Evolution of the global virtual water trade network

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Global freshwater resources are under increasing pressure from economic development, population growth, and climate change. The international trade of water-intensive products (e.g., agricultural commodities) or virtual water trade has been suggested as a way to save water globally. We focus on the virtual water trade network associated with international food trade built with annual trade data and annual modeled virtual water content. The evolution of this network from 1986 to 2007 is analyzed and linked to trade policies, socioeconomic circumstances, and agricultural efficiency. We find that the number of trade connections and the volume of water associated with global food trade more than doubled in 22 years. Despite this growth, constant organizational features were observed in the network. However, both regional and national virtual water trade patterns significantly changed. Indeed, Asia increased its virtual water imports by more than 170%, switching from North America to South America as its main partner, whereas North America oriented to a growing intraregional trade. A dramatic rise in China's virtual water imports is associated with its increased soy imports after a domestic policy shift in 2000. Significantly, this shift has led the global soy market to save water on a global scale, but it also relies on expanding soy production in Brazil, which contributes to deforestation in the Amazon. We find that the international food trade has led to enhanced savings in global water resources over time, indicating its growing efficiency in terms of global water use.

hydrology | trade policy | water savings

Socioeconomic development, population growth, and climate change present challenges to sustainably feed our planet with limited freshwater resources and land (1, 2). Agriculture, the most freshwater-consuming process by far (80% of total use) (3), has become the focus of efforts to reduce water use, particularly because other sectors are increasing their demands for water resources. The water used throughout the production process of a good is referred to as virtual water. In the case of products containing virtual water (i.e., requiring water for their production), international trade is a means of transferring water resources between regions. Besides, food trade may help save water on a global scale by encouraging exchanges of virtual water from highly productive countries to less productive countries, resulting in a smaller water use per amount of crop (4). Although virtual water transfers are unlikely to solve inequalities in global water use (5) and could decrease societal resilience to drought under some scenarios (6), the virtual water transfers associated with food trade have been shown to save ∼6% of the water used in agriculture (4), an extremely valuable contribution that must be further explored.

Virtual water trade (VWT) has been studied at different spatial scales but mostly for a specific time period (4, 7–9). Historical trends in China's VWT from 1961 to 2004 (10) and the yearly global VWT volume from 1961 to 2000 (11) have been estimated. However, a temporal analysis of the global VWT network would allow for an assessment of key impacts of policy, economic, and biophysical factors and thus, would greatly contribute to the understanding of the dynamics embedded in the global VWT network. For this reason, we build on previous work (8, 12) and use network theory to characterize the structure of the VWT network over time, proceeding then to study the VWT evolution at different scales from 1986 to 2007, a period of significant economic growth (Fig. 1). This study is different from previous studies of VWT, because we consider the international trade between all nations and incorporate annual model estimates of product-specific water use in each country.

The international VWT constitutes a weighted and directed network, in which link direction is given by the direction of trade (i.e., from exporting to importing country), and link weights are the volumes of virtual water traded between countries. Commodity trade volumes (13) are converted into virtual water volumes using virtual water content (VWC) simulations (13–15), which quantify the amount of water used to produce a unit of each commodity in each country (*Materials and Methods*). We use the global hydrological model H08 (14, 15) to simulate crop water use at 0.5° spatial resolution over time. In this study, we focus on the VWT networks associated with the trade of 58 food commodities made from five major crops (barley, corn, rice, soy, and wheat) and three livestock products (beef, pork, and poultry) (*Materials and Methods*). These commodities account for about 60% of global calorie consumption (13). The total volume of virtual water traded in 2007 was 567 $km^3\ y^{-1}$, which accounts for ∼22% of global freshwater withdrawal for agriculture (16).

The VWT network links the water and food systems through agriculture and trade. Thus, a quantitative analysis of how VWT changes in time is imperative to understand how events and development in the last decades have impacted this important system. By analyzing this network at different scales (namely global, regional, and national scales), we are able to link the evolution of global VWT to changes in regional and national policies, economic circumstances, and agricultural practices. This approach allows us to analyze the contributions of globalization, emerging countries, trade policies, and technological changes in agriculture to global water savings through food trade.

