# Supplementary Information for: Balancing water conservation and food security in China

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The following supplementary information (SI) appendix covers two main sections. The first section describes the methods, materials and models used to obtain our results. The second section presents in further details the results described in the printed version of the paper entitled: “Balancing water conservation and food security in China”.

# 1 Data and Methods

## 1.1 Methods

**Building the Chinese virtual water trade (VWT) network** The Chinese domestic and foreign VWT networks are built for years 2005, 2010 and 2020 and 2030 under three policy scenarios: Baseline -which includes increasing urbanization, population and economy- (noted BL), irrigation reduction in Inner Mongolia (noted IM), and irrigation reduction in both Inner Mongolia and the greater Beijing area (noted IM+B).

We built China’s VWT network by multiplying the traded volume of a specific commodity by the virtual water content of this commodity in the province (or foreign nation) of export:

$$VWT_{i,j,x}^{loc} = VWC_{i,x} \cdot T_{i,j,x}^{loc} \tag{1}$$

$$VWT_{i,j,x}^{for} = VWC_{ROW,x} \cdot T_{i,j,x}^{for} \tag{2}$$

where: $VWT_{i,j,x}^{loc}$ and $VWT_{i,j,x}^{for}$ ($kg_{water}$) are the volume of virtual water exported from province $i$ to province $j$ through trade of commodity $x$ produced locally and abroad (in ROW), respectively. $T_{i,j,x}^{loc}$ and $T_{i,j,x}^{for}$ ($kg_{product}$) are the volume of commodity $x$, produced locally and abroad, respectively, and exported from $i$ to $j$. $VWC_{i,x}$ ($kg_{water}/kg_{product}$) and $VWC_{ROW,x}$ are the virtual water content of commodity $x$ produced in province $i$ and in the $ROW$, respectively.

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. We estimate this foreign VWC as an average of the VWC in China’s trade partners, weighted by the share of each country in Chinese imports in 2005 (FAO, http://faostat3.fao.org). We assume that the virtual water content of foreign goods change towards 2030 will be minimum, as trade partners of China are likely to have already reached their maximum potential yields (e.g. Brazil and the United States).

In this study, we mainly analyze the aggregated VWT network, built by summing the VWT from all selected commodities.

**Trade-induced water savings** WS via trade of a local commodity $x$ from an exporting province $i$ to an importing province $j$ are defined [1] as:

$$WS_{i,j,x} = T^{loc}_{i,j,x} \cdot (VWC_{j,x} - VWC_{i,x}) \tag{3}$$

and water savings from the trade of a foreign commodity from province $i$ to $j$, since $x$ is actually made abroad (in the ROW), are defined as:

$$WS_{i,j,x} = (T^{for}_{i,j,x} - \sum_{k \neq i,j} T^{for}_{j,k,x}) \cdot (VWC_{j,x} - VWC_{ROW,x}) \tag{4}$$

where the subscripts $i$, $j$, $k$ and $ROW$ correspond to the exporting province, the importing province, other provinces and the Rest of the World, respectively. $T^{loc}_{i,j,x}$ and $T^{for}_{i,j,x}$ are the volumes traded from $i$ to $j$ of commodity $x$ locally or internationally produced, respectively. $VWC_{j,x}$ is the virtual water content of commodity $x$ in province $j$, and $VWC_{ROW,x}$ is a weighted average of $VWC$ of $x$ in international trade partners. Note in 4 only the net import of foreign goods is considered to avoid double counting due to re-export.

We compute WS for all trade relationships and aggregate values by commodity's base product (corn, rice, soy, wheat, ruminant, pork and poultry) as follows:

$$WS_x = \sum_{(i,j)} WS_{i,j,x} \tag{5}$$

where (i,j) corresponds to all pairs of nodes, including 31 provinces and the ROW.

**Scenario description** Major exogenous driving forces for China's future agricultural production, consumption and trade in CHINAGRO model include: changes of agricultural land resources, technical progress in agriculture, population growth, urbanization and interregional migration, non-agricultural output growth, changing food preferences, domestic agricultural support policy, trade policy and international price trends. The important role played by these driving forces requires us to make a careful and coherent specification of future trends, derived from the literature and CHINAGRO experts' assessments. The baseline scenario tries to provide a feasible picture of future developments based on central tendencies that are expected in the next few decades (Table 1).

This scenario is characterized by the following projections:

- moderate cropland losses, relatively more for rainfed land than for irrigated land;
- steady improvement of yields and labor efficiency in cropping but only moderate increase of fertilizer efficiency;
- sustained growth of non-agricultural output, albeit at a lower annual rate (average of 6-7%) than those of previous years;
- moderate population growth (to 1459 million people by 2030), with urbanization rising to nearly 60% in 2030;
- gradual shift from consumption of staple food to more "luxury" foods (e.g. meat and dairy products), also in rural areas, as results of income growth and dietary change;
- further trade liberalization by reduction of tariff rates;
- introduction of agricultural subsidies, largely untied but with some degree of grain price support;
- significant increase of industrial use of crop output, in particular maize and vegetable oil, but only to a limited extent for biofuel production;
- continuation of current growth rates in non-agricultural sectors, supported by large investments in the manufacturing and services sectors and a considerable outflow of labor from rural areas;
- urban and industrial expansion leads to increased pressure on agricultural land and water availability in densely populated counties;

- to cope with possible threats on domestic food supply, the government continues its policy of liberalization of agricultural foreign trade, reduces producer taxes and stimulates technical progress by sustained spending on agricultural research and development;
- trends in world food and feed prices are based on the joint projections of the UN Food and Agricultural Organization and the Organization for Economic Cooperation and Development [2], which covers the years between towards 2023, and is extrapolated to 2030. The international agricultural price projections in the baseline show moderate changes, with increases for feed and meat and a mixed picture for food crops.

