Basin, accounting for 36.0% of the total loss. The gains of irrigated cropland in the northern river basins were from multiple sources, with land consolidation project in Hai River Basin and Yellow River Basin accounting for 32.8% and 30.6% of the total irrigated cropland gains. The poles-apart trends of irrigated cropland changes in water scarce north versus water affluent south underline the

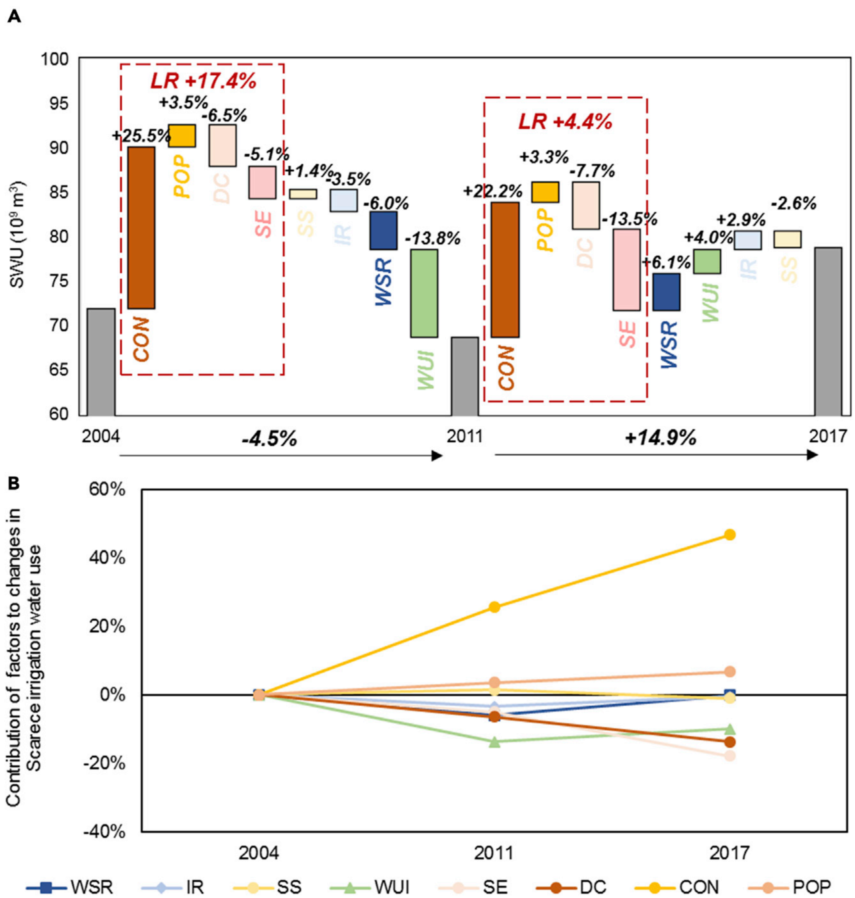


Figure 3. Decomposition results of SWU at the national level

(A) Drivers of SWU from 2004 to 2017 in China.

(B) Contribution shares of factors to changes in SWU from 2004 to 2017. WSR, water scarce ratio; IR, irrigation ratio; SS, self-sufficient ratio; WUI, water use intensity; SE, supply efficiency (which mainly corresponds to the reciprocal of land productivity); DC, dietary structure change; CON, crop consumption per capita; POP, population; LR, land requirement including both domestic sowing areas and the embodied cropland through international food trade. Equations 8–15 in the experimental procedures present calculation formulae of these indicators.

importance of land use regulation for the mitigation of water scarcity. Without surprise, the land-water relation shows different patterns in regions with lower water scarcity. Most of the water-affluent southern river basins remained low-level decoupling relations with low ecosystem impacts from land-use change. Low-level decoupled Southwest River Basin changed into high-level decoupling from P1 to P2, indicating that the SWU changes in Southwest River Basin is not driven by expansion of irrigated cropland but by increasing use of green water with low ecosystem impacts. This evidence supports the spatial heterogeneity features of the land-water relations across different basins in China (Figure 6B).

It is also worth noting the impact of changes in crop mixture on SWU, which is largely overlooked in previous studies. For example, among the total loss of irrigated cropland in Yangtze River Basin (YZR) during 2011–2017, 21.2% came from the conversion from paddy to dryland. By sharp contrast, in the case of Songliao River (SLR), 50.2% of the total irrigated cropland expansion in the same period came from the conversion from dryland to paddy (Figure 6A).

The detailed matrix of coupling characterization is presented in Table 1 to facilitate the analysis. At the national scale, China remained a low-level coupling trend in P1, meaning that both SWU and IRC decrease and the situation is good for the ecosystem. However, from 2011 to 2017, the relation between irrigated croplands and scarce water use turned into high-level coupling, which is characterized by significant expansion of irrigated field and increase of SWU at the cost of ecosystem health (Figure 6B). Overall, 17.3% cities in China experienced high-level coupling relation in P2, rising from 11.7% in P1; 81.4% of them were located in the north. This finding indicates that land conversion and expansion of irrigated cropland in the north led to increased water scarcity in the region, exerting negative impact on ecosystem there.

