Balancing water resource conservation and food security in China

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China's economic growth is expected to continue into the next decades, accompanied by sustained urbanization and industrialization. The associated increase in demand for land, water resources, and rich foods will deepen the challenge of sustainably feeding the population and balancing agricultural and environmental policies. We combine a hydrologic model with an economic model to project China's future food trade patterns and embedded water resources by 2030 and to analyze the effects of targeted irrigation reductions on this system, notably on national agricultural water consumption and food self-sufficiency. We simulate interprovincial and international food trade with a general equilibrium welfare model and a linear programming optimization, and we obtain province-level estimates of commodities' virtual water content with a hydrologic model. We find that reducing irrigated land in regions highly dependent on scarce river flow and nonrenewable groundwater resources, such as Inner Mongolia and the greater Beijing area, can improve the efficiency of agriculture and trade regarding water resources. It can also avoid significant consumption of irrigation water across China (up to 14.8 km^3/y, reduction by 14%), while incurring relatively small decreases in national food self-sufficiency (e.g., by 3% for wheat). Other researchers found that a national, rather than local, water policy would have similar effects on food production but would only reduce irrigation water consumption by 5%.

virtual water | food trade | trade policy | sustainable agriculture | water saving

China's geographic mismatch between its arable land and water availability has led to unsustainable agricultural expansion in dry areas, further supported by food self-sufficiency objectives. In particular, Inner Mongolia (in the Yellow River basin) and the greater Beijing area (Beijing, Tianjin, and Hebei provinces, in the Hai River basin) are suffering increasingly severe water scarcity. Major associated environmental issues include soil degradation, water resource overexploitation and pollution, and land subsidence from groundwater overdraft, threatening both ecosystems and human activity (1). Current solutions to water scarcity are focused on sustaining existing activities; for example, the South to North Water Transfer (SNWT) project will increase water supply in the north through physical transfers. However, China's agricultural and water resources strategies could change. The country recently increased its trade openness significantly [e.g., soy imports (2)], and major policy plans, in addition to supporting sustainable agriculture (3), newly emphasize land conservation and reduction of groundwater use as water-saving strategies (4). Quantifying the effects of targeted agricultural water conservation measures will both allow for comparison with current water-saving solutions and inform policy-makers of the trade-offs between environmental conservation and food self-sufficiency. Here, we estimate multiple effects of targeted water conservation efforts, notably on food self-sufficiency, by integrating agricultural production, water resource use, and domestic and international food trade.

We project China's future food trade and embedded water resource transfers (i.e., virtual water trade; VWT) and analyze the effects of reducing irrigated areas, concentrating on the dry regions of Inner Mongolia and the greater Beijing area. Elliot et al. project that freshwater limitations in regions of China could require conversion of cropland from irrigated to rainfed by the end of the century (5). We explore here the effects of reducing irrigated cropland in areas with particularly scarce water resources. We previously identified Inner Mongolia as a target for water-use efficiency improvements in China, because of its large crop production with particularly low water productivity (6). The region's surface and groundwater resources are further threatened by projected droughts (7) and by the development of the water-intensive coal industry (8, 9), which also affects river flow into more water-productive (6), important food-producing provinces downstream (10). In addition, growing industrial and domestic demand will very likely worsen water scarcity in the greater Beijing area, which represents the largest urban region in arid Northern China (11, 12) and sources 70% of its water withdrawals (i.e., 20 km^3/y) from the North China Plain aquifers, one of the most quickly depleting groundwater systems in the world (13, 14). We previously found that China's domestic food trade induced irrigation water losses (6), reflecting that provinces with relatively lower irrigation water productivity, such as Inner Mongolia, export to areas with higher productivity. The efficiency of trade regarding water resource consumption at a global level is referred to as trade-induced water savings (WS).

We address the following questions: How will future socioeconomic changes affect China's food trade and associated water transfers? To what extent can localized reductions in irrigated area decrease agricultural water use while maintaining grain self-sufficiency? How would these strategies affect China's domestic and international VWT flows and trade-induced WS?

Significance

Agriculture represents the largest water-consuming sector in China, while industry and cities are growing competitors. To sustain a rapidly increasing population with richer diets, high levels of food production have come at significant environmental costs, such as groundwater overdraft and soil degradation. As socioeconomic growth and the associated pressure on water resources continue to increase, it is crucial to evaluate the effects of water-saving measures on agriculture, food trade, and water resources. This article estimates China's future food trade patterns and associated water transfers and quantifies the effects of targeted irrigated land reductions on water consumption and food self-sufficiency, accounting for production displacement and local water productivity. Our findings provide important insights to policy-makers on trade-offs between environmental and agricultural objectives.