Results

Global Network Evolution. The number of food trade relationships and the associated virtual water volumes both grew significantly from 1986 to 2007 (Fig. 1). The total number of trade relationships doubled from 1986 to 2001 and then leveled off around 6,500 links. The global VWT volume (i.e., the total flow in the network) initially grew at a lower rate than the trade links but then started increasing faster in 1999, and it also doubled during the study period. This difference in trends induced a 25% increase of the average link weight (i.e., the volume of virtual water traded between each pair of trading partners) between 1999 and 2007. Moreover, both the number of trade relationships (3.7% per year) and the global VWT volume (3.8% per year) grew at a faster rate than global population (1.4% per year) and global crop yield (1.9% per year) but slower than global gross domestic product (GDP; 6.9% per year) (Fig. 1).

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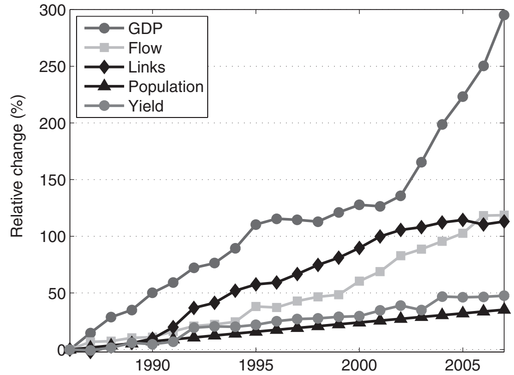

Fig. 1. Evolution of global variables relative to 1986 values (percent difference). GDP and population information was from ref. 20. Virtual water flow and number of links information was from this study. Total crop yield of five crops information was from ref. 13.

Despite this general growth of the VWT network, each country's number of trade partners (i.e., node degree) (*Materials and Methods*) and that country's volume of VWT (i.e., node strength) maintain a power law relationship during the 22-y period (Fig. 2 *A* and *B*). The power law coefficient is relatively constant throughout this time period (less than 10% change) and larger than two (average = 2.5 ± 0.2), revealing a highly nonlinear relationship between node strength and node degree (i.e., by increasing its number of trade partners, a country increases its VWT to a much greater extent).

The number of links doubled (Fig. 1), whereas the number of countries remained relatively constant [the main change (10%) being the breakup of the USSR into 15 countries in 1991]; thus, the mean node degree significantly increased from 25 trade partners in 1986 to 47 trade partners in 2007, reflecting the growing interconnectedness of world trade. Despite the mentioned change in the mean node degree over the period, the node degree distribution is fit well by an exponential distribution each year (Fig. 2 *C* and *D*). Similarly, the mean node strength has increased (from 2.6 to 5.4 km^3/y) as a consequence of the growth of total VWT (Fig. 1), but the node strength distribution is always fit well by a stretched exponential distribution (Fig. 2 *E* and *F*). The fat-tail characteristic of the node strength distribution implies the existence of large extreme values of node strength. This finding reveals a high heterogeneity of virtual water flows between nations in every year. Several countries—many more than would be expected with a log-normal distribution or a distribution with an exponentially decaying upper tail—trade much more virtual water than average.

These types of distributions are present in the network analysis literature. The exponential distribution of node degree, suggested in the work by De Montis et al. (17) for interurban traffic, was verified for the 2000 VWT network (8), and the stretched exponential distribution of node strength and power law relationship between node strength and node degree were observed for the 2000 VWT network (8, 12).

Regional and National Changes. To identify the changes in the major players of the global VWT network, it is important to analyze the evolution of the VWT at the regional and local scales. To this goal, we grouped nations into six regions (i.e., Africa, Asia, Europe, North America, Oceania, and South America) (18) (Fig. 3, regional map) and analyzed the evolution of the regional VWT networks. The growth of VWT volume takes place unevenly among the world's regions. Exports from South America to Asia contributed the most to the VWT volume increase between 1986 and 2007 (30%) followed by internal trade in North America (11%) (Fig. 3). We observe that South America has become a major virtual water exporter, with exports to all other main regions except North America and negligible imports. Asia more than doubled its imports, importing mostly from South America (39%) and North America (25%), with an important internal VWT (29%). Exports from North America to Europe have shrunk, whereas exports from North America to Asia have increased (by 60%) but less than North American internal trade did (mostly between the Unites States, Canada, and Mexico; by 310%); therefore, North American internal trade is now comparable in volume with North American exports to Asia.