At the basin scale, most river basins in the water-scarce north had the coupled land-water relation. Hai River Basin and Songliao River Basin remained high-level coupling relations in both P1 and P2, which means SWU in these two river basins had been driven by significant expansion of irrigated croplands, which consume large amounts of scarce water. By contrast, Huai River Basin remained at low-level decoupling, meaning that the moderate decrease in scarce water use is accompanied by moderate decline in the extent of irrigated cropland. The land-water relation in Yellow River Basin changed from high-level coupling to low-level decoupling, indicating a reduced tension between irrigation demand and water scarcity. However, the significant expansion of irrigated cropland in Inland River Basin exacerbated the tension between land and water relation, resulting in a shift to high-level coupling from high-level decoupling (Figure 6B).

The leading role of land requirement and grain imports

Figure 3 shows that the increase in land requirement played a prominent role in driving up SWU, with a contribution share of 21.6% during the study period and 17.4% during P1. Although the rising per capita crop consumption (46.7%) and population (6.7%) led to an SWU increase in the decomposition accounting, the dietary structure change, which shifted away from water-intensive rice and wheat (−13.8%) to protein-rich food (fed by soybean and maize), and production efficiency improvement (−17.9%) partially released the water-use stress. Due to the transformation of food consumption patterns in China, the feed demand for soybean and maize will continue to increase in the future. According to the FAO, China's food demands for grains are expected to increase by more than 60% by 2050.[47] This

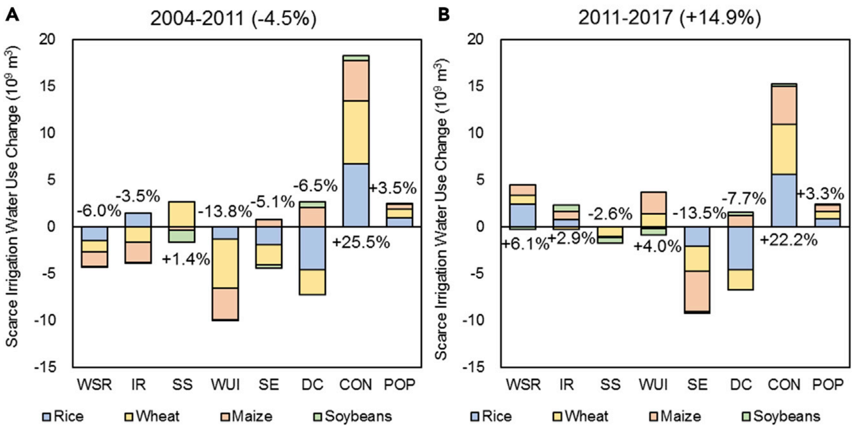


Figure 4. Contribution volumes and shares of decomposition factors of SWU for the four crops

(A) Decomposition results in P1.

(B) Decomposition results in P2. WSR, water scarce ratio; IR, irrigation ratio; SS, self-sufficient ratio; WUI, water use intensity; SE, supply efficiency; DC, dietary structure change; CON, crop consumption per capita; POP, population; LR, land requirement. Equations 8–15 in the experimental procedures present calculation formulae of these indicators.

will lead to an inevitable increase in land requirement, despite the expected improvement in supply efficiency (land productivity) through technological progress[48] and the further shifts of consumption structure may partially mitigate the increasing effect of land requirement.

In addition, international food imports has been proved to be able to partially alleviate the pressure on domestic resources and the environment.[49–51] However, the size of international grain market is small in comparison with China's demand for grains. China's imports of the four crops involved in this study had increased by 3.8 times between 2004, when China became the net crop importer, and 2017.[52] In 2017, grain imports helped China save about 32.5 million hectare cropland, which is equivalent to 24.1% of cultivated land in China, and 17.1 10^9 m^3 blue water, which is equivalent to 8.0% of China's annual irrigation water consumption. The results of our decomposition analysis show that international trade contributed 1.1 percentage points to the total 9.7% decrease in scarce irrigation water from 2004 to 2017 (Figure 3B). Nevertheless, the instability of bilateral trade relation would add uncertainties to the dependence on international markets.[53] In order to ensure national food security, China has maintained a high cereal self-sufficiency rate,[54] with soybeans consumption mainly relying on imports. The self-sufficiency rate of soybean was only 12.6% in 2017–2018.[52] Our analysis shows that even though China had increased the import of agricultural products to relieve the pressure on domestic resources and environment since 2011, the effect of imports in reducing scarce water use was moderate under the circumstance of irrigated cropland expansion in the water scarce north.

