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Virtual water trade flows and savings under climate change

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Abstract

The international trade of food commodities links water and food systems, with important implications for both water and food security. The embodied water resources associated with food trade are referred to as "virtual water trade". We present the first study of the impact of climate change on global virtual water trade flows and associated savings for the year 2030. In order to project virtual water trade under climate change, it is essential to obtain projections of both bilateral crop trade and the water-use efficiency of crops in each country of production. We use the Global Trade Analysis Project (GTAP) to estimate bilateral crop trade flows under changes in agricultural productivity. We use the H08 global hydrologic model to estimate the water-use efficiency of each crop in each country of production and to transform crop flows into virtual water flows. We find that the total volume of virtual water trade is likely to go down under climate change. However, the staple food trade is projected to save more water across most climate impact scenarios, largely because the wheat trade re-organizes into a more water-efficient structure. These findings indicate that trade may be an adaptation measure to climate change with ramifications for policy.

1 Introduction

The repercussions of a changing climate for water and food security are receiving increasing attention (FAO, 2011). Of particular importance, the spatial patterns of precipitation and evapotranspiration are projected to be redistributed globally under a changing climate (IPCC, 2007). As the spatial distribution of these climatic factors changes, some countries will become better suited for agricultural production, while other countries will become less well-suited for agricultural production (Rosegrant et al., 2002). As the comparative advantage of agricultural production of some countries shifts, so too will patterns of food trade.

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The redistribution of food trade has been presented as a potential adaptation measure to a changing climate (Nelson et al., 2009). This is because agricultural trade flows may create an agricultural system that is resilient to uncertain spatial climate impacts (Tobey et al., 1992; Reilly et al., 1994). However, international trade may, instead, exacerbate the negative consequences of climate change for food security (Hertel et al., 2010). Thus, it is essential to understand how the world food trade system will interact with a changing climate.

The international trade of food commodities links water and food systems (Konar et al., 2011), since freshwater supply is a key factor in agricultural production. In the literature, this concept is referred to as "virtual water trade", which refers to the water that is embodied throughout the entire production process of a traded commodity, or the "water footprint" of a particular commodity (Hoekstra and Chapagain, 2008). The world food trade system, and associated virtual water trade, has important implications for both food and water security.

One of the main reasons that the topic of virtual water trade has proliferated in the literature is because it has been shown to save water globally (Chapagain et al., 2006; Aldaya et al., 2010; Hanasaki et al., 2010), increasingly so over time (Dalin et al., 2012; Konar et al., 2012). Thus, one of the major benefits of the food trade system is that it saves water resources at a global scale. For this reason, when quantifying the impacts of trade on water and food security under a changing climate, one of the key indicators of whether trade will be a suitable adaptation measure or not will be whether trade is projected to save more or less water under future climates.

The concept of virtual water trade is inherently interdisciplinary, drawing primarily from hydrology and economic trade. In particular, the topic of virtual water trade fits into the new science of "socio-hydrology" (Sivapalan et al., 2012). Projecting changes in the dual social-hydrologic system was laid out as a fundamental challenge for hydrologists (Sivapalan et al., 2012). In this paper, we make the first attempt at projecting future virtual water trade flows and associated water savings under climate change.

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2 Methods

In this paper, we quantify the virtual water trade flows between nations and the associated water savings under a changing climate, with 2001 as the baseline year and projections to 2030. We estimate the potential impacts of climate change on virtual water trade flows by projecting both bilateral food trade patterns and crop water use. To do this, we utilize both an economic model of international trade and a hydrologic model of agricultural water-use.

We employ the Global Trade Analysis Project (GTAP) general equilibrium trade model (Hertel, 1997) to quantify how changes in agricultural productivity as a result of climate change will impact bilateral trade flows of crops. To estimate crop virtual water content under climate change we utilize the H08 global hydrologic model (Hanasaki et al., 2010). Virtual water flows under climate change are calculated by multiplying the projected international trade flows of a particular commodity by the associated virtual water content of that commodity in the country of export under climate change. We describe our methodology in further detail below.

2.1 Crop trade projections

To estimate virtual water trade flows under climate change, it is essential to first project bilateral commodity trade flows. We use the Global Trade Analysis Project (GTAP) general equilibrium model to project crop trade (CT) flows under climate change. GTAP is a well-documented and established, comparative static, economic trade model which explicitly models consumption and production of each national economy in order to determine bilateral trade flows. This model operates under the key assumptions of producers maximizing profits and factor market clearing prices (Hertel, 1997).

We use the regionally disaggregated version of GTAP with 92 countries for the base year of 2001. Please refer to Table 1 for the list of countries included in this study. Note that some countries are regional aggregates. We provide regional definitions in Table 2. For simplicity, we will refer to the units of trade analysis as countries for the

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remainder of this paper, unless we specifically refer to a region. From GTAP, we obtain baseline data and projections of bilateral trade flows for the three available major crop commodities: rice, oil seeds, and wheat.

Climate change impacts trade flows in the GTAP model through scenarios of agricultural productivity. To isolate the impact of climate change on crop trade we utilize a comparative static modeling approach and adjust agricultural productivity, maintaining all else contstant to baseline values (i.e. population and income fixed to 2001). In GTAP, agricultural productivity is an input parameter that we tune according to expert assessments in the literature of how climate change will impact crop yields in the year 2030. These expert assessments were collected and synthesized by Hertel et al. (2010) for each country-crop pair in the GTAP model. For each country-crop pair a "most-likely" or "medium-productivity" yield outcome was established.

Following Hertel et al. (2010), a "low-productivity" and "high-productivity" yield outcome was determined, in addition to the most-likely outcome, for each country-crop pair. The low-productivity estimate was established based on a world with rapid temperature change, in which CO_2 fertilization is at the lower end of published estimates, and crops are highly sensitive to this warmer climate. The high-productivity scenario, on the other hand, presents a world with slower warming, high CO_2 fertilization, and low crop-sensitivity to warming (Christensen, 2007; Ainsworth et al., 2008; Tebaldi and Lobell, 2008). The low- and high- productivity estimates are meant to envelope a range of plausible yield outcomes, and should be thought of as the 5th and 95th percentile values, respectively, in a distribution of potential climate impacts on yield outcomes (Hertel et al., 2010).

The yield shocks for each country, crop and scenario are provided in Table 3. Each yield shock represents the projected percentage change in crop yield from 2001 to 2030. Note that the magnitude and direction (i.e. positive or negative) of each yield shock differs by country-crop pair. For example, yields in Japan are predicted to increase for both rice and soy under the low-productivity scenario, while they tend to

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decrease for most other countries under the low-productivity scenario. Maps of the yield shocks used to force the GTAP model are provided in Fig. 1.