## 1.2 Materials and Modeling

**Food Trade Model** The inter-regional trade of agricultural products was obtained from the CHINAGRO general equilibrium welfare model [3] for the 4 major crops (corn, rice, soybean and wheat) and 3 livestock products (ruminant, pork and poultry) between 8 regions of China. After conversion to equivalent weight or water volume (see Virtual Water Content Estimates subsection, last paragraph), several commodities are grouped by base product (rice bran and milled riced are aggregated to rice, wheat bran and wheat flour to wheat, and soybean oil and cakes to soy). CHINAGRO conducted its analysis within a modeling framework that (i) represents the consumer, producer and government decisions in the various regions, (ii) accounts for transportation costs in the economy, (iii) builds the supply response based on a spatially explicit assessment of the resource base and its biophysical characteristics, and (iv) describes agricultural processing and supply of farm inputs. Due to this set-up, CHINAGRO is a nationwide, regionalized applied general equilibrium (AGE)-model with a great deal of geographical detail. A distinctive feature of the model is that it pays close attention to the large spatial and social diversity of the country. This goal is achieved by conducting analysis at the county level, distinguishing over 2,400 of these administrative units. The model distinguishes eight regional markets, which are linked to each other and to the world market through commodity flows. Hence, this welfare model is rather large, comprising around 50,000 truly endogenous variables including prices, as well as consumption by every consumer group (including urban and rural population and three income groups) in every region, and agricultural production and input demand for every land use type (included irrigated and rainfed cropland) in every county.

We provide here further discussion of CHINAGRO structure relevant for our scenario analysis. This model has been applied for future projections in other contexts, such as the analysis of biofuel policy scenarios [4]. On the agricultural production side, the model is based on the assumption of farmers' profit maximization. Input-output production functions act as the technology constraint. On the consumption side, consumers maximize their utility under a budget constraint. Thus, the model does not include any explicit price elasticity. For interested readers, we have derived price elasticities through changes in prices and productions (neglecting the cross commodity price elasticities and the consumption side price elasticity). Based on the results of BL and IM+B scenario, the average production price elasticities of rice, wheat, and corn in China are 0.43, 0.35, and 0.21, respectively. These elasticities are comparable with results of other studies [5]. In addition, the national level price elasticities of crop production are lower than elasticities at household level (around 0.50), which is expected given the aggregated constraints of land and other agricultural input resources.

International trade in CHINAGRO has been model as world trade functions of international food prices (which is exogenous as explained above) and China's domestic agricultural commodity prices (which is endogenous). Government taxes (for example, the 13% value added tax for imported foods), tariffs, quotas, and transport costs are also being considered. The basic idea behind this it that when China's domestic price is higher than international prices, the model will increase China's import until when the domestic prices equals international price plus other import costs, such as, tariffs, taxes and transportation cost. The parameters of the world trade functions have been estimated on the basis of dedicated simulations with the GTAP-model [6] for a sample of exogenous trade flows of China, supplemented with information on price effects from other worldwide models [7, 8], which led to upward adjustment of the GTAP-based reaction coefficients. Additional details on the model structure can be found in the Appendix of CHINAGRO report [3].

**Downscaling food trade to the provincial level: linear programming optimization** CHINAGRO simulates food trade between 8 Chinese regions for years 2005, 2010, 2020 and 2030, in the three scenarios. To obtain a more detailed and more complete representation of Chinese domestic food trade, we use an optimization model to downscale the inter-regional trade to inter-provincial trade, i.e. between the 31 Chinese provinces. By doing so, we capture a significantly larger part of domestic trade flows in China, and provide insightful information to guide water-saving trade and agricultural policies.

We use a linear programming optimization procedure, aiming at minimizing the cost of inter-provincial trade (which includes transaction - due to price differences - and transportation costs) under several constraints, one of which is the compatibility of optimized inter-provincial trade with inter-regional trade simulated by the CHINAGRO welfare model. The optimization procedure is as follows:
objective: minimize cost of inter-provincial trade
subject to the following constraints:

- inter-provincial trade flows are positive and we impose foreign trade with 4 harbor provinces
- supply equals demand in each province, based on local production and consumption of each commodity and on net foreign and local imports
- the sum of exports from all provinces in region N to all provinces in region M equals the inter-regional export from N to M, as simulated by CHINAGRO
- net export of local goods is bounded by local production
- net export of foreign goods is either bounded by imports from abroad if these are positive, or null if no foreign import

We implement this procedure mathematically as follows:

$$\text{Minimize: } TC_c = \sum_{i,j}(t_{i,j,c}^{loc} + t_{i,j,c}^{for}) \cdot tc_{i,j,c}$$

subject to:

- $\forall(i,j) : t_{i,j,c} \geq 0$; $\forall i : t_{i,i,c} = 0$ and $FI_{32,i}$ for 4 harbors $i$ (exogenous net foreign trade)

- $\forall i \in [1:31]:$
  $P_{i,c} + FI_{i,c} + \sum\limits_{j \neq i, j=1:32} (t^{loc}_{j,i,c} - t^{loc}_{i,j,c}) + \sum\limits_{j \neq i, j=1:32} (t^{for}_{j,i,c} - t^{for}_{i,j,c}) = D^{urb}_{i,c} \cdot pop^{urb}_{i} + D^{rur}_{i,c} \cdot pop^{rur}_{i} + OU_{i,c} + \Delta S_{i,c}$

- $\forall N, M \in [1:8]: \sum\limits_{i \in N, j \in M} t^{loc}_{i,j,c} + t^{for}_{i,j,c} = T_{N,M,c}$

- $\sum\limits_{j \neq i, j=1:32} (t^{loc}_{i,j,c} - t^{loc}_{j,i,c}) <= P_{i,c}$

- $\sum\limits_{j \neq i, j=1:32} (t^{for}_{i,j,c} - t^{for}_{j,i,c}) <= max(0, FI_{i,c})$

where:

- $t^{loc}_{c}$ and $t^{for}_{c}$ ($kg_{crop}$) are the unknown inter-provincial trade matrix for commodity $c$, produced locally and abroad (foreign), respectively,
- $TC_c$ ($Yuan$) is the total cost of inter-provincial trade of commodity $c$,
- $tc$ ($Yuan/kg$) is the inter-provincial trade cost matrix.
- Indices $i, j$ refer to 31 provinces and indices $N, M$ refer to 8 regions.
- $P_{i,c}$, $FI_{i,c}$, $\Delta S_{i,c}$ and $OU_{i,c}$ ($kg_{crop}$) are respectively province $i$'s production, net foreign import, net stock increase and other uses of commodity $c$.
- $D^{urb}_{i,c}$ and $D^{rur}_{i,c}$ ($kg_{crop}/cap$) are province $i$'s consumers demand per capita for commodity $c$, respectively from urban and rural area.
- $pop^{rur}_{i}$ and $pop^{urb}_{i}$ ($cap$) are respectively province $i$'s rural and urban population.
- Finally, $T_c$ ($kg_{crop}$) is the inter-regional trade matrix simulated by CHINAGRO, for commodity $c$.