DISCUSSION

Building on previous agricultural water use analysis in China, this study expands knowledge in the following four fundamental aspects. Firstly, although the growth of irrigation water use has decelerated due to the reduced water use intensities of irrigation,[22] we show that in terms of SWU, the trend reversed to rising after 2011. Secondly, drivers of irrigation water use in Zhou et al.[22] included change in irrigated area, shift in crop mix, and change in WUI only. Our analysis adds five more drivers at the national level (Figures 3 and 4) and two more at the prefecture level (Figure 5). This addition enables us to discover the contribution share of grain import in curbing water stress in China. Thirdly, thanks to the availability of the unique nationally coordinated survey data on land use to this study, we are able to conduct a more spatially detailed analysis on the relationship between land and water. We have discovered the presence of low-level versus high-level coupling and low-level versus high-level decoupling relationships between scarce water use and irrigated cropland change at both the river-basin and prefecture scales (Figure 6). Fourthly, this categorized analysis of land-water relationship enables this research to evaluate the impact of China's land use policy such as Land Requisition-Compensation Balance policy[13] on SWU more systematically and spatially explicitly, as will be further discussed below.

China has undergone rapid urbanization and industrialization, which compete for high-quality farmland in more developed regions.[55] In response to food security concerns, the central government launched the "toughest" land regulatory regime with the aim to maintain the quantity and quality of cultivated land across China.[56] Cropland requisition-compensation balance system is one of the core policies in China's cultivated land preservation system,[57] which was formally codified in the amended "Land Management Ordinance" of 1998. The policy enforces that within an administrative jurisdiction and for a given period, any area taken out of cultivation must be compensated by reclaiming at least an equal area into cultivation in the same or other jurisdictions.[57,58] According to this approach, if a plot of cultivated land was replaced by non-farming construction, the land developer should reclaim another plot of cultivated land with the same-sized area in an alternative location. Previous studies have found that the implementation of this policy led to the reclamation of marginal cropland for the required compensation, and therefore only a quantitative balance was achieved, resulting in a reduction in the overall farmland productivity and the capacity of carbon storage.[26,57]

Evidence in this study shows that the shift of the irrigated cropland pattern to the northern river basins exacerbated water scarcity in these regions. The high-level coupling relationship between irrigated farmland expansion and scarce water use in most northern river basins largely driven by food security concerns and cropland compensate quota led to the reversal of the national trend in scarce water use from declining to rising after 2011 (Figure 3A). In more detail, the data analysis of this study indicates that 89.5% of the increase in irrigation water use was in the area where the WSI is greater than 0.5, which is the threshold between moderate and severe water stress.[15] The coupling analysis shows that in the relatively water-scarce