Initially largely supplied by North American countries, Asia's virtual water imports (VWIs) have grown from 97 km^3 in 1986 to 261 km^3 in 2007, and they are now mainly coming from South America. Indeed, South America's share in Asian imports went up from 8% in 1986 to 39% in 2007, whereas North America's share decreased from 42% to 25% (Fig. 3). At a smaller scale, Europe's VWIs grew from 72 km^3 in 1986 to 127 km^3 in 2007. North American exports were also overshadowed in the European market. Indeed, North America's share in Europe's VWIs declined from 34% in 1986 to 5% in 2007, whereas South

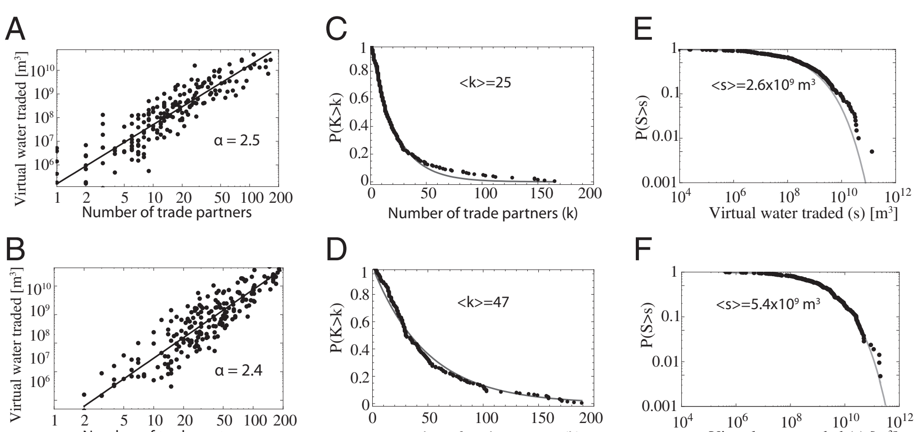

Fig. 2. Networks statistics and best functional fit in 1986 (*A*, *C*, and *E*) and 2007 (*B*, *D*, and *F*). (*A* and *B*) Volume of virtual water traded (i.e., node strength) vs. number of trade partners (i.e., node degree) and power law fit $s(k) \propto k^{\alpha}$ (fitting with least squares method). (*C* and *D*) Node degree exceedance probability distribution with its mean value and corresponding exponential fit. (*E* and *F*) Node strength exceedance probability distribution with its mean value and corresponding stretched exponential fit.