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We use socioeconomic projections and an economic model to assess the future state of China's agricultural supply and demand, including domestic and foreign food trade. A detailed description of the baseline (BL) scenario used for these projections, which includes increasing urbanization, population, and economic growth, is provided in the *SI Appendix*. We then apply a hydrologic model to estimate water resources embedded in the produced and traded food. Next, we quantify the effects of two agricultural scenarios on China's VWT network and on the efficiency of food trade in terms of water resources. The first scenario (IM) reduces irrigated land area in Inner Mongolia by 50% in 2020 and 2030, relative to BL. The second scenario (IM+B) simultaneously reduces irrigated land in Inner Mongolia and in the greater Beijing area by 50% in 2020 and 2030, relative to BL. We adapt inputs of both the economic model and the hydrologic model accordingly, to estimate the effects of these two scenarios on China's agricultural trade and embedded water resources.

Analysis of the scenarios' effect requires economic and hydrological modeling tools that adequately account for input changes (e.g., shift in irrigated land area affects food price, production in other locations, and international imports). Most existing studies of China's VWT have used input–output methods to estimate current trade patterns (8, 15). In contrast, computable general equilibrium models offer larger flexibility, in particular in the face of changes in the supply side (16), making this type of model more suitable for an accurate study of the scenarios' effect. Here, we combine the CHINAGRO applied general equilibrium model (17) and the H08 hydrologic model (18) to build the Chinese domestic and foreign VWT network in each scenario (BL, IM, and IM+B). We combine provincial crop and livestock's virtual water content (VWC; water resources consumed for agricultural production) estimates from the H08 global hydrologic model (19) (*Materials and Methods*) with detailed interregional food trade simulations from the CHINAGRO general equilibrium welfare model [eight regions (17)], downscaled to the interprovincial level (31 provinces; *Materials and Methods*). We take into account "green" (i.e., soil moisture) and "blue" (i.e., rivers, reservoirs, and groundwater) sources of water and seven major crops and livestock products (i.e., corn, rice, soy, wheat, ruminant meat, pork, and poultry). These products accounted for about 93% of China's domestic food calorie supply in 2005 (Food and Agriculture Organization of the United Nations, faostat3.fao.org).

Agriculture is a key sector in which to apply water-saving strategies, as it drives most water withdrawals across the globe [59% on global national average, 65% in China (20)]. Previous work has focused on the effect of water shortages on future food production (21). In contrast, we analyze the effects of adjustments in agricultural production on water resource use and food trade. Yang and Zehnder first proposed international grain imports as a solution to China's water scarcity (22), and further analysis of the role of VWT would help inform the trade-offs between food security and environmental integrity (23, 24). Although large infrastructure investments are devoted to improving irrigation water use efficiency in China (25), potential improvements are unlikely to compensate for food production loss in a low groundwater use scenario (24), showing the importance of trade-offs between food self-sufficiency and water conservation.

In this analysis, we focus on particularly water-scarce areas of China that have high potential water savings relative to associated decreases in food production when removed from cultivation. We integrate here, for the first time, provincial production with detailed interprovincial and foreign trade to analyze the effects of a local agricultural production change on the entire water consumption and food supply system, focusing on the three main questions identified earlier.

Results

Future Food and Virtual Water Trade. We find that virtual water transfers through China's agricultural trade will significantly intensify by 2030 (Fig. 1), as the volumes involved will almost double, going from 239 km^3 in 2005 to 445 km^3 in 2030 (86% increase). This growth is mostly driven by a rise in international food imports, corresponding to foreign virtual water imports increasing from about 49 km^3 in 2005 to 137 km^3 in 2030. Domestic food trade and associated virtual water transfers are expected to increase less significantly, going from 183 to 201 km^3, including exports from dry provinces such as Inner Mongolia and Xinjiang (from 13.4 to 16.7 km^3 and 8.3 to 11.6 km^3, respectively). Thus, international virtual water imports are projected to account for a larger share of China's total VWT (about 30% in 2030 vs. 20% in 2005).

As food trade intensifies over time, we find that associated trade-induced WS rise from 47 km^3 to more than 70 km^3, mainly as a result of increased imports of foreign commodities, which are made relatively more water-productively than in China. However, some inefficiencies due to exports from provinces with low agricultural water productivity relative to their trade partners will worsen with time. For example, exports from Inner Mongolia, the most inefficient trade flows, are projected to induce 6.4 km^3 of blue water losses (i.e., negative WS, accounting for blue water sources alone) in 2030 versus 5.4 km^3 in 2005 (Fig. 1).