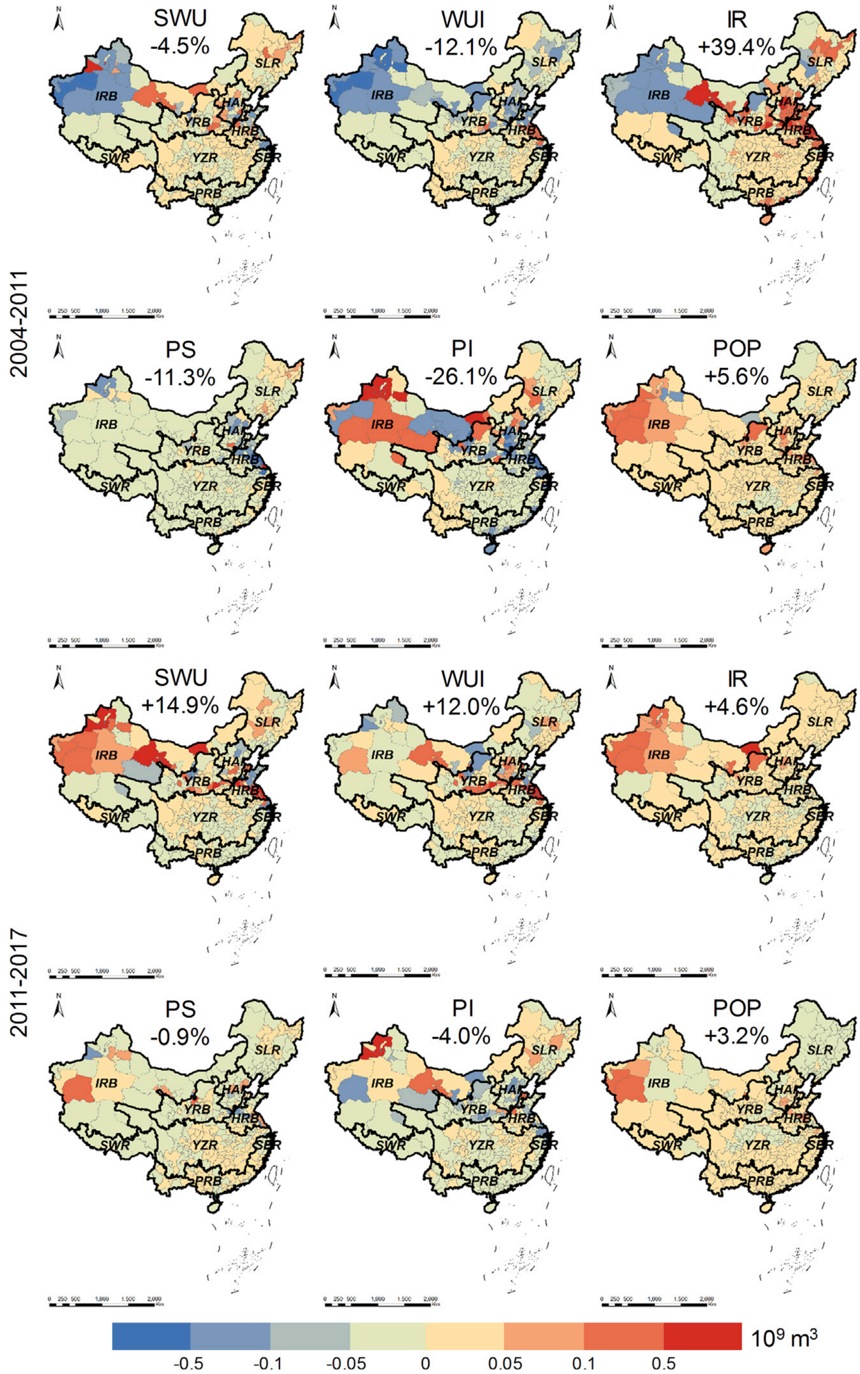
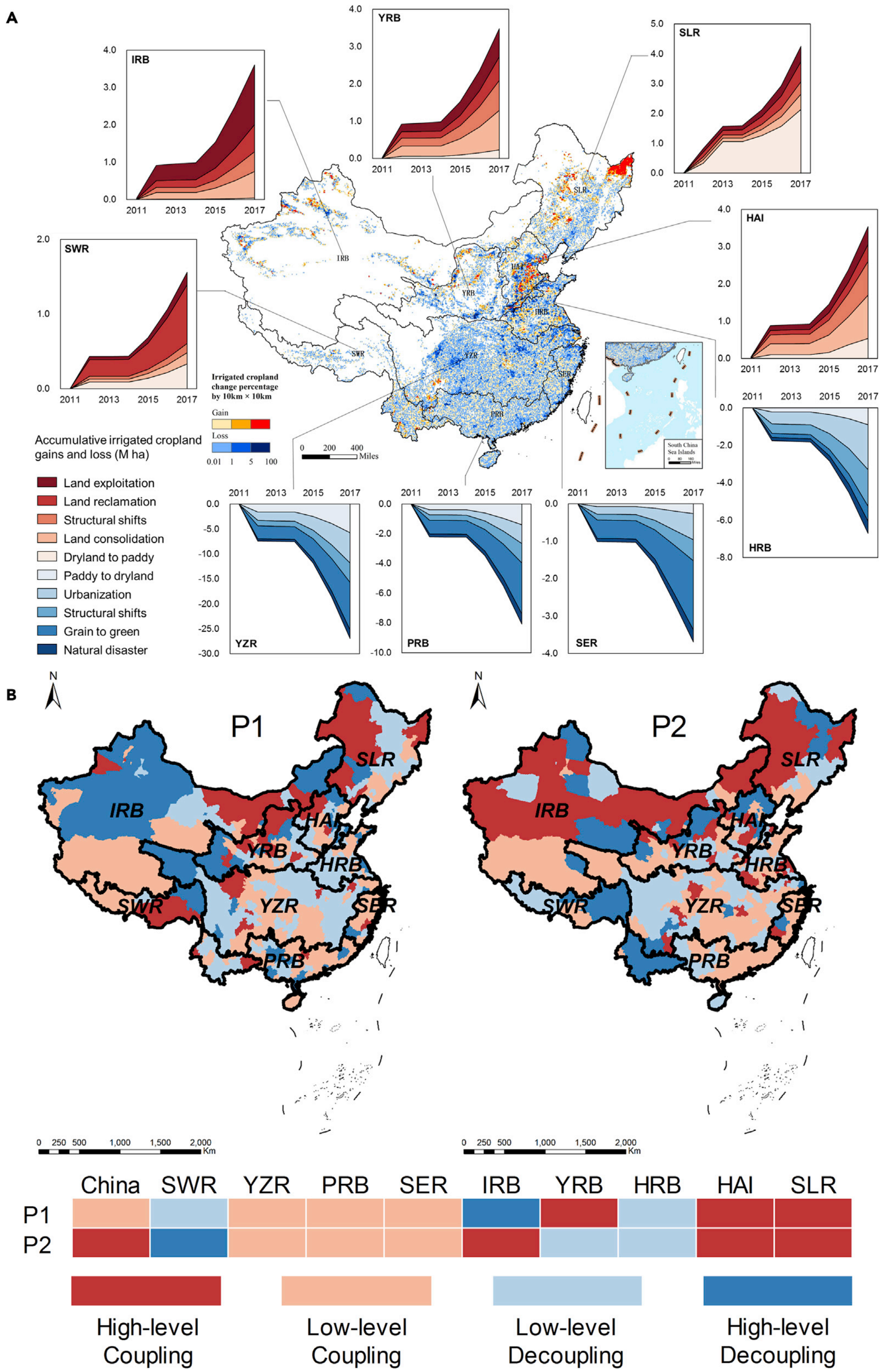