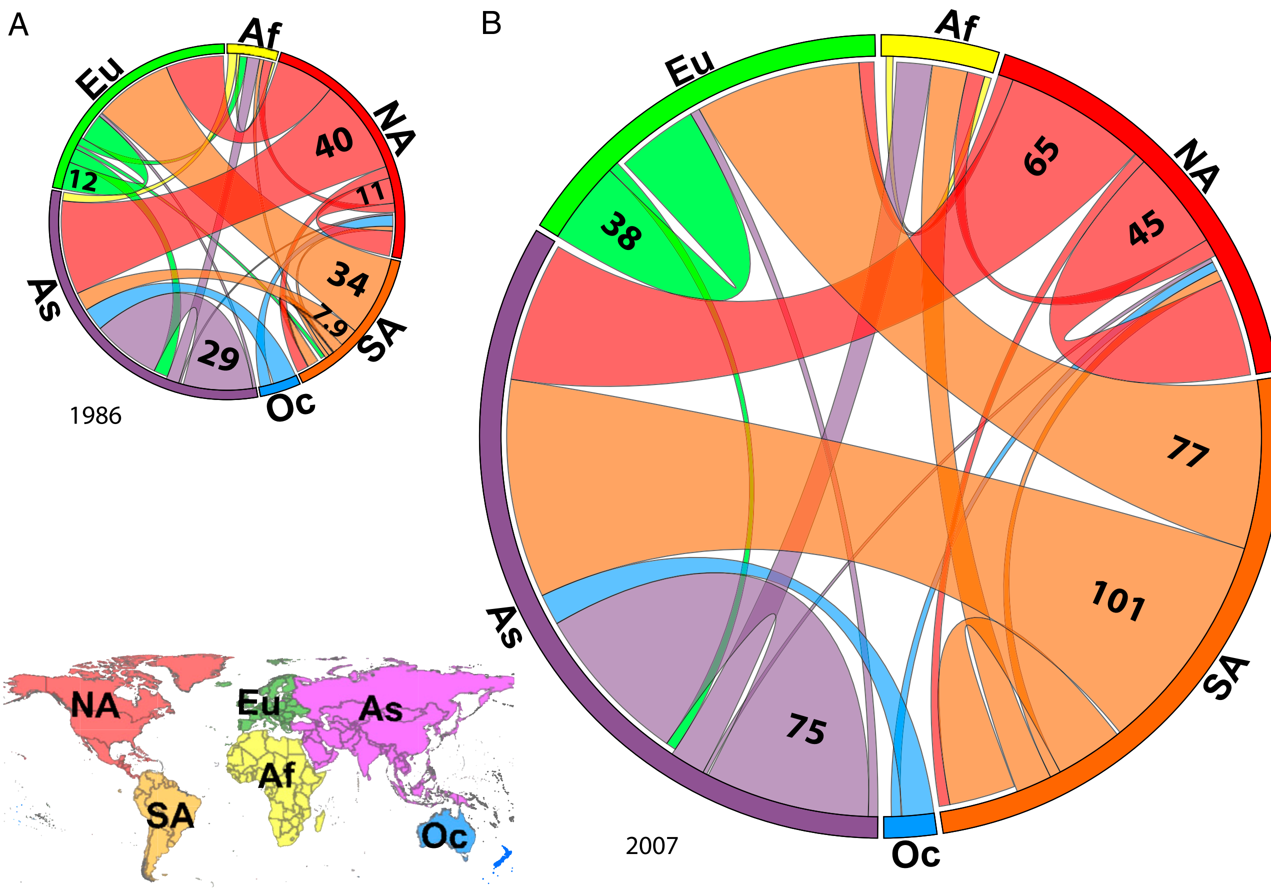

Fig. 3. Virtual water flows between the six world regions: Africa (Af), North America (NA), South America (SA), Asia (As), Europe (Eu), and Oceania (Oc). (*A*) Regional VWT network in 1986. (*B*) Regional VWT network in 2007. Numbers indicate the volume of VWT in cubic kilometers, and the links' colors correspond to the exporting regions. The regional map at the bottom left provides a key to the color scheme and acronyms of the regional VWT networks. The circles are scaled according to the total volume of VWT. Note the large difference between total VWT in 1986 (*A*; 259 km^3) and 2007 (*B*; 567 km^3).

America's share increased from 47% to 61%, and the share of internal European trade itself went up from 16% to 30%.

As suggested by the fat tail of the node strength distribution, some specific countries play a very important role in the global VWT network. Based on the staple food items considered, the United States has remained the largest virtual water exporter during the 22-y study period, except from 2004 to 2006, when Brazil was the leading exporter. The United States exported 115 km^3 of virtual water in 2007, accounting for 22% of the global VWT volume that year. China became the largest virtual water importer in 2001, a position formerly occupied by Japan. We find that the world's largest national VWIs slightly increased until