Each estimate of the low-, medium-, and high-productivity outcome is based on expert assessments of the impact of climate on crop yield. These yield outcomes only account for the impact of climate, without consideration of potential adaptation measures to climate change (Hertel et al., 2010). However, in this paper, we uniformly implement the low-, medium-, and high-productivity outcomes in the model. In other words, we run three scenarios of agricultural productivity: low, medium, and high. In each scenario, every country in the GTAP model is assigned the same level of the productivity shock (i.e. the shocks are not identical, but each country experiences the same of either the low-, medium-, or high-productivity shocks in each scenario; refer to Table 3 for the specific shocks).

Thus, we implement yield scenarios in the GTAP model, which we assume correspond to adaptation measures, in addition to the country-crop yield outcomes based upon climate impacts only. Our assumption is that the "low-yield scenario" represents a world where no adaptation measures to climate change are taken, the "most-likely yield scenario" represents a world where current trends continue, and the "high-yield scenario" represents a world where agricultural technology is widely implemented (i.e. high performing cultivars).

GTAP produces bilateral trade flows in value terms [millions of USD]. In order to convert these value flows into crop volume flows, we divide by the projected price along each trade link in the year 2030. The GTAP model produces a relative price change for each trade link between 2001 and 2030. We project prices to 2030 by using the relative price change data from GTAP [%] and price data for the year 2001. We obtain agricultural producer price data [USD/ton] for the year 2001 from the Food and Agricultural Organization (FAOSTAT, 2012). For instances where there is no data for a particular country, price data for a neighbor country was used. For GTAP regions, price data was collected for countries within that region and averaged across the member countries.

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2.2 Virtual water content projections

To convert crop trade flows under climate change into virtual water flows, we use the H08 global hydrologic model. The H08 model is a state-of-the-art hydrologic model incorporating both natural and anthropogenic water flows, with energy and water balance closure. The H08 model consists of six modules: land surface hydrology, river routing, crop growth, reservoir operation, environmental flow requirements, and water withdrawal for human use (Hanasaki et al., 2008b,a, 2010).

Virtual water content (VWC) is a country-specific estimate of the volume of water used to produce a unit of agricultural output (Hanasaki et al., 2010). Thus, volumes of crop trade are translated into volumes of virtual water trade by multiplying the crop trade volume by the VWC of that crop in the country of export. Using the H08 model, we calculated the VWC of three unprocessed crops: rice, soy, and wheat. VWC is defined as the total evapotranspiration ($\overline{\mathrm{ET}}$) during a cropping period [$\mathrm{kg\,m^{-2}}$] divided by the total crop yield (Y) [$\mathrm{kg\,m^{-2}}$], e.g. $\mathrm{VWC} = \overline{\mathrm{ET}}/Y$. Large values of VWC indicate a large amount of water used for a unit of crop output, while low values of VWC indicate less water used per unit of crop output. Thus, large values of VWC represent low water-use efficiency, while small values of VWC indicate high water-use efficiency.

Two types of input data are used to force the H08 model: land use and meteorological. For land use, the global distribution of cropland (Ramankutty et al., 2008), major crops (Monfreda et al., 2008), irrigated areas (Siebert et al., 2005), and cropping intensity (Doll and Siebert, 2004) were used to run the model. These land use data were fixed to the year 2000. VWC under the baseline scenario is obtained by forcing the H08 model with Integrated Project Water and Global Change (EU WATCH) meteorological data (Weedon et al., 2011), while yield data is obtained from the Food and Agriculture Organization of the United Nations (FAOSTAT, 2012).

Projections of the $\overline{\mathrm{ET}}$ component of VWC under climate change were obtained by forcing the H08 model with climate data from 14 global climate models (GCMs) driven with emissions from the IPCC SRES A2 scenario (IPCC, 2007) for 2030. Assumptions

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regarding the A2 scenario are that there will be relatively slow convergence in regional fertility patterns, relatively slow convergence in inter-regional GDP per capita differences, relatively slow end-use and supply-side energy efficiency improvements, and delayed developments of renewable energy. The A2 scenario is amongst the most pessimistic carbon emission scenarios (IPCC, 2007). However, note that recent carbon dioxide emissions are actually above those provided by the A2 scenario, indicating that this scenario may be more conservative than initially intended, though future emissions do remain uncertain (Karl et al., 2009).

A list of the 14 GCMs used to obtain climate change projections of $\overline{\mathrm{ET}}$ are provided in Table 4. Projections of air temperature, incoming long wave radiation, and precipitation were obtained from each of the 14 GCMs. Climate grids for each of the GCMs were input separately into the H08 model. In this way, 14 estimates of VWC by GCM are obtained for each country-crop pair. The time average of $\overline{\mathrm{ET}}$ from 2020–2039 is used to represent $\overline{\mathrm{ET}}$ for 2030.

In order to account for yield changes, we harmonize information on new evapotranspiration levels given by the H08 model with the yield shocks used in the GTAP model. Thus, we project VWC according to the following equation:

$$\mathrm{VWC}_{e,c,\mathrm{GCM},s} = \frac{\overline{\mathrm{ET}}_{e,c,\mathrm{GCM}}}{Y_{e,c,\mathrm{baseline}}} \cdot \left(\frac{1}{1 + r_{e,c,s}}\right) \tag{1}$$

where e, c, GCM, r, and s indicate country of export, crop, global climate model (GCM), rate of change in crop yield, and yield scenario, respectively. The rate of change in crop yield is indexed by the country of export, crop, and yield scenario (i.e. low-, medium-, and high-productivity). Refer to Table 3 for the list of yield shocks by country, crop, and scenario.

Note that GTAP provides trade data for oil seeds, but we use FAO price data and H08 VWC data for soy only. This is because FAO price data for soy is more readily available than for oil seeds and H08 data is only available for soy. For this reason,

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for the remainder of this paper we refer to virtual water flows associated with the soy commodity trade, rather than the oil seed trade.

2.3 Virtual water trade projections

Projections of both crop trade (CT) and virtual water content (VWC) allow us to construct virtual water trade (VWT) under climate change. Virtual water flows under climate change are calculated by multiplying the projected international trade flows of a particular commodity by the associated virtual water content of that commodity in the country of export under climate change. The construction of virtual water trade flows under climate change is expressed as:

$$\mathrm{VWT}_{e,i,\mathrm{GCM},s} = \sum_{c} \mathrm{VWC}_{e,\mathrm{GCM},s} \cdot \mathrm{CT}_{e,i,s} \tag{2}$$

where the subscripts e, i, GCM, s, and c denote country of export, country of import, global climate model (GCM), yield scenario, and commodity, respectively. Note that VWT in the above equation is summed over the commodities. For this reason, we refer to these virtual water trade flows as the "aggregate" flows. For flows associated with a particular commodity only, we refer to the commodity by name (i.e. rice, soy, or wheat).