Effects of Targeted Irrigation Reductions on Water Resources and Food Self-Sufficiency. When irrigated land area in both Inner Mongolia and the greater Beijing area is reduced by half (IM+B scenario), national corn and wheat production decreases by only 4.3% and 4.5%, respectively (*SI Appendix*, Table S2), whereas production reduction in the four provinces alone corresponds to a 4.6% and a 5.5% drop in national production, respectively. Indeed, higher crop prices (resulting from the reduced supply) increase production in other provinces, which compensates for part of the local decline. These local decreases mainly concern corn (in Inner Mongolia and Hebei) and wheat (mostly in Hebei) production. However, the national decrease in soy production (0.4% in the IM scenario) is even greater than the reduction imposed in Inner Mongolia (0.3% of national soy production). Because Chinese soy is poorly competitive on world market, the price increase only enhances international imports, not production in other Chinese provinces, as observed for other crops.

Even as crop production increases in provinces other than Inner Mongolia and the greater Beijing area, the net effect of the reductions in irrigated land is a decrease in China's water consumption. Remarkably, 14.8 km^3 of blue water consumption is avoided in scenario IM+B relative to BL (14% decrease in China's agricultural blue water consumption), including 6.2 km^3 in the greater Beijing area (47% decrease in agricultural blue water consumption) and 5.2 km^3 in Inner Mongolia (43% decrease in agricultural blue water consumption; Table 1 and *SI Appendix*, Tables S4 and S5). This saved water resource represents about a third of the total annual water transfer projected for 2050 via the SNWT scheme. These direct water savings come at the cost of a relatively small drop in China's food self-sufficiency (Table 1 and *SI Appendix*, Tables S2 and S3). We define the self-sufficiency ratio of a commodity as production divided by the sum of production and net international imports (26). The largest change in self-sufficiency affects corn, with a 1.8 and 3.6 percentage point decrease in IM and IM+B scenarios, respectively. The corn self-sufficiency ratio thus decreases only from 86.1% at the BL to 84.3% and 82.4% in the IM and IM+B scenarios, respectively (Table 1).

Effects of Targeted Irrigation Reductions on Virtual Water Trade and Its Water-Efficiency. As food production and trade patterns shift due to decreased irrigated land areas (in the IM and IM+B scenarios), we observe three major effects on VWT flows (Fig. 2). First, a 30% decrease in virtual water exports from the net exporter Inner Mongolia in the IM scenario; second, a 5% increase in virtual water imports by the greater Beijing area (a net importer) in the IM+B scenario; and third, an increase in China's foreign virtual water imports of 2% and 6% from BL to IM and IM+B, respectively.

In both IM and IM+B scenarios, irrigation-intensive commodity exports from Inner Mongolia decline, and corresponding