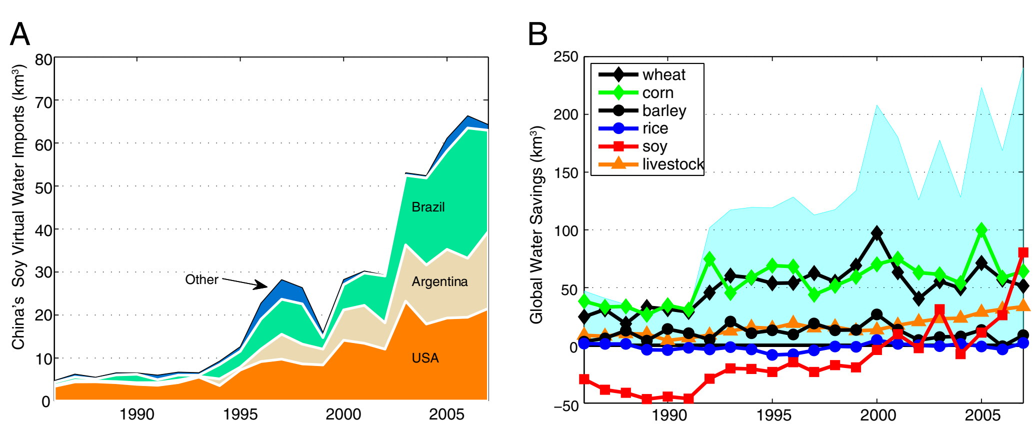

Fig. 4. Evolution of important features of VWT. (*A*) China's VWI associated with soy over time broken down into the corresponding exporting countries. (*B*) Global water savings over time. The shaded area shows the total global water savings from crops and livestock (beef, poultry, and pork) trade. Individual lines show the global water savings associated with trade of that particular crop. Note that the dramatic increase in global water savings from soy trade corresponds to the increase in China's imports from more efficient countries of production (the United States, Argentina, and Brazil).

2001, but then China's VWIs more than doubled between 2001 and 2007 to reach a total of 71 km^3, which accounted for 13% of the global VWT. This dramatic increase is mainly caused by China's growing VWIs derived from soybean-based products, which alone corresponded to 90% of China's total VWIs in 2007 (Fig. 4*A*). Only three main exporters (the United States, Brazil, and Argentina) supplied these vast quantities of soybean-based commodities to China. Although the United States was China's largest supplier of soybean at one time, Argentina's and Brazil's shares in China's soybean VWIs have been increasing since the mid-1990s, and Brazil's share has been exceeding the United States' share since 2004. In 2007, the shares for Argentina, the United States, and Brazil were 28%, 33%, and 37%, respectively (Fig. 4*A*).

Water Savings Evolution. A trade relationship contributes to global water savings if it is directed from a relatively more efficient country (with lower VWC) to a relatively less efficient country (*Materials and Methods*). We find that international food trade is leading to global water savings (Fig. 4*B*) and that these savings have increased faster than VWT volumes; they represented 18% of the global VWT volume in 1986 and 42% in 2007. In particular, the water savings associated with the trade of wheat-based (108% increase) and corn-based (68% increase) products show a dramatic increase. Furthermore, the water savings from trade of soybean-based products shifted from negative to positive in 2000–2001 and have increased eightfold from 2004 to 2007, reflecting a greater efficiency of soybean trade in terms of global water use (Fig. 4*B*).

Discussion

We have shown that the VWT network has grown significantly between 1986 and 2007; the network became more interconnected, and more virtual water was traded internationally (Fig. 1). Despite this growth, the node degree and node strength remained exponentially and stretched exponentially distributed, respectively, and a power law relationship between node degree and node strength has remained quite stable throughout the years (Fig. 2). These resilient structural characteristics of the network are of fundamental importance for the development of predictive models of the statistical characteristics of the global VWT network. The observed growth of the global VWT network is a picture of globalization and a reflection of the dramatic increase in the underlying food trade.

It is important to note the impacts on the VWT network of relevant trade agreements that took place during this period. Some of these trade agreements were made between specific countries and subsidized by national governments. A significant example is the United States–Mexico trade agreement for agriculture (part of the North American Free Trade Agreement) introduced in 1994, which has led to the intensification of internal North American trade (19). It has allowed the United States to satisfy the rising Mexican demand for meat and cattle feed consecutive to the development and increased GDP per capita (GDPPC) of Mexico in the 1990s [GDPPC multiplied by 5.1 from 1986 to 2000 (20)]. This trade agreement is an important component of a general shift from interregional exports to a more intraregional trade system in North America. Indeed, on the one hand, exports from North America to Europe have shrunk, and exports to Asia and South America are relatively less important than in the late 1980s; on the other hand, internal VWT in North America has more than quadrupled during the study period (Fig. 3).