Global water savings (GWS) is a theoretical measure of how much water is saved by the global food trade. For each trade link, the water use efficiency of the country of export is subtracted from the water use efficiency of the country of import. The difference in water use efficiencies between trade partners is multiplied by the volume of crop trade occuring on that trade link. Positive values indicate that water is being saved by that trade link; Negative values indicate trade-based water losses. GWS is the sum across all trade links. We calculate GWS under climate change as:

$$\mathrm{GWS}_{\mathrm{GCM},s} = \sum_{e,i,c} T_{e,i,c} \cdot (\mathrm{VWC}_{i,c,\mathrm{GCM},s} - \mathrm{VWC}_{e,c,\mathrm{GCM},s}) \tag{3}$$

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where the subscripts e, i, c, GCM, and s are as above. T is the volume of commodity c traded from exporting country e to importing country i. The difference in water use efficiency between i and e is $\mathrm{VWC}_{i,c,\mathrm{GCM},s} - \mathrm{VWC}_{e,c,\mathrm{GCM},s}$, which is indexed by country, crop, GCM, and yield scenario. As with VWT, note that GWS is aggregated across the commodities. For water savings associated with a specific commodity, we refer to the commodity by name.

3 Results and discussion

Here, we present our results on the impacts of climate change on crop trade, virtual water content, virtual water trade flows, and water savings from trade. These results were obtained using three yield scenarios and one climate scenario (i.e. the IPCC SRES A2 emissions scenario). Since we harmonized our projections of VWC under the A2 emissions scenario with the three crop yield scenarios, we refer to all projections as occurring under "scenarios" of climate change.

3.1 Crop trade under climate change

We obtain the total volume of crop trade under the baseline scenario from the GTAP trade data. The total commodity trade by crop and scenario is provided in Fig. 2a–c. In the baseline data, the volume of wheat trade is higher than either soy or rice. The total wheat trade under the baseline scenario is 1.52×10^8 metric tons, while the total soy and rice trade under the baseline scenario is 8.86×10^7 t and 9.62×10^6 t, respectively.

In the climate change scenarios, the volume of the wheat trade continue to be the largest of the commodity trades. Additionally, the total wheat trade volume exhibits more variability under the yield scenarios than either soy or rice, seen by the larger spread in values along the y-axis in Fig. 2c as compared with Fig. 2b. This indicates that the wheat trade is more sensitive to yield shocks than either rice or soy.

3.2 Virtual water content under climate change

Graphs of VWC for each crop and yield scenario are provided in Fig. 2d–f. Note that the water-use efficiency tends to go down (i.e. VWC increases) under the low yield scenario for both rice and soy, but remains relatively unaffected under the low yield scenario for wheat. For the medium and high yield scenarios, on the other hand, the water-use efficiency increases (i.e. VWC decreases) for all crops. This is due to decreased planting times in the H08 model and increased crop yields. Decreased cropping times are particularly pronounced for the northern mid-latitudes.

3.3 Virtual water trade flows under climate change

In this section, we quantify how changes in staple crop trade patterns and water productivity under climate change will impact virtual water trade (VWT). Total VWT by crop and yield scenario is provided in Fig. 3. For all commodities, the total VWT tends to decrease across climate change scenarios, as compared to the baseline scenario (year 2001). VWT decreases under the medium and high yield scenarios primarily due to decreased VWC. Slight increases in VWC under the low yield scenario are outweighed by decreased crop trade.

The top 10 exporters and importers of virtual water by crop and scenario are provided in Tables 5 and 6, respectively. The USA remains the top exporter of virtual water under both the low and high yield scenarios. Under the low yield scenario, Argentina moves from being the 2nd to the 4th largest exporter. Canada benefits under the high yield scenario, moving from 4th to 2nd position. Thus, changes in agricultural productivity in some countries disproportionately impacts their export prospects.

China and Japan remain the dominant importers under all scenarios, with little change in the rest of the top 10. China and Japan import the largest volumes of virtual water primarily due to their large imports of soy, though Japan is also a top wheat importer. The Rest of North Africa exhibits high sensitivity to price fluctuations, importing

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less under the low yield (and higher price) and importing more under the high yield (and lower price) scenarios.

The largest links by volume of virtual water traded by crop and by yield scenario are provided in Table 7. In 2001, the largest link is that from the USA to Japan. This link remains the largest under the low yield scenario, but becomes the export from the USA to China under the high yield scenario. Note that the Rest of the Former Soviet Union exhibits significant trade amongst its member nations under the baseline scenario, but falls out of the top 10 under both the low and high yield scenarios. The USA and Argentina are the only 2 countries with top export links across all 3 crops.

The dominant link in the rice trade across all scenarios is that from Pakistan to the Rest of the Middle East. However, the volume traded on this link decreases by approximately 20 % under the high yield scenario (i.e. from 2.35×10^8 m^3 water traded under the baseline scenario to 1.90×10^8 m^3 water traded under the high yield scenario). Pakistan continues to trade very large volumes of virtual water to the UK across all 3 scenarios.

The link between the USA and China is the largest in the soy trade under the baseline scenario. However, both Argentina and Brazil export more water to China through the soy trade under the low yield scenario. The trade link between the USA and Mexico remains strong across climate scenarios, likely because of free trade policies between these two countries.

For the wheat trade, the largest link is that from Argentina to Brazil across the three scenarios. The USA and Canada stand to benefit under the high yield scenario, with the USA serving as the exporter in 4 of the top 5 links, and Canada gaining 2 export links to the USA and Iran.

3.4 Water savings under climate change

Of particular importance, the international trade in food commodities has been shown to save water (Chapagain et al., 2006; Yang et al., 2006; Fader et al., 2011), increasingly so over the last few decades (Dalin et al., 2012; Konar et al., 2012). This

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trade-based global water savings (GWS) occurs when food tends to be exported by countries with a higher water-use efficiency than the importing countries. Our goal in this section is to understand how changes in trade patterns and water productivity under climate change will impact GWS.

The difference in water use efficiency between two trade partners provides a theoretical measure of how much water would have been used had the commodity been produced in the importing country, rather than in the exporting country. When this difference is positive, it indicates that the trade relationship is saving water. When the difference is negative, the trade is inefficient in terms of water resources. This measure assumes that countries would produce to consume what they currently import to consume, without any changes to agricultural water use efficiency.

Figure 4 shows GWS by crop and yield scenario. GWS is projected to increase across almost all future scenarios, with the exception of the soy trade. This indicates that the aggregate food trade is projected to re-organize into a more water-efficient pattern under climate change. The rice trade is organized in a pattern that loses 3.67×10^9 m^3 of water under the baseline scenario. Under all three yield scenarios, rice is projected to become much more efficient (i.e. lose less water). This indicates that the rice trade is re-organizing into a pattern that is more water efficient. However, the rice trade continues to lose water under all scenarios (Note negative y-axis in Fig. 4b).