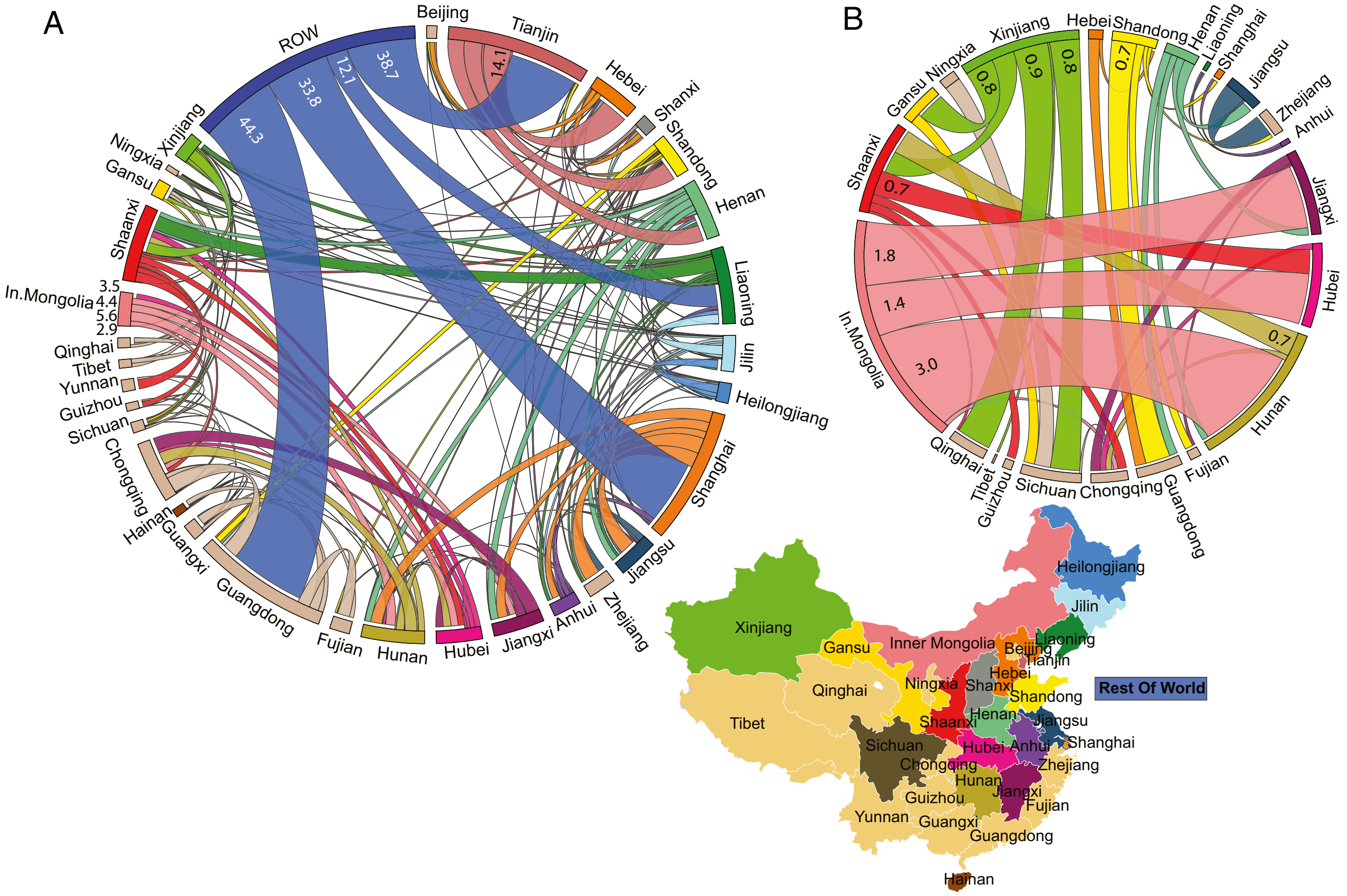

Fig. 1. VWT between Chinese provinces and the ROW (*A*, 445 km^3) and trade-induced losses of blue water—from rivers, reservoirs, and aquifers—(*B*, 16.9 km^3) in 2030 under the BL scenario. Numbers indicate the volume of water in cubic kilometers, and the link color corresponds to the exporting province. The map at the lower right provides a key to the color scheme. Note that China's international imports account for 30% of all VWT. Inner Mongolia exports induce the largest blue water losses across provinces (6.4 km^3). These graphics are created using a network visualization software (44).

virtual water exports are reduced by 5 km^3, accounting for ~3% of all VWT flows in the BL scenario by 2030 (Fig. 2*A*). In 2030, Inner Mongolia is displaced from the third (in BL) to the eighth (in IM) and ninth (in IM+B) top agricultural exporter (*SI Appendix*, Tables S8–S10). As this province uses significantly more irrigation per unit crop than others (i.e., high blue VWC; *SI Appendix*, Table S8), this export decline improves the efficiency of food trade in terms of water resources. We observe that these local changes also have significant indirect effects on China's domestic and international VWT, such as an increase in foreign virtual water imports by Liaoning and Shanghai, redistributed to Shaanxi and then to Hunan/Hubei (previously supplied by Inner Mongolia) and Zheijang (previously supplied by Jilin; Fig. 2 *A* and *B*).

In the IM+B scenario, in which irrigated land of the greater Beijing area is also reduced by half, we observe an increase of 3.1 km^3 in virtual water imports by this area, relative to BL in 2030 (Figs. 1 and 2 *C* and *D*). This corresponds to the volume of water embedded in additional domestic and international food imports, required to fill the gap left by a decrease in agricultural production in that location. Importantly, this volume is smaller than the direct blue water savings (avoided irrigation water consumption) gained from reducing irrigated land (Table 1), leading to a net reduction of water consumption at the national level. Production is thus displaced from the greater Beijing area to more water-productive regions in China and the rest of the world (ROW), resulting in enhanced water efficiency of food trade. Importantly, corresponding reductions in water withdrawals for agriculture are even larger than the reductions in irrigation water consumption presented here, as they include avoided water losses through distribution systems [average loss rate is 55% in China (27)].