Figure 5. Spatial decomposition of factors for SWU changes at the prefecture level
WUI, water use intensity; IR, irrigated ratio; PS, production structure; PI, production intensity; POP, population.

northern river basins such as Inland River Basin, Hai River Basin, and Songliao River Basin, there was a high-level coupling trend between scarce water use and irrigated cropland, indicating that the increase in scarce water use was largely driven by the expansion of irrigated cropland in these basins (Figures 5 and 6). The results also imply evidence of ground subsidence[59] caused by groundwater over-exploitation in the Hai River Basin. In these areas, excessive use of groundwater for irrigation has caused severe ecological and environmental consequences.[60]

Compared with the conventional perspective of reducing water pressure by optimizing allocation of irrigation water[44] or adjusting domestic planting structure,[33] this study reveals the impact of land use spatial patterns on scarce water use and further explores the possibility of reducing water scarcity through land use control. Following the theory of change, policymakers of cropland protection should pay more attention to the ecosystem impacts, sustainability of compensated cropland and risk levels of regional water scarcity than stringently holding the balance of cropland quantitatively.[61,62] This asks for better-defined guidelines for the implementation of the cropland requisition-compensation balance policy. The guidelines should take into account the level of water scarcity to avoid unsustainable irrigation expansion in water scarce regions and restrict the scale of irrigated land reclamation in areas with severe water scarcity. Moreover, China has recently launched "Soybean Revitalization Plan" with the aim to extend soybean sowing areas and increase the yield of soybean,[63] thus reducing dependence on international market. This plan may put additional pressure on water resources in major soybean growing areas in north and northeast China, and therefore, it is important to promote soybean growing in other parts of China where water is less scarce. Given the condition of severe water shortage in China's breadbasket regions, China needs to actively integrate into the global agricultural market and import agricultural products from areas with comparative advantage in water resources to alleviate water pressure within the country.[64] In addition, China needs to use the WSI as an instrument to facilitate the optimization of the country's planting structure.

Regional water scarcity and irrigation expansion will also be affected by climate change,[65] which generates important uncertainties.[66] Climate warming would change precipitation patterns and affect water resources and irrigation demand across different regions. The northward shift of cropland and irrigated area revealed in this research was also in part attributed to warming in northern China and precipitation increase in



(legend on next page)

Table 1. The water-land relation and coupling principles

	Low level	High level
Decoupling	SWU increases but IRC decreases: it is not a favored case in which the area of irrigated croplands is shrinking but the irrigation water use efficiency is worsening	SWU decreases but IRC increases: it is the preferred case in which the expansion of irrigated cropland is associated with significant improvement in irrigation water use efficiency
Coupling	both SWU and IRC decrease: the situation is good for ecosystem but may not be favored in terms of satisfying supply requirement	both SWU and IRC increase: the situation is good for increasing crop production but may not be favored in terms of ecosystem impacts

northwest China in last few decades. A recent study[67] using UK Met Office's regional climate model PRECIS (Providing Regional Climates for Impacts Studies), which is capable of capturing complex topography and land surface characteristics at a 25 × 25 km resolution, indicated precipitation increases in every region of China, most significantly in the northwest and southeast. If this set of projections comes true, the tension between scarce water use and farmland expansion would be reduced in the future. However, whether the blue water scarcity in China will be really alleviated under future climate change and how effective land management strategies can be implemented to adapt to the climate-induced blue water scarcity are still uncertain and should be a focus of future research.

Some limitations of this study are worth mentioning. Firstly, due to the fact that the survey data for irrigation water use at the prefecture level were up to 2013, the average WUI of 2011–2013 is used to estimate irrigation water consumption for 2014–2017. Nevertheless, this data compromise does not affect the trend of irrigation water use in each region, and in addition, we employ the GEPIC model to control the influence of the WUI per crop over these years to overcome the limitation of data. Secondly, because fewer data are available at the prefecture level, the decomposition factors and effects at the national and prefecture scales are different. However, the trends of changes and impacts are consistent.