Both the soy and wheat trade save water under the baseline scenario. The soy trade saves 1.86×10^{10} m^3 water, while the wheat trade saves 1.05×10^{11} m^3 water. Under all yield scenarios, the soy trade is predicted to save less water in the future. The wheat trade, on the other hand, is predicted to save more water under all future scenarios. Aggregate virtual water trade exhibits water savings patterns that mimic those of the wheat trade (i.e. compare Fig. 4a with Fig. 4d). This is because large wheat trade volumes drive the aggregate flows.

Maps of VWC averaged across crops and GCMs under the low-yield and high-yield scenarios are provided in Fig. 5a, d, g. Each country is assigned a color to indicate its water-use efficiency, or VWC. Large values of VWC indicate a large amount of water

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used for a unit of crop output, while low values of VWC indicate less water used per unit of crop output. Thus, large values of VWC represent low water-use efficiency, while small values of VWC indicate high water-use efficiency. The water-use efficiency tends to increase under the high-yield scenario (refer to Fig. 5g; VWC scale goes to 5589), but decrease under the low-yield scenario (refer to Fig. 5d; VWC scale goes to 7167).

The links that save the most water by commodity and climate change scenario are provided in Table 8. The link that saves the most water under the aggregate food trade is that from Canada to Venezuela. This link saves 12.1×10^9 m^3 of water in the baseline scenario and is driven by the trade in wheat. This indicates that Venezuela is much less water-efficient in wheat production than is Canada, and that a large volume of wheat is traded from Canada to Venezuela. Thus, this trade relationship saves water when compared to the theoretical, autarky world with no trade where Venezuela instead produces the wheat itself that it currently imports from Canada. This link is projected to save even more water in the future (i.e. 13.8×10^9 m^3 and 15.8×10^9 m^3 under the low and high yield scenarios, respectively; refer to Table 8).

The links that lose the most virtual water by crop and by yield scenario are provided in Table 9. The link that loses the most water under the baseline scenario is that from Pakistan to Rest of Middle East (i.e. losing 2.27×10^9 m^3). The link that loses the most water under both climate scenarios is that from Brazil to the Netherlands (i.e. losing 3.01×10^9 m^3 and 2.46×10^9 m^3 under the low and high yield scenarios, respectively). However, the link from Pakistan to the Rest of Middle East remains the largest loser of water for rice across all scenarios. Pakistan features in the exporter relationship for 6 of the 10 most negative rice trade links in the baseline scenario and continues to export to more water-efficient countries under climate change scenarios. This indicates that water-inefficient links originating in Pakistan may arise due to domestic support for agricultural production. In fact, irrigation subsidies in Pakistan have been estimated to be approximately 0.6 billion $\$ yr^{-1}$ (Rosegrant et al., 2002), comparable with the estimated 1 billion $\$ yr^{-1}$ irrigation subsidies in the United States (Berthelot, 2007).

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Food trade is often not rational from a crop yield or water efficiency perspective. In addition to comparative advantage, trade links are driven by economic and trade policies, such as the North American Free Trade Agreement (NAFTA). This may help to explain why some of the trade links amongst NAFTA partners exhibit large water losses. For example, the trade of wheat from the USA to Mexico represents the largest loss of water associated with the wheat trade. This link continues to lose the most water under climate change. The export of wheat from Canada to Mexico also features in the top 5 most water-inefficient links associated with the wheat trade across all scenarios.

Figure 5 maps the five links that save and lose the most water under the baseline, low-yield, and high-yield scenarios. The width of the arrows indicates the volume saved by the trade link and the color of the arrow indicates if it is saving or losing water (i.e. black arrows indicate links that are saving water and red arrows indicate links that are losing water). In the baseline scenario, trade from the USA to China and Korea are the 3rd and 4th ranked links in terms of water savings, respectively. However, under the low-yield scenario, trade from the USA to Asia no longer features in the most beneficial links from a water-savings perspective, since water-use efficiency is negatively impacted in the USA under this scenario.

4 Conclusions

In this paper, we quantify, for the first time, future virtual water trade flows and associated water savings under climate change. This is an important first step in projecting changes in the dual social-hydrologic system, which was recently laid out as a fundamental challenge for hydrologists (Sivapalan et al., 2012). To project virtual water trade flows, we utilize both an economic model of international trade (e.g. the Global Trade Analysis Project) and a hydrologic model of agricultural water-use (e.g. the H08 global hydrology model).

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We find that rice trade volumes remain relatively constant under climate change. Soy trade volumes oscillate with climate change scenarios and wheat trade volumes exhibit the most variability. Wheat trade volumes are much larger than either soy or rice, but the VWC of soy is larger than it is for wheat. This leads to volumes of virtual water trade associated with the soy commodity trade being larger than they are for wheat. However, much larger volumes of water are saved through the wheat trade, which is why the pattern of global water savings for aggregate crops mirrors the wheat-only commodity trade.

Trade-related water savings are projected to increase with crop yield for the aggregate, soy, and wheat commodities. The wheat commodity trade is very sensitive to yield scenarios, and exhibits the largest gains in water savings with increasing agricultural productivity. The soy commodity trade is more sensitive to climatic changes and exhibits the highest variability across global climate models. However, the high yield scenario does not necessarily translate into more trade-related water savings. For the rice commodity trade, the spatial distribution of precipitation and crop yields and other economic factors, lead to more trade-related water savings in the low- productivity scenario, indicating that the rice trade is not rational from a water-use perspective.

It would be advantageous to reduce trade links that result in large water losses and encourage water-efficient links, in an effort to make food trade more water-efficient. Opportunities to reduce water-inefficient links include improving the water-use efficiency and optimizing crop and cultivar choice in producing countries. These actions may be encouraged through certain policies, such as market pricing of water and food, and removing distortionary subsidies in producer countries. One potential opportunity to enhance trade on water-efficient links would be the removal of tariffs and other trade barriers. However, free trade agreements may amplify trade on links that lose water. For this reason, one potential policy mechanism could be to link free trade policies with reductions in domestic support for agricultural production.

This study indicates that trade may serve as an important adaptation measure to climate change at the global scale. Here, the international food trade is re-configured according to yield shocks and subsequent adjustments in food prices and trade regimes only. Even without targeted policies, we project that the world food trade system will re-organize under climate change in a manner that saves more water globally. Thus, international trade may help us adapt to climate change at no extra cost. With targeted policies, trade may become an even more beneficial adaptation measure to climate change.

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Table 1. Countries in the GTAP trade database.