This enhanced water efficiency of food trade is particularly observed for blue water resources (*SI Appendix*, Fig. S1). Indeed, blue WS induced by domestic trade of local goods increase from −2.4 km^3 (5.4 km^3 for all water sources) in BL to 0.4 km^3 (5.0 km^3 all sources) in IM and to 0.4 km^3 (5.5 km^3 all sources) in IM+B. Blue WS from both domestic and foreign food trade rise from 38 km^3 in BL (71.6 km^3 all sources) to 41 km^3 (7% increase) in both IM and IM+B (71.2 km^3 and 71.8 km^3 all sources, respectively) (*SI Appendix*, Fig. S1).

We observe the effect of reduction in irrigated crop production in Inner Mongolia (IM scenario) through the reduced water losses induced by Inner Mongolian food exports: 3.0 km^3 of blue water losses versus 6.4 km^3 in the BL in 2030 (*SI Appendix*, Fig. S2). These losses are lowered back below the 2005 level (i.e., 5.4 km^3). Agricultural trade becomes more efficient regarding irrigation water resources, with 3 km^3 additional savings, mostly resulting from corn trade shifts (*SI Appendix*, Fig. S1) and decreased exports from Inner Mongolia (Fig. 2).

Discussion

Although foreign imports are projected to account for a larger share of China's future VWT, water-inefficient trade flows, originating in low-water-productive and dry regions, are expected to increase (Fig. 1). This further supports the need to explore additional domestic strategies to cope with water scarcity.

To increase production per unit water withdrawn, agricultural water supply-side options include improving water-use efficiency

Table 1. Differences in irrigation water consumption (all products combined), by area, and in China's self-sufficiency ratios for three major crops, for IM and IM+B scenario, relative to BL (year 2030)

Scenario and area	Δ Irrigation water consumption, km^3	Δ Corn self-sufficiency ratio, percentage points	Δ Wheat self-sufficiency ratio, percentage points	Δ Soy self-sufficiency ratio, percentage points
IM				
Inner Mongolia	−5.2			
China	**−7.7**	−1.8 [84.3%]	−0.3 [97.9%]	−0.2 [21.4%]
IM+B				
Inner Mongolia	−5.2			
Beijing	−0.2			
Tianjin	−0.3			
Hebei	−5.7			
China	**−14.8**	−3.6 [82.4%]	−3.0 [95.2%]	−0.7 [20.9%]

Numbers in brackets indicate the self-sufficiency ratio in each scenario, and those in bold font highlight national changes in irrigation water consumption. Note that in the IM+B scenario, about 15 km^3 of freshwater are saved (14% decrease in irrigation water consumption) without significantly altering China's food self-sufficiency (by 4.2% for corn, the largest relative decrease).

(consumption by plants over withdrawal) and crop water productivity (plant yield over water consumption, inverse of VWC) (28), whereas demand-side strategies can range from incentives such as water pricing to policies focused on limiting groundwater overdraft. Future scenarios of possible coping strategies for water scarcity have been analyzed, including water pricing and reduction of groundwater overdraft globally (24) and in nine of China's water basins (29). Water pricing affecting all sectors in China has been projected to reduce consumption of irrigation water by about 16% by 2025, and to be associated with a 4% decrease in irrigated cereal production (24). These changes are comparable to the effects on consumption of irrigation water and land use change estimated in this article's IM+B scenario (*SI Appendix*, Tables S2 and S4). In addition, strong limitations on groundwater withdrawal were estimated to lead to a 3% decrease in China's cereal production and a 4% decrease in irrigated area (24). Our IM+B scenario, corresponding to a comparable land use change, similarly affects China's cereal production in 2030. However, we find a larger decrease in irrigation water consumption (by about 14%, vs. 5% in ref. 24). This suggests the geographic focus of our scenario (e.g., Inner Mongolia, with low VWC) leads to the expected effects: greater water savings per unit of avoided food production. This comparison shows our results are quite robust with regard to varying socioeconomic and agricultural projections. More studies would be needed to assess a comprehensive range of possible effects of future scenarios.