Conclusions

By incorporating the WSI into the water footprint accounting at the prefecture level in China, this study found that China's agricultural use of scarce water experienced fluctuating decline over 2004–2011, then reversed to rapid increase after 2011. At the national aggregation, though the consumption structure shifts (−13.8%) and improvement of supply efficiency (−17.9%) helped reduce the increasing effects of land requirement, and grain imports directly contributed to the alleviation of the national water pressure (−1.1%), changes in the WSR, WUI, and IR still led to the rising of SWU in China after 2011.

The decomposition analysis at the prefecture level indicates that the 14.9% increase in SWU during P2 was mainly driven by Hai River Basin and Inland River Basin, contributing 7.7 and 6.0 percentage points, respectively. WUI and IR are two dominant drivers in these two basins. Both the SWU decrease in P1 and increase in P2 are mainly determined by the corresponding dynamics in the water-scarce northern river basins. This means that effective management of water consumption in the water-sensitive northern river basins is crucial for relieving the pressure on scarce water in China. In addition, the persistent high-level coupling between scarce water use and farmland expansion in these regions highlights the issue of spatial imbalance of land versus water use.

The findings of the study have the following implications for mitigating agricultural water scarcity in China. (1) It is highly desirable for China to actively participate in the global trade and import water-intensive agricultural products from countries/regions with comparative advantage in water resources. (2) It is necessary to upgrade the guidelines for the implementation of the cropland requisition-compensation balance policy with due attention to the water scarcity level across different jurisdictions. (3) It is important to incorporate land control measures such as territorial spatial planning with ecosystem preservation policy to avoid the ecological externalities of farmland expansion. Despite the deceleration of China's agricultural water use, the expansion and spatial shifts of irrigated cropland to water-scarce regions drove the rising scarce water ecosystem impact, which overwhelmed the water use alleviation of increasing agricultural imports. China's Land Requisition-Compensation Balance Policy attempts to quantitatively keep the total extent of cropland stable so as to ensure national food security, and the evidence provided in this study highlights the urgency of incorporating ecological impacts into the assessment of national land management policies.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Kuishuang Feng (kfeng@umd.edu).

Materials availability

This study did not generate any new materials.

The GEPIC model for consumptive water use

In this research, we used the GIS-based Environmental Policy Integrated Climate (GEPIC) model[68] to simulate total water consumption which contains both blue and green water for main agricultural crops at the grid-cell level, and the grid resolution is 5 arc-minutes. The GEPIC model is designed to simulate the spatial and temporal dynamics of the major processes of the

Figure 6. Changing pattern of irrigated cropland and coupling results from irrigated croplands change and SWU change

(A) Irrigated cropland change in China from 2011 through 2017. For a river basin that experienced a net increase in irrigated cropland, we presented the source structure of the increase in an area chart. For a river basin that experienced a net decrease in irrigated cropland, we presented the destination structure of the decrease in an area chart.

(B) Changes in the land-water coupling and decoupling relations at multi-level in China from 2004 through 2017 (Table 1).

soil-crop-atmosphere-management system, which has been used to calculate water consumption in agriculture at the global, national and regional scales and the model has been used in several studies focusing on water research in China.[69] Detailed simulation processes of the GEPIC model are available in Liu and Yang.[68] The input data consist of GIS raster maps of crop-specific land use, elevation, slope, irrigation, fertilizer application, climate, and soil data. The output are raster GIS maps of crop yield and evapotranspiration for both rainfed and irrigated agricultural systems. The original validation processes in Liu and Yang[68] were conducted through comparing output yield with the statistical national average yields from FAO. The simulated yields and the statistical yields are quite comparable, as indicated by high and statistically significant R^2 values (ranged from 0.6 to 0.95 for wheat, maize, and rice) and F-tests (the p values are all higher than 99%). The GEPIC mode has been widely applied and regarded as a mature model nowadays. In our application of the GEPIC model to the Chinese context, the uncertainties of the simulated water consumption can be attributed to the following three assumptions. Firstly, irrigation is not applied in non-growing periods because there are no data on irrigation for land preparation. Secondly, in the GEPIC setting, irrigation and fertilizer application are specific to a few major crops only and it is impossible to take weeds and intercropping into account. This may lead to underestimation of consumptive water use in irrigation. Thirdly, flood irrigation was used for all irrigated crops for all regions, meaning that variations in irrigation methods (e.g. surface, sprinkler, sub surface, micro) were not considered.

Specifically, total water consumption calculations of this study were focused solely on the agricultural growing season, which was concerned with the actual water consumption by agricultural output. In order to match the land and water survey data in the prefecture level, we first matched grid level data with prefecture-level unit and then aggregated water consumption data into 9 river basins (Figure S1)."