Number	Country Name	Number	Country Name
1	Australia	47	Ireland
2	New Zealand	48	Italy
3	Rest of Oceania	49	Luxembourg
4	China	50	Netherlands
5	Hong Kong	51	Portugal
6	Japan	52	Spain
7	Republic of Korea	53	Sweden
8	Taiwan	54	Switzerland
9	Rest of East Asia	55	Rest of EFTA
10	Indonesia	56	Rest of Europe
11	Malaysia	57	Albania
12	Philippines	58	Bulgaria
13	Singapore	59	Croatia
14	Thailand	60	Cyprus
15	Vietnam	61	Czech Republic
16	Rest of Southeast Asia	62	Hungary
17	Bangladesh	63	Malta
18	India	64	Poland
19	Pakistan	65	Romania
20	Sri Lanka	66	Slovakia
21	Rest of South Asia	67	Slovenia
22	Canada	68	Estonia
23	United States of America	69	Latvia
24	Mexico	70	Lithuania
25	Rest of North America	71	Russian Federation
26	Bolivia	72	Rest of Former Soviet Union
27	Colombia	73	Turkey
28	Ecuador	74	Iran, Islamic Republic of
29	Peru	75	Rest of Middle East
30	Venezuela	76	Morocco
31	Argentina	77	Tunisia
32	Brazil	78	Rest of North Africa
33	Chile	79	Botswana
34	Uruguay	80	South Africa
35	Rest of South America	81	Rest of South African Customs Union
36	Central America	82	Malawi
37	Rest of Free Trade Area of the Americas	83	Mauritius
38	Rest of the Caribbean	84	Mozambique
39	Austria	85	Tanzania
40	Belgium	86	Zambia
41	Denmark	87	Zimbabwe
42	Finland	88	Rest of Southern African Development Community
43	France	89	Madagascar
44	Germany	90	Nigeria
45	UK	91	Uganda
46	Greece	92	Rest of Sub Saharan Afaric

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Table 2. Definition of regions in the GTAP trade database.

Region Name	Country List
Rest of Oceania	American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, Niue, Norfolk Islands, Northern Mariana Islands, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis & Futuna
Rest of East Asia	Democratic People's Republic of Korea, Macau, Mongolia
Rest of Southeast Asia	Brunei Darussalam, Cambodia, Lao People's Democratic Republic, Myanmar, Timor-Leste
Rest of South Asia	Afghanistan, Bhutan, Maldives, Nepal
Rest of North America	Bermuda, Greenland, Saint Pierre & Miquelon
Rest of South America	Falkland Islands, French Guiana, Guyana, Paraguay, Suriname
Central American	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama
Rest of Free Trade Area of the Americas (FTAA)	Antigua & Barbuda, Bahamas, Barbados, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Puerto Rico, Saint Kitts & Nevis, Saint Lucia, Saint Vincent & the Grenadines, Trinidad & Tobago, US Virgin Islands
Rest of the Caribbean	Anguilla, Aruba, Cayman Islands, Cuba, Guadeloupe, Martinique, Montserrat, Netherlands Antilles, Turks & Caicos, British Virgin Islands
Rest of European Free Trade Area (EFTA)	Iceland, Liechtenstein, Norway
Rest of Europe	Andorra, Bosnia & Herzegovina, Faroe Islands, Gibraltar, Macedonia, Monaco, San Marino, Serbia & Montenegro
Rest of Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kygyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Rest of Middle East	Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestinian Territory, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen
Rest of North Africa	Algeria, Egypt, Libyan Arab Jamahiriya
Rest of South African Customs Union (SACU)	Lesotho, Namibia, Swaziland
Rest of Southern African Development Community (SADC)	Angola, The Democratic Republic of Congo, Mauritius, Seychelles
Rest of Sub Saharan Afaric	Benin, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote dÍvoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Mali, Mauritania, Mayotte, Niger, Nigeria, Reunion, Rwanda, Saint Helena, Sao Tome & Principe, Senegal, Sierra Leone, Somalia, Sudan, Togo

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Table 3. Yield shocks by country, crop, and scenario. Each shock represents the projected percentage change [%] from 2001 to 2030. These values follow Hertel et al. (2010).

Country	Rice			Soy			Wheat		
	Low	Med	High	Low	Med	High	Low	Med	High
Australia	−5	7	19	−10	2	14	−5	7	19
New Zealand	−5	7	19	−10	2	14	−5	7	19
Rest of Oceania	−5	7	19	−10	2	14	−5	7	19
China	−12	0	12	−12	0	12	−10	2	14
Hong Kong	−10	−3	4	−10	−3	4	−10	−3	4
Japan	2	9	16	2	9	16	−3	4	11
Republic of Korea	5	12	19	5	12	19	5	12	19
Taiwan	5	12	19	5	12	19	5	12	19
Rest of East Asia	−10	−3	4	−10	−3	4	−10	−3	4
Indonesia	0	7	14	0	7	14	0	7	14
Malaysia	−10	−3	4	−10	−3	4	−10	−3	4
Philippines	−10	−3	4	−10	−3	4	−10	−3	4
Singapore	5	12	19	5	12	19	5	12	19
Thailand	−10	−3	4	−10	−3	4	−10	−3	4
Vietnam	−10	−3	4	−10	−3	4	−10	−3	4
Rest of Southeast Asia	−10	−3	4	−10	−3	4	−10	−3	4
Bangladesh	−10	−3	4	−10	−3	4	−10	−3	4
India	−15	−5	4	−10	−3	4	−10	−3	4
Pakistan	−15	−5	4	−10	−3	4	−10	−3	4
Sri Lanka	−15	−5	4	−10	−3	4	−10	−3	4
Rest of South Asia	−15	−5	4	−10	−3	4	−10	−3	4
Canada	−10	−3	4	0	12	24	−5	7	19
United States of America	−10	−3	4	−10	2	14	−10	2	14
Mexico	−15	−3	9	−15	−3	9	−15	−3	9
Rest of North America	−10	−3	4	0	12	24	−5	7	19
Bolivia	−10	−3	4	−10	−3	4	−10	−3	4
Colombia	0	7	14	0	7	14	0	7	14
Ecuador	−10	−3	4	−10	−3	4	−10	−3	4
Peru	0	7	14	0	7	14	0	7	14
Venezuela	−10	−3	4	−10	−3	4	−10	−3	4
Argentina	−10	−3	4	−10	−3	4	−10	−3	4
Brazil	−10	−3	4	−5	2	9	−10	−3	4
Chile	−10	−3	4	−10	−3	4	−10	−3	4
Uruguay	−10	−3	4	−10	−3	4	−10	−3	4
Rest of South America	−10	−3	4	−10	−3	4	−10	−3	4
Central America	−15	−3	9	−15	−3	9	−15	−3	9
Rest of FTAA	−15	−3	9	−15	−3	9	−15	−3	9
Rest of Caribbean	−15	−3	9	−15	−3	9	−15	−3	9
Austria	−5	7	19	−5	7	19	−5	7	19
Belgium	−5	7	19	−5	7	19	−5	7	19
Denmark	−5	7	19	−5	7	19	−5	7	19
Finland	−5	7	19	−5	7	19	−5	7	19
France	−5	7	19	−5	7	19	−5	7	19
Germany	−5	7	19	−5	7	19	−5	7	19

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Table 3. Continued.