Direct measures, for example, important water transfer projects, have been adopted to release pressure on scarce resources while maintaining current agricultural output in China. The total transfer projected through the SNWT scheme by 2050 (45 km^3/y) is about three times the volume saved in the IM+B scenario relative to BL. However, providing more water to these regions with both scarce resources and inefficient use may encourage the development of wasteful water-intensive activities in dry areas (30), thus failing at improving environmental sustainability. In addition, the SNWT canals will not provide resources to the driest agricultural lands in Northwest China, where the coal industry and agriculture compete for increasingly scarce water resources. Finally, long-distance water transfers have serious socioeconomic and environmental costs, such as population displacement, in addition to important benefits (31).

We showed that reducing irrigated land in Inner Mongolia and the greater Beijing area would save water nationally. In addition to conserving surface and groundwater resources, reducing irrigation in these regions would also benefit the local environment. Indeed, irrigation in arid lands can reduce crop yields by increasing soil salinity (32), and continued groundwater overdraft hinders a sustained availability of fossil water, threatening both socioeconomic activities and ecosystems. These issues are of particular concern in North China, where, even though mining of renewable and nonrenewable water resources supports economic activities in the short term (33), there is an urgent need to reduce groundwater use (33, 34).

Grain self-sufficiency is historically a central political issue in China [a 95% target was set in 1996 (35)], but increasing food demand and limited available resources have induced a decreasing trend in self-sufficiency and led to less-constraining recent policies [a "high rate" target in 2013 (4)]. In the scenarios studied, China's corn and wheat self-sufficiency would decrease from 86.1% and 98.2%, respectively, to between 84.3% (IM) and 82.4% (IM+B) and between 97.9% (IM) and 95.2% (IM+B), respectively (Table 1). This is a relatively small effect, especially as China is already increasing its international imports and as the government recognizes the need to complement domestic food supply with foreign products (3). However, the corresponding agricultural expansion in other nations might have negative environmental consequences there, affecting land and water resources, even if major trade partners (e.g., Brazil and the United States) have a significantly more water-productive agriculture than China (2).

Reducing irrigation would likely come at a small financial cost, mostly devoted to farmer support (e.g., by government transfers, such as ecological compensation) and additional foreign food imports. We found that the overall effects of IM+B scenario are a 1% increase in China's cropping revenue (by 25.6 billion yuan/y; *SI Appendix*, Table S7) and an 11% increase in cost of foreign imports (by 29.1 billion yuan/y). The national cropping revenue increase results from income loss due to production decline in provinces in which irrigated land is cut, compensated for by a larger income increase in the rest of China, induced by higher crop prices. Importantly, we find that China would save 14.8 km^3/y of irrigation water while increasing national cropping revenue (+1%, IM+B scenario). The provincial income loss in the most stringent scenario (IM+B), mainly in Inner Mongolia and Hebei, could thus be transferred domestically. The farmers' compensation could also be funded through some of the important water conservation investments planned in China (30).

Financial means to implement changes in irrigation practices as explored here are largely available. The Chinese government's 2011 No. 1 Document outlined a plan to expedite water conservation development and to achieve sustainable management of water resources within this decade (36). It plans to bring total investment in solving water problems to 4 trillion yuan (U.S.$635 billion) in the next 10 y. Political will is shifting in favor of environmental protection, but implementation, governance, and integrated management are still lacking (30). It is too early to know whether such funds could be directed to farmers abandoning unsustainable irrigation, but specific references have been made to focus on water-scarce areas and to convert irrigated cropland to conservation areas in a section of the 2013 No. 1 Document ["The Institutional Development of Ecosystem Civilization" (4)]. Subsequently, a "Special planning program for integrated water use for Beijing-Tianjin-Hebei" is in preparation