The inter-provincial transport cost is obtained through a GIS based dataset of different transportation modes (rail, river, road) between the provinces capital cities [9] and the corresponding transportation costs [10]. We note that institutional barriers to inter-provincial agricultural trade in China (i.e. regulations that could alter the costs accounted for here) have been cleared since at least the early 2000s [11, 12].

We solve this optimization problem for each of the 7 products, year, and scenario using the linear program tool embedded in MATLAB [13]; and obtain the corresponding inter-provincial trade matrices.

**Virtual Water Content Estimates** Virtual water content (*VWC*, $kg_{water}/kg_{product}$) of raw crops is defined as the evapotranspiration during a cropping period divided by the crop yield:

$$VWC_{i,c} = \frac{\overline{ET}_{i,c}}{Y_{i,c}} \tag{6}$$

where $ET_{i,c,s}$ is the average evapotranspiration over the area cultivated with crop $c$ in country $i$ ($kg_{water}/m^2$) and $Y_{i,c}$ is the yield of crop $c$ in country $i$ ($kg_{crop}/m^2$).

The VWC of unprocessed livestock products ($kg_{water}/kg_{meat}$) is defined as the water consumption per head of livestock (including virtual water from feed, drinking and cleaning water) divided by the livestock production per head:

$$VWC_{i,l} = \frac{WC_{i,l}}{P_{i,l}} \tag{7}$$

where $WC_{i,l}$ is the water consumption per head of livestock ($kg_{water}/head$) and $P_{i,l}$ is the livestock production per head ($kg_{livestock}/head$) in country $i$.

$WC$ takes into account cleaning and drinking water as well as the VWC of the feed consumed by each animal throughout its lifetime. An important part of animal feed (i.e. maize, Carbohydrate and Protein feed mixes) is traded across provinces and national boarders. Thus, we have calculated feed VWC in each province by taking into account trade flows of maize, Carbohydrate and Protein feed mixes simulated by CHINAGRO.

To transform the VWC of raw crops into that of a processed commodity made with that crop (e.g. soybean oil), we multiplied equation 6 by $p_x c_x / r_x$, following the method of Hanasaki et al. [14]. The price ratio $p$ is the ratio between the price of the raw crop and that of the commodity produced from that crop. The content ratio $c$ refers to the fraction of crop into the commodity's ingredients. The yield ratio $r$ indicates the fraction of crop ingredient in the raw crop. The coefficients for each commodity are listed by [15].

**Virtual water content of crops**

Virtual water content (VWC) of crops was defined as follows. The total VWC (VWCTOT $kg/yr$), originated from green water (VWCG) and blue water (VWCB), was expressed as

$$VWCTOT = \frac{\overline{ET}_R + \overline{ET}_I}{Y \cdot (A_R + A_I)} \tag{8}$$

$$VWCG = \frac{\overline{ET}_R}{Y \cdot (A_R + A_I)} \tag{9}$$

$$VWCB = \frac{\overline{ET}_I}{Y \cdot (A_R + A_I)} \tag{10}$$

where $A_R$, $A_I$, and $Y$ denote harvested area of rainfed and irrigated cropland, and crop yield respectively. $\overline{ET}_R$ and $\overline{ET}_I$ are the total amount of evapotranspiration during a cropping period from rainfed and irrigated cropland respectively ($kg_{water}/yr$), and expressed as follows:

$$\overline{ET}_R = \sum_c \sum_{DOY=plant}^{harvest} ET_{R,c,DOY} \cdot (A_{R,c} + A_{I,c}) \tag{11}$$

$$\overline{ET}_I = \sum_c \sum_{DOY=plant}^{harvest} ET_{I,c,DOY} \cdot A_{I,c} \tag{12}$$

where $ET_{R,c,DOY}$ is daily evapotranspiration for the date DOY (day of year) of a calculating grid cell of crop $c$ from rainfed cropland, $ET_{I,c,DOY}$ is that from irrigated land. Subscripts $plant$ and $harvest$ denote planting and harvesting date, respectively. In this study, $A_{R,c}$ and $A_{I,c}$ were derived from MIRCA2000 [16]. MIRCA2000 includes harvested area for 26 crop types with the separation of irrigated and rainfed area globally circa 2000. It covers the whole globe at the spatial resolution of 5 minute. In case $Y$ is not available (e.g. the climate is not suited for the crop), it was substituted by the global mean value. $ET_{R,c}$ and $ET_{I,c}$ were simulated using the H08 hydrological model [17, 18].

**Virtual water content of livestock** First, the VWC of feed ($F_l$) for livestock products $l$ (ruminant, pork and poultry) was calculated as follows:

$$F_l = \sum_c VWC_c \cdot f_{l,c} \tag{13}$$

where $VWC_c$ is the virtual water content of feed products $c$, and $c$ designates carbohydrate feed (CH feed), protein feed (PROT feed) and maize, as defined in CHINAGRO [3]. These feed products' VWC were calculated for each province taking into account the international and domestic trade simulated with CHINAGRO, and assuming the following ingredient mix: CH feed made of rice and wheat, PROT feed made of soybean cakes, rice bran and wheat bran. Then, the livestock diets from CHINAGRO are used to calculated the resulting livestock VWC.

The numbers are shown in Table 1, which is derived from the proportion of national averaged feed consumption of CHINAGRO.

Note that VWC for other ingredients was neglected, since it is considered substantially smaller than the VWC of crops. However, for raised livestock, VWC can be expressed as

$$VWC_l = a_l \cdot F_l + b_l \tag{14}$$

where $a_l$ is per product feed consumption, and $b_l$ is water consumption other than feed. In the case of grazed cattle, $VWC_{graze}$ can be expressed as,

$$VWC_{graze} = a_{graze} \cdot VWC_{pasture} \tag{15}$$

Where $a_{graze}$ is per product pasture consumption and $VWC_{pasture}$ is VWC of pasture. Water use other than the growth of pasture is neglected for grazed cattle.