WSI and scarce water use accounting

The WSI is commonly defined as the ratio of total annual freshwater withdrawals to hydrological availability.[70] Pfister et al.[15] proposed a standardized WSI in 2009, ranging from 0 (no stress) to 1 (maximum stress), to represent commonly accepted thresholds for water stress levels. This standardized index has been frequently used for water scarcity analysis since then.[16] In this study, we applied Pfister et al.'s method to calculate WSI for each prefecture in China. The WSI is obtained at each of 50 km grid cells (0.5 arc minutes resolution). The prefectural WSI is calculated from the average value of all grid cells within the prefecture boundary (Figure S1), weighted by the respective water consumption in each cell. The irrigation water use in each prefecture is then multiplied by the prefectural WSI to derive prefectural SWU. In this study, annual WSI was calculated based on water resources survey data from 2004 to 2017. To control the impact of extreme drought and wet years on WSI, we use the average WSI from 2004 to 2017.

Calculation of net virtual land use embodied in international trade of crops

In order to detect the impact of international crop trade on scarce water use in China, we introduced the notion of virtual land to represent the cropland use embodied in food trade.[71,72] This study uses country- and crop-specific yield data to identify virtual land imports and exports embodied in the trade flows.

For imports, the virtual land use of a primary product is calculated with the yield data based on each origin country, so the virtual land import of the crop i from country j is as follows:

$$VLI = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{I_{i,j}}{Y_{i,j}} \qquad \text{(Equation 1)}$$

where VLI is the virtual land import, $I_{i,j}$ indicates China's import quantity of crop i from country j, and $Y_{i,j}$ presents the yield of the primary crop i in country j. The virtual land use of export is calculated by domestic yields and can be expressed as follows:

$$VLE = \sum_{i=1}^{n}\frac{E_i}{DY_i} \qquad \text{(Equation 2)}$$

where VLE is the virtual land export, E_i indicates China's export quantity of crop i from domestic production, and Y_i presents the yield of the primary crop i in China. The net virtual land use (NVL) embodied in international food trade can be expressed as follows:

$$NVL = VLE - VLI \qquad \text{(Equation 3)}$$

LMDI decomposition analysis

The Logarithmic Mean Divisia Index (LMDI) initiated by Ang et al. (1998) was employed to analyze the driving force of changes in Chinese agricultural water footprint. LMDI has the advantage of zero residual errors.[73] In previous study, crop irrigation water consumption has been shown to be highly related to factors such as changes in sowing area, crop structure, and WUI.[22] In this study, we focused on crop irrigation water use scarcity, so we introduced WSR and IR into the decomposition. Additionally, international food trade has been proved to compensate water resource deficiency for China,[74] as increasing import of water intensive crops can alleviate the pressure of domestic water use. Therefore, in this study we take the measurements of self-sufficiency and land requirement into consideration. Overall, the changes in the Chinese SWU are decomposed into the effects of crop mixture, irrigation management, food trade, total demand, and water use efficiency. The following decomposition formulae describe the total SWU at the national level (Equation 4) and prefecture level (Equation 5).

$$SW_N = \sum_i WUI_i * \frac{SWU_i}{IRR_i} * \frac{IA_i}{SA_i} * \frac{SA_i}{LR_i} * \frac{LR_i}{CON_i} * \frac{CON_i}{CON} * \frac{CON}{POP} * POP \qquad \text{(Equation 4)}$$

$$SW_P = \sum_i WUI_i * \frac{SWU_i}{IRR_i} * \frac{IA_i}{SA_i} * \frac{SA_i}{SA} * \frac{SA}{POP} * POP \qquad \text{(Equation 5)}$$

Where SW_N and SW_P denote the scarce water use for crop irrigation at the national and prefecture levels, respectively; WUI_i denotes irrigation water-use intensity of crop i; SWU_i denotes scarce water use of crop i for the whole country (Equation 4) or prefecture (Equation 5); IRR_i denotes irrigation water use of crop i for the whole country (Equation 4) or prefecture (Equation 5); IA_i denotes irrigated area of crop i; SA_i denotes sowing area of crop i; LR_i denotes land requirement of crop i, which equals sowing area plus net import of virtual land; CON_i denotes total consumption of crop *i*; *CON* denotes total consumption of the four crops (wheat, rice, maize, and soybean); and *POP* denotes the total population of China or the prefecture. Because data on food trade and the total consumption of the four crops are not available at the prefecture level, the decomposition at the prefecture level includes six factors, with *SA* denoting sowing area of all four major crops.