Table 1. National soy VWC and yield: Evolution from 1997 to 2007 and value in 2007

	Change from 1997 to 2007 (%)		2007	
Country	VWC	Yield	VWC (kg_{water}/kg_{crop})	Yield (kg_{crop}/m^2)
China	23	−18	3,378	0.15
United States	−13	7	1,656	0.28
Brazil	−20	22	1,515	0.28
Argentina	−43	72	1,429	0.30

Table 2. Global average of crops and livestock VWC and yield: evolution from 1986 to 2007 and value in 2007

	Change from 1986 to 2007 (%)		2007	
Product	VWC	Yield	VWC ($kg_{water}/kg_{product}$)	Yield (kg_{crop}/m^2)
Barley	−7.5	10	1,699	0.26
Corn	−17	47	1,732	0.38
Rice	−12	18	1,161	0.36
Soy	−15	16	2,120	0.16
Wheat	−17	22	1,487	0.29
Beef	−6.6	—	8,025	—
Poultry	−10	—	3,805	—
Pork	−10	—	4,760	—

The impacts of policy changes and economic development are also observed in the example of China's soy trade. Remarkably, the trade of soy from Brazil, the United States, and Argentina to China plays a significant role in the recent global VWT increase (19% of the increase from 1986 to 2007). China's GDP growth has led to a dietary change to greater meat consumption and thus, an increased demand for meat and animal feed [GDPPC multiplied by 9.5 from 1986 to 2007 (20); meat production per capita multiplied by 3.25 (13)]. Restrictions on the import of soy commodities to China were raised by a domestic trade policy that took effect in 2000–2001 (21), allowing the country to import greater amounts of soybean meal used for animal feed. This policy shift led to the large increase in China's soy imports and a dramatic increase of China's VWI (Fig. 4*A*).

Importantly, China imports soy mostly from Brazil, the United States, and Argentina (Fig. 4*A*), and all these three countries produce soy with less water than China would use to grow this crop domestically (e.g., in 2007, the soy VWC was higher in China than in the three exporting countries) (*Materials and Methods*) (Table 1). Thus, imports of soybean to China contributed to saving water resources globally, and they were actually responsible for a substantial part (96%) of the global water savings associated with soy trade in 2007 and a significant part (36%) of the total global water savings in 2007 (Fig. 4*B*).

In general, the increase in global water savings from VWT (*Materials and Methods*) may be because of changes in three factors: an increase in the proportion of water-efficient relationships (i.e., relationships for which the importing country has a higher VWC), an increase in volumes of food traded through efficient trade relationships, and an increase in the gap between the product VWC in the importing country and the exporting country. The last two factors are the most prominent in this study. In the case of China's soybean imports, there is both an increase in the soy trade volume and a decrease of the VWC of soybean in exporting countries. Indeed, the VWC of soy in Argentina and Brazil dropped by 43% and 20% in 10 y, respectively, whereas China's soy VWC has slightly increased in the last 10 y (Table 1).

On a global average, water use efficiency has improved during the 22-y period (globally averaged VWC of all five crops has decreased and yields have increased) (Table 2). This evolution of crops VWC takes into account important changes in harvested area (*Materials and Methods*), which are most significant for soybean (22). Similar global crop yield increases were estimated in the literature (Table 2) (22). In particular, major soy exporters have significantly reduced their water use for soybean production, notably by increasing soy yield (Table 1). Interestingly, Brazil and Argentina have changed their soy yield and VWC fast enough to reach a slightly higher level of water use efficiency for soy production than the United States by 2007 (Table 1). Thus, as countries become major exporters of a certain crop, they tend to increase their agricultural water use efficiency for this crop—notably through higher yield per area—more than other countries do on a global average (Fig. 4*A* and Tables 1 and 2). This finding is also reflected in the positive global water savings from food trade (Fig. 4*B*).

Thus, although water is only one of the many factors of agricultural production and trade (other factors being the economy, labor, agricultural land, etc.), overall, less water-efficient countries have been increasingly importing from more efficient countries. We find that, in 2000, global water savings represented 4% of the water used in agriculture (a value comparable with other studies) (4), and this percentage increased to 9% in 2007. This finding illustrates that food trade actually reduces global water use by transferring commodities to relatively less-efficient regions, because irrigation requirement per unit of crop varies widely among world regions (14, 15, 22). Particularly, the soy trade dramatically evolved from a system that lost water at the global scale to the most efficient food trade system in terms of water. However, deforestation of the Amazon rainforests, partially because of the expansion of Brazil's soybean production (23), has important impacts on the water cycle (24). Analysis of these aspects and other environmental externalities related to food production is beyond the scope of the present study.