Country	Rice			Soy			Wheat		
	Low	Med	High	Low	Med	High	Low	Med	High
UK	−5	7	19	−5	7	19	−5	7	19
Greece	−5	7	19	−5	7	19	−5	7	19
Ireland	−5	7	19	−5	7	19	−5	7	19
Italy	−5	7	19	−5	7	19	−5	7	19
Luxembourg	−5	7	19	−5	7	19	−5	7	19
Netherlands	−5	7	19	−5	7	19	−5	7	19
Portugal	−5	7	19	−5	7	19	−5	7	19
Spain	−5	7	19	−5	7	19	−5	7	19
Sweden	−5	7	19	−5	7	19	−5	7	19
Switzerland	−5	7	19	−5	7	19	−5	7	19
Rest of EFTA	−5	7	19	−5	7	19	−5	7	19
Rest of Europe	−5	7	19	−5	7	19	−5	7	19
Albania	−5	7	19	−5	7	19	−5	7	19
Bulgaria	−5	7	19	−5	7	19	−5	7	19
Croatia	−5	7	19	−5	7	19	−5	7	19
Cyprus	−5	7	19	−5	7	19	−5	7	19
Czech Republic	−5	7	19	−5	7	19	−5	7	19
Hungary	−5	7	19	−5	7	19	−5	7	19
Malta	−5	7	19	−5	7	19	−5	7	19
Poland	−5	7	19	−5	7	19	−5	7	19
Romania	−5	7	19	−5	7	19	−5	7	19
Slovakia	−5	7	19	−5	7	19	−5	7	19
Slovenia	−5	7	19	−5	7	19	−5	7	19
Estonia	−5	7	19	−5	7	19	−5	7	19
Latvia	−5	7	19	−5	7	19	−5	7	19
Lithuania	−5	7	19	−5	7	19	−5	7	19
Russian Federation	−5	7	19	−5	7	19	−5	7	19
Rest of Former Soviet Union	−5	7	19	−5	7	19	−5	7	19
Turkey	−5	2	9	−5	2	9	−5	2	9
Iran, Islamic Republic of	−5	2	9	−5	2	9	−5	2	9
Rest of Middle East	−5	2	9	−5	2	9	−5	2	9
Morocco	−5	2	9	−5	2	9	−5	2	9
Tunisia	−5	2	9	−5	2	9	−5	2	9
Rest of North Africa	−5	2	9	−5	2	9	−5	2	9
Botswana	−15	−3	9	−15	−3	9	−15	−3	9
South Africa	−20	−8	4	−20	−8	4	−20	−8	4
Rest of SACU	−15	−3	9	−15	−3	9	−15	−3	9
Malawi	−15	−3	9	−15	−3	9	−15	−3	9
Mauritius	−15	−3	9	−15	−3	9	−15	−3	9
Mozambique	−15	−3	9	−15	−3	9	−15	−3	9
Tanzania	−15	−3	9	−15	−3	9	−15	−3	9
Zambia	−15	−3	9	−15	−3	9	−15	−3	9
Zimbabwe	−15	−3	9	−15	−3	9	−15	−3	9
Rest of SADC	−15	−3	9	−15	−3	9	−15	−3	9
Madagascar	−15	−3	9	−15	−3	9	−15	−3	9
Nigeria	−15	−3	9	−15	−3	9	−15	−3	9
Uganda	−15	−3	9	−15	−3	9	−15	−3	9
Rest of Sub Saharan Afaric	−15	−3	9	−15	−3	9	−15	−3	9

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Table 4. List of the 14 GCMs that were used to obtain estimates of the evapotranspiration component ($\overline{ET}$) of virtual water content (VWC) under climate change in the H08 global hydrology model.

Number	Global Climate Model
1	UKMO-HadGEM1
2	ECHAM5/MPI-OM
3	UKMO-HadCM3
4	GFDL-CM2.1
5	CGCM3.1 (T47)
6	CSIRO Mk3.0
7	CCSM3
8	MIROC3.2 (medres)
9	GFDL-CM2.0
10	MRI-CGCM2.3.2
11	CNRM-CM3
12	INM-CM3.0
13	PCM
14	IPSL-CM4

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Table 5. Top exporters of virtual water by crop under the baseline, low, and high yield scenario. All values are in billions of cubic meters. "RFSU" indicates Rest of Former Soviet Union, "RSA" indicates Rest of South America, "RNA" indicates Rest of North Africa.

Rank	Baseline		Low		High	
	Volume	Country	Volume	Country	Volume	Country
Agg						
1	110	USA	77.6	USA	115	USA
2	37.5	Argentina	37.3	Brazil	37.4	Canada
3	33.4	Brazil	36.7	Canada	35.0	Argentina
4	33.6	Canada	27.0	Argentina	31.2	Brazil
5	23.3	RFSU	12.0	Australia	18.7	Australia
6	15.2	Australia	8.78	RFSU	10.6	RFSU
7	12.2	India	7.76	India	9.12	India
8	7.99	France	7.10	France	7.43	France
9	6.67	China	4.43	Germany	7.07	Russia
10	4.93	Germany	4.26	Russia	5.06	Germany
Rice						
1	3.35	Pakistan	3.51	Pakistan	2.73	Pakistan
2	2.38	USA	1.86	USA	1.99	USA
3	1.65	India	0.71	India	1.55	India
4	0.88	Thailand	0.70	RSA	1.04	Thailand
5	0.65	RSA	0.63	Thailand	0.56	RSA
6	0.52	Uruguay	0.50	Uruguay	0.50	Uruguay
7	0.39	Japan	0.37	Japan	0.41	Argentina
8	0.33	Argentina	0.25	Argentina	0.37	Japan
9	0.20	China	0.17	RNA	0.19	China
10	0.13	RNA	0.12	RFSU	0.14	Italy
Soy						
1	65.3	USA	43.0	USA	72.3	USA
2	33.8	Brazil	37.5	Brazil	31.9	Brazil
3	18.7	Argentina	15.2	Argentina	17.0	Argentina
4	7.11	India	8.14	Canada	8.98	Canada
5	6.64	Canada	5.02	India	5.76	India
6	6.10	China	3.42	RFSU	3.76	China
7	3.03	RFSU	3.16	China	3.16	RFSU
8	2.11	Australia	1.77	Australia	2.19	Russia
9	1.66	RSA	1.48	France	2.06	Australia
10	1.61	France	1.45	RSA	1.68	RSA
Wheat						
1	42.4	USA	28.3	USA	46.2	USA
2	26.9	Canada	28.2	Canada	31.8	Canada
3	20.2	RFSU	13.4	Argentina	16.1	Argentina
4	18.4	Argentina	10.4	Australia	16.0	Australia
5	13.0	Australia	5.68	France	7.21	RFSU
6	6.35	France	5.21	RFSU	6.08	France
7	3.55	Germany	3.14	Germany	4.55	Russia
8	3.39	India	2.86	Russia	3.64	Germany
9	3.12	Russia	2.05	India	1.78	India
10	1.52	Turkey	1.49	Turkey	1.58	Hungary

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Table 6. Top importers of virtual water by crop under the baseline, low, and high yield scenario. All values are in billions of cubic meters. "RME" indicates Rest of Middle East, "RNA" indicates Rest of North Africa. "RFTAA" indicates Rest of Free Trade Area of the Americas, "REA" indicates Rest of East Asia, "RSSA" indicates Rest of Sub-Saharan Afaric, "RFSU" indicates Rest of Former Soviet Union.