**H08 Model** H08 is a global water resources model which deals with both natural hydrological processes and major human activities related to water use. Complete model formulations and validation results are explained by Hanasaki et al. [17, 18]. H08 consists of six sub-models: land surface hydrology, river routing, crop growth, reservoir operation, water withdrawal, and environmental flow requirement sub-model. The land surface hydrology sub-model is based on a bucket type model [19, 20]. A simple subsurface flow process, which is similar to the process used in [21], is included. The effective flow velocity is set at globally uniform 0.5 $m/s$. The crop growth sub-model is based on the SWIM model [22]. The model uses a concept of phenological crop development model based on daily accumulated heat units, Monteith's approach [23] for potential biomass, stress factors for water, temperature, and nutrients [22]. In this simulation, the crop growth sub model is mainly used to estimate cropping period globally.

First using the land surface hydrology model, evapotranspiration from rainfed cropland ($ET_{R,c,DOY}$) was estimated globally at daily interval, assuming that all of the grid cells contained cropland. Second, using the same model, evapotranspiration from irrigated cropland ($ET_{I,c,DOY}$) was estimated similarly, assuming that all of the grid cells contained irrigated cropland. In irrigated cropland, the soil moisture is kept higher than 75% of field capacity throughout a year with unrestricted water supply. Third, using the crop growth model, planting and harvesting date of four crops was estimated globally. We assumed that all four crops were sown in all of the grid cells (e.g. rice is sown even in arctic). We repeated simulations 365 times by shifting planting date from January 1 to December 31. The crop growth model judges the suitability of climate condition for crop growth at a daily interval. It kills crops when and where climate conditions are not suitable (e.g. rice sown on January 1 in the Arctic is killed). It calculates the growth of crops at daily interval. When the crop is matured, the date and crop yield is recorded. After finishing 365 simulations, the crop yield of twenty-one days running mean was calculated for each planting date, and the date that produced the maximum crop yield was assumed as planting date. The performance of this simulation has been evaluated [18].

In each 0.5 ° by 0.5 ° grid cell, the crop-wise rainfed and irrigated harvested area [16] were fixed circa year 2000, for which detailed data is available (5 minute spatial resolution). Meteorological information is input from the GMFD [24], with precipitation, temperature, relative humidity and radiation averaged around year 2005 (2003-2007).

To ensure consistency between the crops VWC values estimated by the H08 model and the trade volumes obtained from the CHINAGRO model, which produces province-level crop production estimates, crop yield per area sown from CHINAGRO was used as the crop yield per area ($Y$) in calculations of province-level crops VWC (Equation 6). Thus, each crop's yield per area sown (irrigated and rainfed cropland, [3]) is used to scale crop yield up to the province level. This scaling is required for three reasons: (i) CHINAGRO does not include gridded information necessary for the ET estimation using H08 model, (ii) cropland area of CHINAGRO at the base year is quite different from MIRCA2000 values (possibly because these two data used different data sources), and (iii) CHINAGRO projects substantial changes in cropland area in the future for each province.

# 2 Results

- Tables S2 and S3: relative and absolute changes in food production at local and national levels, consumption, foreign imports and self-sufficiency ratio, by product. The scenarios' impacts on meat supply and demand are relatively small. For the four crops, the production decline is partly compensated for by other Chinese provinces, except for soy (see main text). Consumption declines slightly due to price increase (induce by the supply reduction). Foreign import rise and China's food self-sufficiency declines, however it is maintained at high levels for grains (corn, rice and wheat, Table S3).

- Tables S4 and S5: relative and absolute changes in water withdrawals, at local and national level, by source of water. Importantly, the largest percentage decrease in water withdrawals concerns blue water sources, i.e. surface and groundwater resources. Tables S6 presents detailed irrigation use reduction by product. We find that corn and pork account for most of the avoided irrigation consumption.
- Tables S9 and S10: top virtual water exporting provinces in IM and IM+B scenarios. We observe top exporters are more water-efficient in these scenarios than those in the baseline, especially as Inner Mongolia is overpassed by other provinces (e.g. blue water content - irrigation per unit crop - of crops produced in Hunan is $48kg_{water}/kg_{crop}$, vs. $509kg_{water}/kg_{crop}$ for crops made in Inner Mongolia).
- Tables S11, S12 and S13: top virtual water importers. No significant change from BL to IM or IM+B.
- Figure S1: total national water savings, by crop and water source. Major blue water losses (negative WS) in the baseline are due to Inner Mongolia corn export. We observe the reduction of these losses, and increase in WS from soy because of increased imports from abroad, where soy is made more water-efficiently than in China.
- Figure S2: detailed blue water losses in BL and IM scenario.
- Figure S3: detailed blue water losses in IM+B scenario.

# References and Notes

[1] A. K. Chapagain, A. Hoekstra, H. Savenije, *Hydrology and Earth System Sciences* **10**, 455 (2006).

[2] OECD-FAO, *Agricultural outlook 2014-2023* (Organization for Economic Co-operation and Development, Paris and Food and Agriculture Organization of the United Nations, Rome, 2014).

[3] G. Fischer, *et al.*, *http://eprints.soas.ac.uk/12657/* (2007).

[4] J. Y. M. K. W. v. V. S. R. G. F. Qiu Huanguang, Huang Jikun, T. Ermolieva, Biofuel development, food security and the use of marginal land in china (2011).

[5] J. Han, *China's Food Security and Agriculture Going-out Strategy Research* (Development Press of China, Beijing, 2014 - Available in Chinese).

[6] T. Hertel, *Global trade analysis: modeling and applications.* (Cambridge University Press, Cambridge, 1997).

[7] C. S. M. T. S. T. Z. Rosegrant, M.W., S. Cline, *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): model description* (International Food Policy Research Institute, Washington, 2008).

[8] FAPRI, *Iowa State University and University of Missouri-Columbia, Ames* (2011).

[9] GIS, *http://www.webmap.cn/index2.php* (2012).

[10] NSBC, *China Statistical Yearbook* (National Statistical Bureau China, China Statistical Press, 2006).

[11] J. Huang, S. Rozelle, Y. Xie, *Journal of Chinese Economic and Business Studies* **1**, 97 (2003).

[12] J. Huang, S. Rozelle, M. Chang, *World Bank Economic Review* **18**, 59 (2004).