We have quantified the important changes in the water and food systems as linked through trade. The imprints of globalization and trade policies are evident in the dynamics of the global VWT network. Importantly, the food trade has become more efficient in terms of global water resources use over time, highlighting the important role of international trade in driving efficient allocation of resources.

Materials and Methods

In the global VWT network, each node represents a country, 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 node degree k refers to the number of connections of a node; here, the node degree is the number of trading partners of each country (exporter or importer). The node strength s refers to the sum of the weights assigned to each node's links; here, the node strength is the volume of virtual water exported and imported by each country. We used two main pieces of information to construct the VWT network each year from 1986 to 2007: the detailed international food trade and the VWC of each commodity in all nations. We built the global VWT network by multiplying the traded volume of a specific commodity by the VWC of this commodity in the country of export. In this study, we analyze the aggregated VWT networks built by summing the VWT from all commodities in a given year.

The international trade of agricultural products was obtained from the FAOSTAT database (13) for the 58 selected commodities (list in ref. 14) made from five major crops (barley, corn, rice, soybean, and wheat) and three livestock products (beef, pork, and poultry). We corrected any divergence in the trade volumes reported between two nations by taking the average volume. In cases in which only one country reported a trade, we kept the reported trade value, and if no data were reported between two nations, we assumed that no trade was taking place between these two nations.

VWC ($kg_{water}/kg_{product}$) of raw crops is defined as the evapotranspiration during a cropping period (kg_{water}/m^2) divided by the crop yield (kg_{crop}/m^2). The VWC of unprocessed livestock products is defined as the water consumption per head of livestock ($kg_{water}/head$) divided by the livestock production per head ($kg_{meat}/head$). The VWC value of each commodity for each year until 2001 was calculated using national crop yield time series from FAOSTAT (13) and evapotranspiration (ET) simulated with the H08 global hydrological model (14, 15). The ET simulation used WATCH meteorological forcing data (25), which cover the whole globe at 0.5° spatial resolution, from 1901 to 2001 at 6-h intervals. The cropland area (26), irrigated area (27), and crop type (28) were fixed circa year 2000 for which detailed data are available. However, ET simulation did account for yearly changes in national harvested area for each crop (13–15). From 1985 to 2005, global harvested area is estimated to have grown in a larger extent (about 7%) than global cropland area (only 2.4%) (22). We used the yearly H08 VWC estimates from 1986 to 2001. From 2002 to 2007, the VWC of livestock products was kept constant at 2001 values, and the VWC of crops was changed according to national crop yield time series (13) as (Eq. **1**)

$$VWC_{i,c,n} = VWC_{i,c,2001} \cdot \frac{Y_{i,c,2001}}{Y_{i,c,n}}, \qquad [1]$$

where the subscripts i, c, and n correspond to the considered country, crop, and year, respectively. $VWC_{i,c,n}$ is the estimated VWC of crop c in country i for year n (n = 2002–2007), Y is the yield of crop c in the country i and year n, and $VWC_{i,c,2001}$ is the VWC from H08 simulations for year 2001. Thus, ET change from 2002 to 2007 was not accounted for because of limitations of H08 forcing data. The ET values were kept constant at the year 2001 values, which are relatively close to the means over the 1986–2000 period.

The global water savings (WS) through the trade of a commodity x from an exporting country i to an importing country j are defined (4) as (Eq. **2**)

$$WS_{i,j,x} = T_{i,j,x} \cdot (VWC_{j,x} - VWC_{i,x}), \qquad [2]$$

where the subscripts i, j, and x correspond to the exporting country, the importing country, and the commodity traded, respectively. T is the volume of commodity x traded from exporting country i to importing country j, and VWC is the VWC of commodity x in each country.

We computed the water savings for all trade relationships and aggregated WS values by commodity's base product (barley, corn, rice, soy, wheat, beef, poultry, and pork) as (Eq. **3**)

$$WS_x = \sum_{(i,j)} WS_{i,j,x}, \qquad [3]$$

where (i, j) corresponds to all pairs of countries. WS_x is the global water savings associated with global trade of commodity x.

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