Rank	Baseline		Low		High	
	Volume	Country	Volume	Country	Volume	Country
Agg						
1	36.8	China	30.2	China	37.1	China
2	26.7	Japan	23.7	Japan	25.4	Japan
3	17.3	Mexico	14.2	Mexico	16.9	Netherlands
4	16.2	Netherlands	13.4	Netherlands	16.1	Mexico
5	15.1	RME	12.0	RME	15.0	RME
6	13.8	Spain	10.1	Spain	14.8	RNA
7	13.6	RNA	9.91	Brazil	13.2	Brazil
8	12.4	Iran	9.30	RNA	11.7	Spain
9	12.1	Brazil	8.69	Iran	11.3	Iran
10	11.6	Italy	8.61	Italy	10.9	Italy
Rice						
1	3.13	RME	3.52	RME	2.81	RME
2	1.30	UK	0.99	UK	1.38	UK
3	0.80	Brazil	0.71	Brazil	0.89	Brazil
4	0.73	Mexico	0.65	Mexico	0.69	Mexico
5	0.63	CA	0.54	CA	0.57	CA
6	0.39	RFTAA	0.45	RFTAA	0.40	Netherlands
7	0.39	REA	0.37	REA	0.37	RFTAA
8	0.38	Netherlands	0.32	Netherlands	0.37	REA
9	0.36	France	0.24	France	0.36	USA
10	0.35	USA	0.24	USA	0.25	France
Soy						
1	34.7	China	28.6	China	36.2	China
2	15.9	Japan	13.8	Japan	16.0	Japan
3	13.2	Netherlands	11.5	Netherlands	14.5	Netherlands
4	12.2	Mexico	8.73	Mexico	12.2	Mexico
5	8.63	Spain	7.48	Spain	8.62	Spain
6	8.06	Germany	7.32	Germany	7.39	Germany
7	5.56	Taiwan	4.58	Taiwan	6.84	Taiwan
8	4.35	Belgium	3.70	Belgium	4.79	Belgium
9	4.29	Indonesia	3.36	Korea	4.47	Korea
10	4.06	Korea	3.30	UK	4.01	Indonesia
Wheat						
1	11.4	Iran	9.09	Japan	13.0	RNA
2	11.3	RNA	8.72	Brazil	11.1	Japan
3	10.7	Brazil	7.81	Iran	11.0	Brazil
4	10.5	Japan	7.53	RNA	10.5	Iran
5	8.68	RME	5.85	RME	9.14	RME
6	7.48	Italy	5.27	Italy	6.99	Italy
7	6.38	RFSU	4.14	Mexico	5.31	Philippines
8	5.68	Korea	4.05	Phillipines	4.85	RSSA
9	5.13	Spain	3.63	Korea	4.81	Mexico

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Table 7. Largest links by volume of virtual water traded by crop under the baseline, low, and high yield scenario. All values are in billions of cubic meters. Note that "Export" refers to the country of export and "Import" refers to the country of import. Note that "RFSU" indicates Rest of Former Soviet Union, "RME" indicates Rest of Middle East, "RNA" indicates Rest of North Africa, "CA" indicates Central America, "RFTAA" indicates Rest of Free Trade Area of the Americas.

Rank	Baseline			Low			High		
	Volume	Export	Import	Volume	Export	Import	Volume	Export	Import
Agg									
1	14.3	USA	Japan	10.6	USA	Japan	15.6	USA	China
2	13.9	USA	China	9.99	USA	Mexico	13.9	USA	Japan
3	13.7	USA	Mexico	9.60	USA	China	13.4	USA	Mexico
4	11.8	Argentina	China	8.58	Argentina	Brazil	11.3	Argentina	Brazil
5	10.4	Argentina	Brazil	8.33	Brazil	China	10.9	Argentina	China
6	7.35	Brazil	China	8.19	Argentina	China	7.28	USA	Taiwan
7	6.10	USA	Taiwan	6.85	Canada	Japan	6.84	Brazil	China
8	6.03	Brazil	Netherlands	6.51	Brazil	Netherlands	6.10	Brazil	Netherlands
9	5.40	Canada	Japan	5.17	USA	Taiwan	5.91	Canada	Japan
10	5.29	RFSU	RFSU	3.84	Canada	USA	5.74	USA	RNA
Rice									
1	2.35	Pakistan	RME	2.80	Pakistan	RME	1.90	Pakistan	RME
2	0.74	India	UK	0.64	USA	Mexico	0.79	India	UK
3	0.72	USA	Mexico	0.53	USA	CA	0.68	USA	Mexico
4	0.62	USA	CA	0.47	Uruguay	Brazil	0.64	Thailand	RME
5	0.49	Uruguay	Brazil	0.46	Thailand	RME	0.55	USA	CA
6	0.48	Thailand	RME	0.37	Japan	REA	0.48	Uruguay	Brazil
7	0.39	Japan	REA	0.36	Pakistan	UK	0.38	Argentina	Brazil
8	0.37	Pakistan	UK	0.35	India	UK	0.37	Japan	REA
9	0.30	Argentina	Brazil	0.31	RSA	RFTAA	0.36	Pakistan	UK
10	0.28	USA	Japan	0.22	Argentina	Brazil	0.23	RSA	RFTAA
Soy									
1	13.4	USA	China	9.51	Argentina	China	15.5	USA	China
2	11.8	Argentina	China	8.39	Brazil	China	10.7	Argentina	China
3	9.97	USA	Mexico	8.35	USA	China	9.96	USA	Mexico
4	8.46	USA	Japan	6.56	Brazil	Netherlands	8.69	USA	Japan
5	7.35	Brazil	China	6.31	USA	Mexico	6.70	Brazil	China
6	6.03	Brazil	Netherlands	5.96	USA	Japan	6.24	Brazil	Netherlands
7	4.33	USA	Taiwan	3.58	Brazil	Germany	5.56	USA	Taiwan
8	3.66	USA	Netherlands	3.48	Brazil	Spain	4.60	USA	Netherlands
9	3.32	Brazil	Germany	3.34	Canada	Japan	3.35	USA	Spain
10	3.19	Brazil	Spain	3.19	USA	Taiwan	3.27	Canada	Japan
Wheat									
1	10.1	Argentina	Brazil	8.34	Argentina	Brazil	10.4	Argentina	Brazil
2	5.60	USA	Japan	3.97	USA	Japan	5.66	USA	Japan
3	5.17	RFSU	RFSU	3.35	Canada	Japan	5.44	USA	RNA
4	4.59	USA	RNA	3.05	Canada	USA	4.71	USA	RME
5	3.85	USA	RME	2.42	Canada	Iran	3.64	USA	Philippines
6	3.64	Arg	Iran	2.42	USA	RME	3.54	Australia	Iran
7	3.40	USA	Philippines	2.38	USA	RNA	3.23	USA	Mexico
8	3.00	RFSU	Russia	2.38	USA	Mexico	3.20	Canada	Japan
9	2.96	USA	Mexico	2.37	USA	Philippines	3.12	Canada	USA
10	2.88	Canada	Japan	2.16	Argentina	Iran	3.10	Canada	Iran