[13] MATLAB, *version 7.10.0 (R2010a)* (The MathWorks Inc., Natick, Massachusetts, 2010).

[14] N. Hanasaki, T. Inuzuka, S. Kanae, T. Oki, *J. Hydrol.* **384**, 232 (2010).

[15] M. Konar, *et al.*, *Water Resour. Res.* **47** (2011).

[16] F. Portmann, S. Siebert, P. Doll, *Global Biogeochem Cycles* **24** (2010).

[17] N. Hanasaki, *et al.*, *Hydrol. Earth Syst. Sci.* **12**, 1007 (2008).

[18] N. Hanasaki, *et al.*, *Hydrol. Earth Syst. Sci.* **12**, 1027 (2008).

[19] S. Manabe, *Mon. Weather Rev.* **97**, 739 (1969).

[20] A. Robock, K. Vinnikov, C. Schlosser, N. Speranskaya, Y. Xue, *J. Climate* **8**, 15 (1995).

[21] D. Gerten, S. Schaphoff, U. Haberlandt, W. Lucht, S. Sitch, *J. Hydrol.* **286**, 249 (2004).

[22] V. Krysanova, F. Wechsung, J. Arnold, R. Srinivasan, J. Williams, *SWIM (Soil and Water Integrated Model) User ManualRep* (Potsdam Institute for Climate Impact Research, Germany, 2000).

[23] J. Monteith, *Philos. T. Roy. Soc. B* **281**, 277 (1977).

[24] J. Sheffield, G. Goteti, E. Wood, *J. Climate* **19**, 3088 (2006).

[25] G. Fischer, *IIASA, Laxenburg, Austria and FAO, Rome, Italy* (2008).

[26] J. Pan, H. Wei, *Blue Book of Cities in China* (Social Science Academic Press of China, Beijing, 2013).

# 3 Supplementary Figures and Tables

| Variable | Year | Value in BL scenario |
|---|---|---|
| GDP (index) | 2000 | 100 |
| | 2020 | 370 |
| | 2030 | 610 |
| Population (million) | 2000 | 1275 |
| | 2020 | 1429 |
| | 2030 | 1459 |
| Urbanization* (%) | 2000 | 36 |
| | 2020 | 50 |
| | 2030 | 58 |
| Arable land (million ha) | 2000 | 128.2 |
| | 2020 | 119.4 |
| | 2030 | 116.6 |
| Productivity Growth (% p.a.) | Crops 2000-2030 | 1.2 |
| | Livestock 2000-2030 | 1.3 |

Table S 1: Key parameters for CHINAGRO Baseline scenario (BL), for years 2020 and 2030, compared to year 2000. Source: [25]

* Note: Our assumption for urbanization rate is lower than China's official statistics. It is based on the following considerations. First, although China's official urbanization rate has reached 52.6% in 2012, it is potentially over-estimated, with other estimates for 2012 as low as 42.2% [26], which is about 10 percentage points lower than the official statistics. Second, according to the official criterion, if a farmer stayed more than 6 months in an urban area during the year, s/he will be assumed to be an urban resident. The assumption of urbanization rate can affect the model results through agricultural labor supply and food consumption patterns (the income effect of urbanization is captured by the exogenous assumptions on GDP). Given that many migrant farmers still work seasonally in agriculture and their food consumption habits are close to rural consumers, we believe a lower urbanization rate assumption is more reasonable.

| Scenario | Variable | Area | Corn | Rice | Soy | Wheat | Beef | Pork | Poultry |
|---|---|---|---|---|---|---|---|---|---|
|  | P (% national) | In. Mon. | -2.5 | -0.2 | -0.3 | -0.3 | 0.005 | 0.04 | 0.02 |
|  | P | China | -2.2 | -0.07 | -0.4 | -0.3 | 0.05 | -0.05 | -0.09 |
| IM | C | ” | -0.1 | -0.08 | -0.9 | -0.02 | -0.003 | -0.05 | -0.03 |
|  | FI | ” | 12.6 | 0 | 0.8 | 17 | -0.5 | 0 | 0.5 |
|  | SSR | ” | -2.1 | 0 | -0.9 | -0.3 | 0.05 | 0 | -0.06 |
|  | P (% national) | In. Mg | -2.6 | -0.2 | -0.4 | -0.3 | 0.05 | 0.04 | 0.02 |
|  | ” | Beijing | -0.05 | -0.0007 | 0.003 | -0.1 | 0.0009 | 0.0002 | 0.001 |
|  | ” | Tianjin | -0.04 | -0.02 | -0.01 | -0.1 | -0.002 | 0.01 | 0.007 |
|  | ” | Hebei | -1.8 | -0.1 | -0.2 | -4.9 | 0.02 | 0.2 | 0.2 |
|  | P | China | -4.3 | -0.2 | -1.5 | -4.5 | 0.06 | -0.05 | -0.2 |
| IM+B | C | ” | -0.1 | -0.3 | 2 | -1.5 | 0.001 | -0.05 | -0.08 |
|  | FI | ” | 25.7 | 0 | 2.6 | 167 | -900 | 0 | 3,900 |
|  | SSR | ” | -4.2 | 0 | -3.2 | -3.0 | 0.06 | 0 | -0.2 |

Table S 2: Relative shifts in national food supply and demand (in %): production (P), consumption (C), net foreign imports (FI) and self-sufficiency ratio (SSR) by area and product, in IM and IM+B scenarios relative to BL, for year 2030.