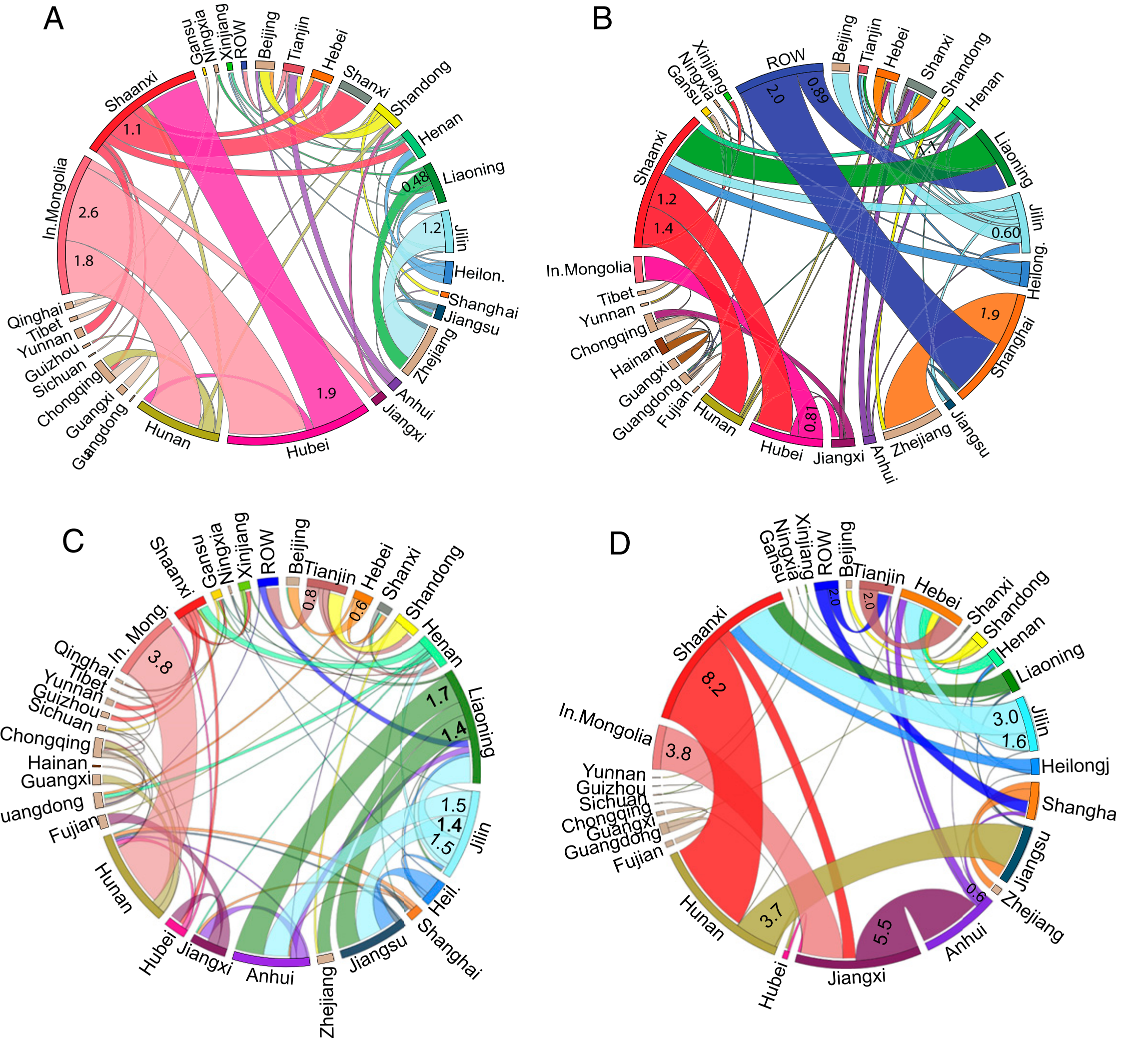

Fig. 2. Negative (*A* and *C*) and positive (*B* and *D*) differences in China's domestic and international VWT flows (km^3) in 2030, between the IM and BL scenario (*A* and *B*) and between the IM+B and IM scenario (*C* and *D*). In the IM scenario, Inner Mongolia's virtual water exports decrease from 16.7 km^3 in the BL to 12.1 km^3 (*A*) and foreign imports increase by about 3 km^3 (*B*). Beijing, Tianjin, and Hebei's virtual water imports increase from 52.4 km^3 in the IM scenario to 55.5 km^3 in the IM+B scenario (*D*).

under the umbrella of the national development strategy of "Integrated Development of Beijing-Tianjin-Hebei," initiated in 2014. In September 2014, these provinces released government guidelines stating that, in addition to improving agricultural water use efficiency, other measures reducing agricultural water use are also critical. Suggestions include conversion of cropland to conservation areas, adoption of drought-tolerant varieties [with specific subsidies for farmers in Hebei (37)], conversion of irrigated land to rainfed land, and water pricing according to local water scarcity. Such measures may well benefit the country in the near future, and many more will be needed to successfully address China's extensive water problems.