Thus, the additive decompositions of LMDI were as follows:

$$\begin{aligned}\triangle SW_N &= \triangle {SW_N}^T - \triangle {SW_N}^{T-1} \\ &= \triangle WUI + \triangle WSR + \triangle IR + \triangle SS \\ &+ \triangle SE + \triangle DC + \triangle CON + \triangle POP\end{aligned} \quad \text{(Equation 6)}$$

$$\begin{aligned}\triangle SW_P &= \triangle {SW_P}^T - \triangle {SW_P}^{T-1} \\ &= \triangle WUI + \triangle WSR + \triangle IR + \triangle PS + \triangle PI + \triangle POP\end{aligned} \quad \text{(Equation 7)}$$

Where SW^T and SW^{T-1} are the scarce irrigation water use during the period of *T* and *T-1*, respectively. *WUI* denotes irrigation water-use intensity which captures the effects of irrigation efficiency; *WSR* denotes water scarce ratio, which mainly captures the effects of crop mixture (more versus less irrigation-demanding crops); *IR* denotes the irrigation ratio, which captures the effects of irrigation infrastructure development and management; *SS* denotes self-sufficiency, capturing the effects of international food trade; *SE* denotes supply efficiency, capturing the effect of supply-demand gap in terms of land requirement versus total consumption; *DC* denotes dietary structure capturing the effect of shift in crop composition of consumption; *CON* denotes per capita total consumption of the four crops; and *POP* denotes population. In Equation 7, *PS* denotes crop composition of production, and *PI* denotes production intensity. The degree to which each effect contributes to the change in the SWU of crop production was estimated by the following Equations 6–10, where *i* denotes crop *i*:

$$\triangle WUI = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{WUI^T}{WUI^{T-1}} \quad \text{(Equation 8)}$$

$$\triangle WSR = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{WSR^T}{WSR^{T-1}} \quad \text{(Equation 9)}$$

$$\triangle IR = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{IR^T}{IR^{T-1}} \quad \text{(Equation 10)}$$

$$\triangle SS = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{SS^T}{SS^{T-1}} \quad \text{(Equation 11)}$$

$$\triangle SE = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{SE^T}{SE^{T-1}} \quad \text{(Equation 12)}$$

$$\triangle DC = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{DC}{DC^{T-1}} \quad \text{(Equation 13)}$$

$$\triangle CON = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{CON^T}{CON^{T-1}} \quad \text{(Equation 14)}$$

$$\triangle POP = \sum_i \frac{SW_i^T - SW_i^{T-1}}{\ln SW_i^T - \ln SW_i^{T-1}} \ln \frac{POP^T}{POP^{T-1}} \quad \text{(Equation 15)}$$

Quantifying the water-land relation

In this study, we focused on the impact of land use change on water consumption. Therefore, two spatially-explicit indicators, irrigated cropland (IRC) and total scarce water use (SWU) for crop production at the prefecture level, were constructed to detect the "land-water" relations. In this context, the spatial heterogeneities of changes in these two indicators can be regarded as the consequences of cropland conversion in China. IRC includes both paddy rice and irrigated field with irrigation equipment/infrastructure. In this setting, changes in SWU captures the water impacts of cropland conversion. In other words, the cropland conversion not only reshapes landscape of crop production but also affects the coupling/decoupling relations between cropland and total scarce water consumption as presented in Table 1 at the national and prefectural levels of China.

Data description

For our analysis the four crops of rice, wheat, maize and soybeans were selected because the total production of these four crops accounted for 93.7% of all grains in China.[75] The basic geographic data are from the Chinese Academy of Sciences, and supplemental information Section S1 presents details of their sources and consolidation procedures. The land use data were collected from the first and second Land Resource Survey led by the Ministry of Natural Resource, which has been used to test the classification accuracy of remote sensing data.[76] Section S2 (Figures S2–S4) presents the method to consolidate these two rounds of national land survey. Irrigated cropland is the sum of paddy field and irrigated land. The data of irrigation water use by subsector and prefecture were obtained from two nationally coordinated surveys led by the Ministry of Water Resources, which was shared by Zhou et al.[22] The total water use data containing both blue and green water in a resolution of 5 arc-minutes were a product of the GEPIC model discussed above. The data of the WSI developed by Pfister et al.[70] were downloaded from http://archive.baug.ethz.ch/www.ifu.ethz.ch/ESD/downloads/Monthly_WSI.html. This study aggregates the monthly average WSI from the resolution of 50 km into the 341 prefectures (Section S1). Crop yield, sowing area, and population in China were collected from the China Statistical Yearbook (http://www.stats.gov.cn/). The prefecture level crop yield, sowing area, and population were collected from the Statistical Yearbook of each city. And the international crop trade data were collected from the FAOSTAT (http://www.fao.org/faostat).

Data and code availability

Data for the main results of this study are provided at https://doi.org/10.5281/zenodo.7109682.This paper does not report the original code. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.09.008.

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AUTHOR CONTRIBUTIONS

Conceptualization, X.Q. and K.F. Methodology, X.Q., Z.L., D. Zhang, and D. Zhao. Investigation, K.F. and X.H. Writing – original draft, X.Q.; Writing – review & editing, L.S., G.B., and K.F. Funding acquisition, X.Q. and X.H. Supervision, K.F., L.S., and X.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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