| Scenario | Variable | Area | Corn | Rice | Soy | Wheat | Beef | Pork | Poultry |
|---|---|---|---|---|---|---|---|---|---|
|  | P | In. Mon. | -5.3E3 | -3.2E2 | -6.2E1 | -2.8E2 | 9.0 | 2.8E1 | 7.3 |
|  | P | China | -4.6E3 | -1.3E2 | -8.1E1 | -2.9E2 | 7.6 | -3.1E1 | -2.4E1 |
| IM | C | ” | -2.5E2 | -1.4E2 | 2.4E2 | -1.4E1 | -4.1E-1 | -3.1E1 | -9.4 |
|  | FI | ” | 4.3E3 | 0 | 5.3E2 | 2.8E2 | -8.0 | 0 | 1.4E1 |
|  | SSR | ” | -1.8 [84.3] | 0 [100] | -0.2 [21.4] | -0.3 [97.9] | 0.05 [91] | 0 [100] | -0.05 [90] |
|  | P | In. Mg | -5.6E3 | -3.4E2 | -7.1E1 | -2.9E2 | 7.8 | 2.6E1 | 6.3 |
|  | ” | Beijing | -1.1E2 | -1.3 | 0.6 | -9.0E1 | 1.4E-1 | 1.0E-1 | 2.5E-1 |
|  | ” | Tianjin | -1.0E2 | -3.6E1 | -1.9 | -1.3E2 | 2.5E-1 | 9.8 | 1.9 |
|  | ” | Hebei | -3.9E3 | -2.1E2 | -4.7E1 | -4.5E3 | 3.7 | 1.6E2 | 3.9E1 |
|  | ” | China | -9.1E3 | -4.3E2 | -2.8E2 | -4.1E3 | 9.2 | -3.3E1 | -6.3E1 |
| IM+B | C | ” | -2.3E2 | -4.6E2 | 5.6E2 | -1.4E3 | 2.1E-1 | -3.3E1 | -2.4E1 |
|  | FI | ” | 8.8E3 | 0 | 1.9E3 | 2.7E3 | -9.0 | 0 | 3.9E1 |
|  | SSR | ” | -3.6 [82.4] | 0 [100] | -0.7 [20.9] | -3.0 [95.2] | 0.05 [91] | 0 [100] | -0.14 [90] |

Table S 3: Shifts in national food supply and demand: production (P), consumption (C), net foreign imports (FI) (in 1000 tons) and self-sufficiency ratio (SSR; in percentage points) by area and product, between IM and IM+B scenarios and BL, for year 2030. Numbers in brackets indicate the self-sufficiency ratio per scenario per commodity.

| Scenario | Area \Avoided WC | Total | Green | Blue |
|---|---|---|---|---|
| IM | In. Mongolia | 19 | 6 | 43 |
|  | China | 2 | 0.2 | **7** |
| IM+B | In. Mongolia | 19 | 6 | 42 |
|  | Beijing | 16 | 2 | 44 |
|  | Tianjin | 10 | -8 | 51 |
|  | Hebei | 20 | 8 | 46 |
|  | China | 3 | 0.3 | **14** |

Table S 4: Avoided water consumption (WC, in %) in IM and IM+B scenarios relative to BL, by area and water source in 2030. Negative values indicate increased water consumption.

| Scenario | Area \Avoided WC | Total | Green | Blue |
|---|---|---|---|---|
| IM | In. Mongolia | 6.4 | 1.2 | 5.2 |
|  | Other provinces | 2.0 | -0.5 | 2.5 |
|  | China | 8.5 | 0.8 | **7.7** |
| IM+B | In. Mongolia | 6.4 | 1.9 | 5.2 |
|  | Beijing | 0.2 | 0.01 | 0.2 |
|  | Tianjin | 0.2 | -0.09 | 0.3 |
|  | Hebei | 7.8 | 2.1 | 5.7 |
|  | Other provinces | 1.8 | -1.6 | 3.5 |
|  | China | 16.3 | 1.6 | **14.8** |

Table S 5: Avoided water consumption (WC, in $km^3$) in IM and IM+B scenarios relative to BL, by area and water source in 2030. Negative values indicate increased water consumption.

| Scenario | Area | Corn | Rice | Soy | Wheat | Beef | Pork | Poultry |
|---|---|---|---|---|---|---|---|---|
| IM | In. Mon. | 3.4 | 0.2 | 0.8 | 0.4 | 0.2 | 0.2 | 0.08 |
|  | Other prov | -0.06 | -0.008 | 0.02 | 0.01 | 0.1 | 2.0 | 0.4 |
|  | China | **3.4** | 0.2 | 0.8 | 0.4 | 0.3 | **2.3** | 0.5 |
| IM+B | In. Mon. | 3.5 | 0.2 | 0.8 | 0.4 | 0.2 | 0.2 | 0.07 |
|  | Beijing | 0.1 | 0.0005 | 0.01 | 0.03 | 0.01 | 0.002 | 0.004 |
|  | Tianjin | 0.1 | 0.01 | 0.01 | 0.04 | 0.01 | 0.06 | 0.007 |
|  | Hebei | 2.8 | 0.1 | 0.2 | 1.1 | 0.5 | 0.9 | 0.2 |
|  | Other prov | -0.008 | -0.01 | 0.1 | -0.1 | 0.2 | 2.8 | 0.5 |
|  | China | **6.5** | 0.3 | 1.0 | 1.4 | 0.8 | **4.0** | 0.8 |

Table S 6: Avoided blue water consumption (in $km^3$) relative to BL, in IM and IM+B scenarios, by product and area for year 2030.

| Scenario | Area | Absolute $\Delta$ Income (BYuans) | Relative $\Delta$ Income | Absolute $\Delta$ blue WC ($km^3$) | Relative $\Delta$ blue WC |
|---|---|---|---|---|---|
| IM+B | In. Mon. | -12.78 | -19% | -5.2 | -43% |
| | Beijing | -0.75 | -23% | -0.2 | -44% |
| | Tianjin | -1.89 | -25% | -0.3 | -51% |
| | Hebei | -35.06 | -26% | -5.7 | -46% |
| | Other prov. | 76.69 | 4% | -3.5 | N/A |
| | China | 26.21 | 1% | -14.8 | -14% |

Table S 7: Impacts of IM and IM+B scenarios on cropping revenue (billion Yuans) and irrigation (blue) water consumption (WC, $km^3$). Relative and absolute changes, in IM+B scenario relative to BL, for year 2030.

| **Rank** | Top exporter | VWE ($km^3$) | Blue VWC ($kg/kg$) |
|---|---|---|---|
| 1 | Jilin | 14.4 | 136 |
| 2 | Liaoning | 11.8 | 137 |
| 3 | InnerMongolia | 16.7 | 509 |
| 4 | Heilongjiang | 11.0 | 113 |
| 5 | Shaanxi | 15.1 | 251 |

Table S 8: Top food exporters -domestic commodities only-, associated virtual water exports (VWE) and mean blue crop virtual water content (VWC), in BL and year 2030. Note that Inner Mongolia is the *third largest food exporter* with a particularly high irrigation use per unit crop.