Materials and Methods

The Chinese domestic and foreign VWT networks are built for 2010, 2020, and 2030 under three policy scenarios: baseline, irrigation reduction in Inner Mongolia, and irrigation reduction in both Inner Mongolia and the greater Beijing area. Here we analyze the results for 2030. In China's VWT network, each node represents a province or the ROW, and each link between a pair of nodes is directed by the direction of trade and weighted by the volume of virtual water involved in the traded commodities. The ROW node can be directly linked only with the four main trading harbor provinces of Guangdong, Shanghai, Tianjin, and Liaoning. We use two main pieces of information to construct the VWT network in each year and scenario: the detailed interregional food trade, downscaled to interprovincial level, and the VWC of each commodity in all provinces. We build the VWT (kilograms of water) network by multiplying the traded volume of a specific commodity (kilograms of product) by the VWC of that commodity (kilograms of water per kilograms of product) in the province of export. The VWT flows corresponding to direct international imports and to domestic trade of foreign commodities are obtained by multiplying the trade volumes by the VWC of the corresponding commodity in the ROW (see *SI Appendix*).

The interregional trade of agricultural products was obtained from the CHINAGRO economic model (17) for four major crops (corn, rice, soybean, and wheat) and three livestock products (ruminant, pork, and poultry). The comprehensive model is a 17-commodity, eight-region general equilibrium welfare model. It comprises six income groups per region, with farm supply represented at the level of 2,433 administrative units (virtually all counties), and accommodates for county outputs of 28 products and 14 land use types in cropping and livestock production. Consumption is depicted at the regional level, separately for the urban and rural populations, and domestic trade is interregional (*SI Appendix*). We apply a linear programming optimization procedure (38) to downscale the interregional trade matrices to interprovincial trade matrices, by minimizing the total cost of trade for each commodity (see details in *SI Appendix*). The optimization constraints ensure the consistency with interregional trade simulated by CHINAGRO and the balance of commodity supply and demand in each province (involving production, consumption, storage change, other uses, and trade flows), including foreign and domestic goods. In addition, foreign commodities appear in each province trade balance, but we allow their net export to be no larger than China's foreign import, whereas net export of domestic commodities is bounded by the local production. Finally, international trade that flows through the four harbors (in Shanghai, Tianjin, Liaoning, and Guangdong) is exogenously imposed, according to reported data (39) and projections. Foreign countries are represented as an aggregate in this model.

The VWC (kilograms of water per kilograms of product) of raw crops is defined as the evapotranspiration (ET) during a cropping period (kilograms of water per square meter) divided by the crop yield (kilograms of crop per square meter). It thus accounts for crop water consumption. Variability of a crop's VWC across Chinese provinces is mainly driven by differences in climate and technology affecting local ET and crop yield (see ref. 6 for further details on commodities VWC in China). The VWC of unprocessed livestock products is defined as water consumption per head of livestock (kilograms of water per head), involving the feed's VWC, drinking, and cleaning water divided by the livestock production per head (kilograms of meat per head). The VWC value of each commodity was calculated using provincial crop yield estimates from CHINAGRO (17) (for rainfed and irrigated lands) and ET simulated with the H08 global hydrologic model (18, 40). The ET simulation used meteorological forcing data (41) covering the whole globe at 0.5° spatial resolution, from 1948 to 2008 at daily intervals; the average from 2003 to 2007 was used in this study (circa 2005) to isolate the effects of policy and socioeconomic changes from climate change effects; the latter are not considered here. Even though global warming is projected to increase evaporative demand by 2030, the combined effect of various climate changes (precipitation, temperature, heat stress, CO_2 fertilization, etc.) and climate-vegetation feedbacks on crop yield and ET remain highly uncertain (42). In this article, we focus on the effects of future socioeconomic changes and specific agricultural scenarios. For each crop, the rainfed and irrigated harvested areas (43) were fixed circa 2000, for which detailed gridded data are available, and then scaled in each year/scenario by using the cropland percentage changes estimated by CHINAGRO. Gridded ET simulation results (0.5° spatial resolution) are then aggregated by province, using the provincial rainfed and irrigated areas simulated by CHINAGRO. Finally, VWC is estimated by dividing this provincial ET by the provincial yield calculated by CHINAGRO for each crop and cropland type (i.e., rainfed and irrigated cropland). We also use these yields to estimate the VWC of livestock feed. The hydroeconomic consistency is thus ensured via H08 VWC simulations relying on CHINAGRO provincial crop yield and the surface of irrigated and rainfed cropland in each province, year, and scenario.

Trade-induced WS from a trade relationship represent the amount of water that is saved (if positive) or lost (if negative) by trade compared with an autarky situation. WS or losses are induced by a relationship in which the exporter is relatively more (less) water-productive than the importer (water productivity being measured by the VWC of the traded commodity in the region; *SI Appendix*).

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