| **Rank** | Top exporter | VWE ($km^3$) | Blue VWC ($kg/kg$) |
|---|---|---|---|
| 1 | Jilin | 14.8 | 136 |
| 2 | Liaoning | 11.4 | 137 |
| 3 | Shaanxi | 14.6 | 251 |
| 4 | Heilongjiang | 11.1 | 113 |
| 5 | Henan | 18.4 | 158 |

Table S 9: Top food exporters -domestic commodities only-, associated virtual water exports (VWE) and mean blue crop virtual water content (VWC), in Inner Mongolia scenario (IM) and year 2030. *Inner Mongolia ranks 8th*, exporting $12.1km^3$ of virtual water.

| **Rank** | Top exporter | VWE ($km^3$) | Blue VWC ($kg/kg$) |
|---|---|---|---|
| 1 | Jilin | 14.7 | 136 |
| 2 | Shaanxi | 23.1 | 250 |
| 3 | Hunan | 19.2 | 48 |
| 4 | Heilongjiang | 11.2 | 112 |
| 5 | Jiangxi | 17.4 | 88 |

Table S 10: Top food exporters -domestic commodities only-, associated virtual water exports (VWE) and mean blue crop virtual water content (VWC), in Northern China scenario (IM+B) and year 2030. *Inner Mongolia ranks 9th*, exporting $12.0km^3$ of virtual water.

| **Rank** | Top importer | VWI ($km^3$) |
|---|---|---|
| 1 | Liaoning | 10.8 |
| 2 | Shaanxi | 20.5 |
| 3 | Guangdong | 17.3 |
| 4 | Chongqing | 21.6 |
| 5 | Henan | 6.5 |

Table S 11: Top food importers (domestic commodities only) and associated virtual water imports, in Baseline scenario (BL) and year 2030.

| **Rank** | Top importer | VWI ($km^3$) |
|---|---|---|
| 1 | Shaanxi | 19.8 |
| 2 | Liaoning | 10.3 |
| 3 | Guangdong | 17.4 |
| 4 | Chongqing | 21.5 |
| 5 | Henan | 6.2 |

Table S 12: Top food importers (domestic commodities only) and associated virtual water imports (VWI), in Inner Mongolia scenario (IM) and year 2030.

| **Rank** | Top importer | VWI ($km^3$) |
|---|---|---|
| 1 | Shaanxi | 25.1 |
| 2 | Hunan | 15.1 |
| 3 | Guangdong | 17.2 |
| 4 | Jiangxi | 14.3 |
| 5 | Hebei | 7.7 |

Table S 13: Top food importers (domestic commodities only) and associated virtual water imports (VWI), in North China scenario (IM+B) and year 2030.

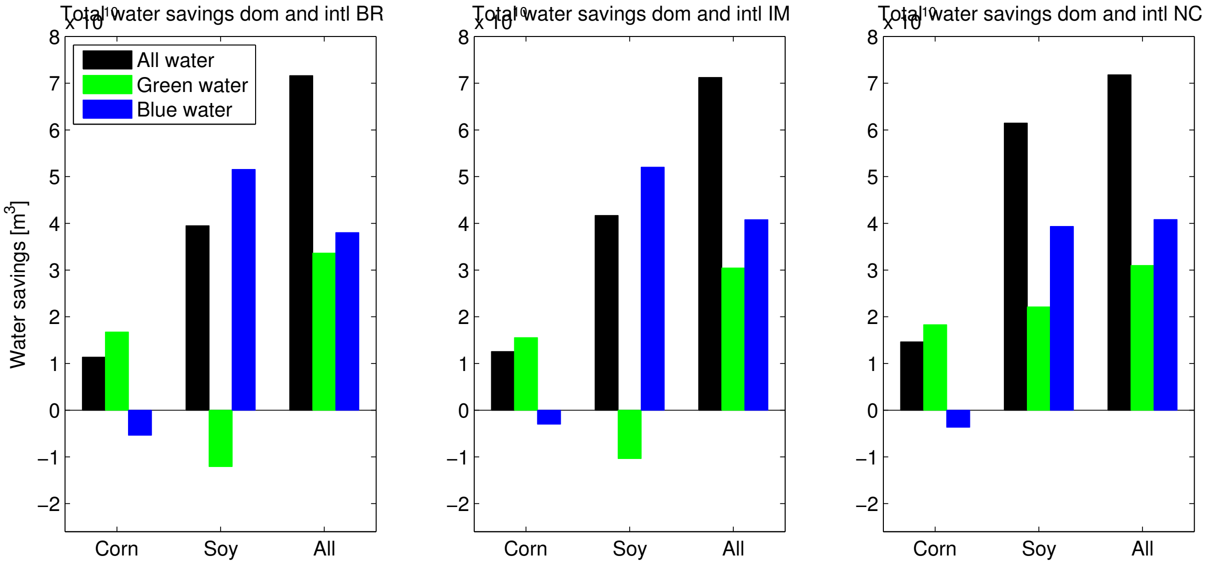

Figure S 1: Total water savings (WS) due to domestic and foreign food trade in 2030 under BL (38 $km^3$ ***blue*** WS, of which -5.4 $km^3$ and 51.6 $km^3$ from corn and soy, resp.), IM (41 $km^3$ blue WS, -3.0 $km^3$ and 52 $km^3$ from corn and soy) and IM+B scenario (41 $km^3$ blue WS, -3.6 $km^3$ and 39.3 $km^3$ from corn and soy), by product (corn, soy and all products) and water source.

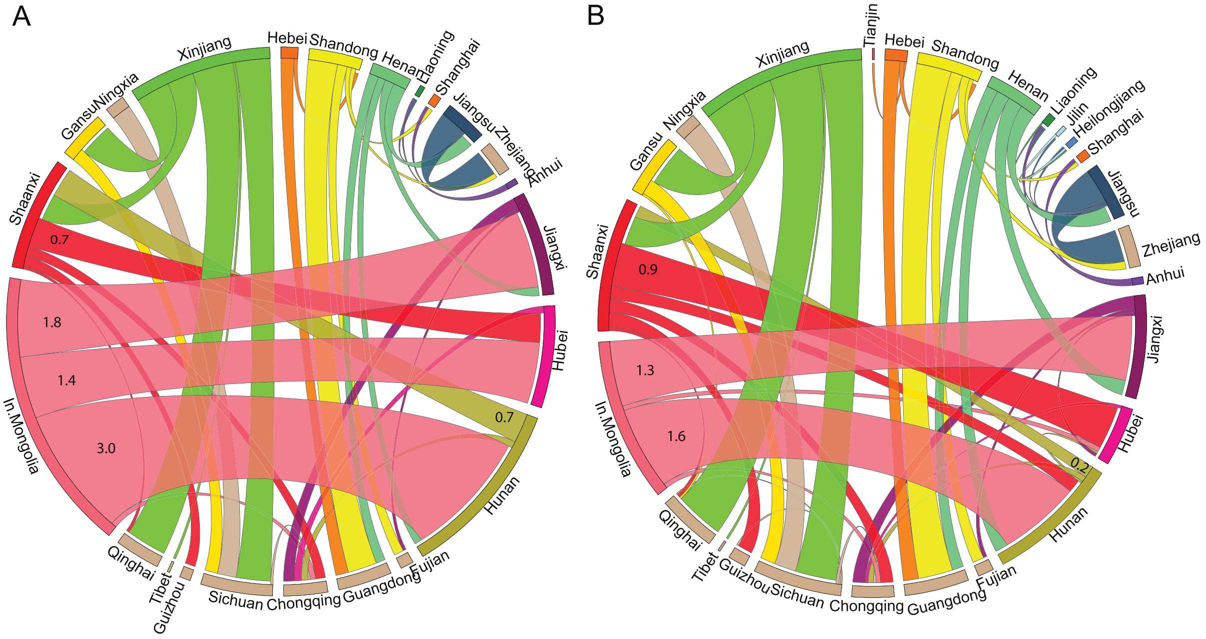

Figure S 2: Trade-induced losses of water from rivers, reservoirs and aquifers ($km^3$) due to domestic and foreign food trade in 2030, under BL (A, total 16.9 $km^3$) and IM (B, total 13.7 $km^3$) scenarios. Note that blue water losses induced by Inner Mongolia exports are the largest across provinces (A), and decrease from 6.4 $km^3$ in BL to 3.0 $km^3$ in IM scenario.

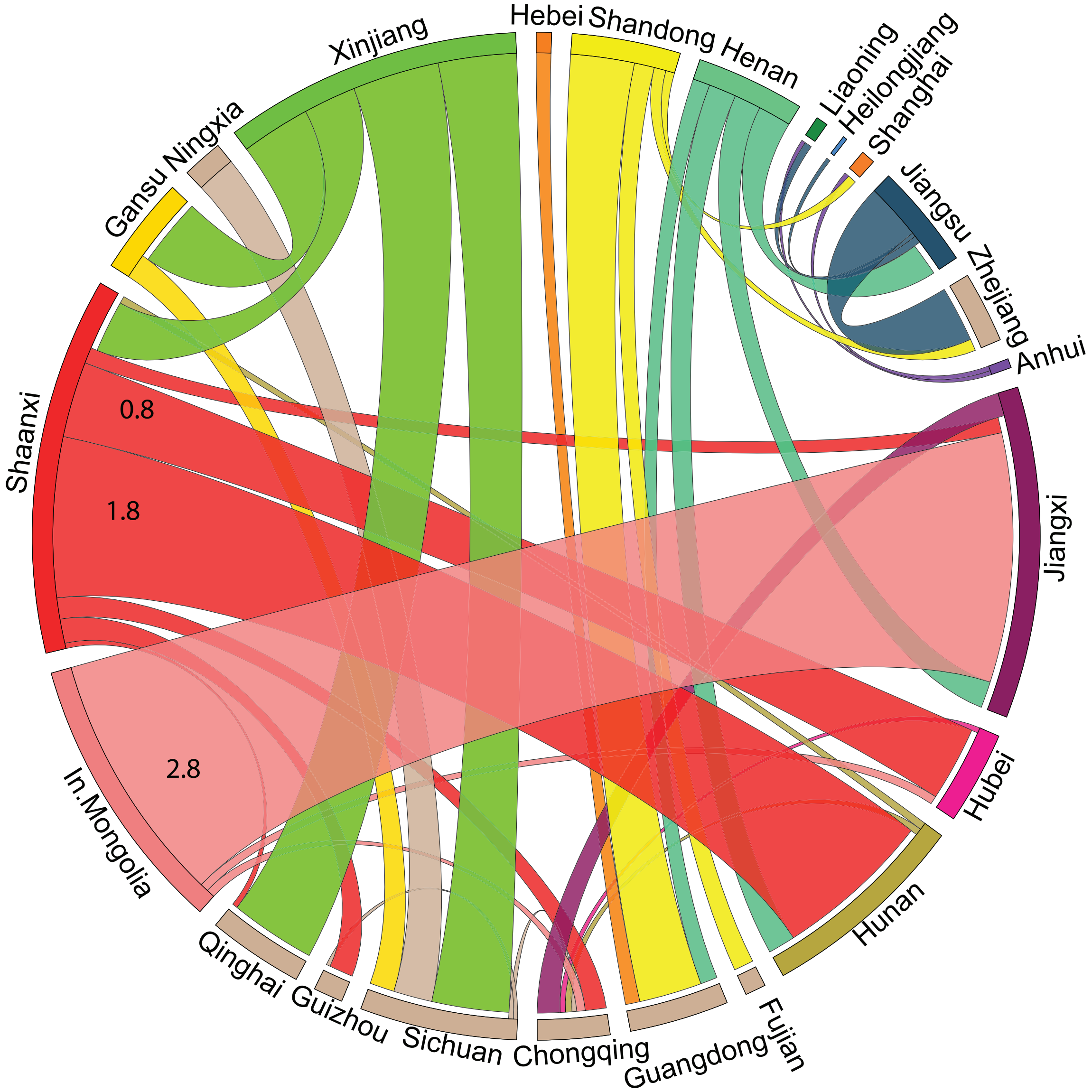

Figure S 3: Trade-induced losses of water from rivers, reservoirs and aquifers ($km^3$, total 14.8 $km^3$) due to domestic and foreign food trade in 2030 under IM+B scenario. Note Inner Mongolia exports induce only 2.9 $km^3$ of blue water losses.