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Table 8. Links that save the most water by crop under the baseline, low, and high yield scenario. Note that "Export" refers to the country of export and "Import" refers to the country of import. Note that "RME" indicates Rest of Middle East, "RNA" indicates Rest of North Africa, "RSSA" indicates Rest of Sub-Saharan Africa, "RSEA" indicates Rest of Southeast Asia. "RFSU" indicates Rest of Former Soviet Union, and "RFTAA" indicates Rest of Free Trade Area of the Americas.

Rank	Baseline			Low			High		
	Volume	Export	Import	Volume	Export	Import	Volume	Export	Import
Agg									
1	12.1	Canada	Venezuela	13.8	Canada	Venezuela	15.8	Canada	Venezuela
2	9.26	Argentina	Brazil	10.2	Argentina	Brazil	12.1	Argentina	Brazil
3	8.90	USA	China	4.79	France	RSSA	6.89	USA	Korea
4	6.58	USA	Korea	4.68	Canada	Japan	6.25	USA	RNA
5	5.14	Brazil	China	4.41	Germany	RNA	5.82	USA	Venezuela
6	4.83	USA	Venezuela	4.29	France	RNA	5.74	Canada	Japan
7	4.82	France	Morocco	3.86	USA	Korea	5.49	France	Morocco
8	4.75	Argentina	China	3.85	France	Morocco	5.32	Germany	RNA
9	4.12	Canada	Morocco	3.46	USA	Venezuela	5.10	France	RNA
10	3.97	USA	Indonesia	3.22	USA	Indonesia	5.09	USA	Indonesia
Rice									
1	0.32	USA	CA	0.37	USA	CA	0.29	USA	CA
2	0.21	USA	RFTAA	0.21	Uruguay	Brazil	0.21	Russia	RFSU
3	0.17	Russia	RFSU	0.20	RSA	RFTAA	0.18	Uruguay	Brazil
4	0.17	Uruguay	Brazil	0.19	USA	Mexico	0.18	USA	RFTAA
5	0.15	RSA	RFTAA	0.17	USA	RFTAA	0.17	Japan	REA
6	0.10	USA	Mexico	0.13	Japan	REA	0.14	RSA	RFTAA
7	0.09	Japan	REA	0.12	Russia	RFSU	0.10	USA	Mexico
8	0.06	Spain	Belgium	0.08	RNA	RSSA	0.08	Argentina	Brazil
9	0.04	USA	RSEA	0.07	USA	RSEA	0.07	Spain	Belgium
10	0.04	Australiatralia	Japan	0.06	Spain	Belgium	0.05	Australiatralia	Japan
Soy									
1	9.06	USA	China	4.86	Canada	Japan	5.23	Canada	Japan
2	5.14	Brazil	China	3.20	USA	Mexico	5.06	USA	Mexico
3	4.75	Argentina	China	3.12	USA	Indonesia	4.89	USA	China
4	3.94	USA	Korea	2.63	USA	Korea	4.83	USA	Indonesia
5	3.84	USA	Indonesia	2.16	Canada	China	4.70	USA	Korea
6	3.55	Canada	Japan	2.13	Canada	Mexico	4.01	USA	Japan
7	2.95	Canada	China	1.48	Brazil	China	2.71	Canada	China
8	2.88	USA	Mexico	1.41	USA	Japan	1.95	Canada	Mexico
9	2.67	USA	Japan	1.34	USA	China	1.10	USA	Thailand
10	1.23	Canada	Mexico	0.77	Canada	USA	0.86	Brazil	China
Wheat									
1	12.1	Canada	Venezuela	13.7	Canada	Venezuela	16.2	Canada	Venezuela
2	9.23	Argentina	Brazil	10.4	Argentina	Brazil	12.6	Argentina	Brazil
3	4.87	USA	Venezuela	4.58	Germany	RNA	6.05	France	Morocco
4	4.80	France	Morocco	4.44	France	RNA	6.03	USA	RNA
5	4.12	Canada	Morocco	4.41	France	RSSA	5.97	USA	Venezuela
6	3.84	RFSU	RFSU	4.31	France	Morocco	5.61	Canada	Morocco
7	2.85	Germany	Morocco	3.50	USA	Venezuela	5.32	Germany	RNA
8	2.63	USA	Korea	2.73	Canada	Morocco	5.04	France	RNA
9	2.47	Australiatralia	Tanzania	2.64	Australiatralia	Tanzania	4.42	France	RSSA
10	2.23	Germany	RNA	2.61	USA	RNA	3.65	Germany	Morocco

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Table 9. Links that lose the most water by crop under the baseline, low, and high yield scenario. All values are in billions of cubic meters of water. Note that "Export" refers to the country of export and "Import" refers to the country of import. Note that "RME" indicates Rest of Middle East, "RNA" indicates Rest of North Africa. "RFSU" indicates Rest of Former Soviet Union, and "RSA" indicates Rest of South America

Rank	Baseline			Low			High		
	Volume	Export	Import	Volume	Export	Import	Volume	Export	Import
Agg									
1	−2.27	Pakistan	RME	−3.01	Brazil	Netherlands	−2.46	Brazil	Netherlands
2	−2.24	USA	Spain	−2.57	Brazil	Spain	−2.04	USA	Spain
3	−1.91	Brazil	Spain	−2.29	Pakistan	RME	−1.90	Brazil	Spain
4	−1.69	Brazil	Netherlands	−1.78	USA	Spain	−1.54	Pakistan	RME
5	−1.48	USA	Italy	−1.60	Brazil	Germany	−1.25	USA	Italy
6	−1.44	USA	Canada	−1.24	USA	Netherlands	−1.19	USA	Canada
7	−1.11	USA	Netherlands	−1.18	USA	Canada	−1.16	USA	Netherlands
8	−1.04	Brazil	Italy	−1.15	Brazil	Italy	−1.08	Brazil	Germany
9	−1.00	Brazil	Germany	−0.97	USA	Italy	−1.00	RFSU	Spain
10	−0.83	India	RNA	−0.94	Brazil	Belgium	−0.94	Brazil	Italy
Rice									
1	−2.24	Pakistan	RME	−2.25	Pakistan	RME	−1.46	Pakistan	RME
2	−0.56	India	UK	−0.31	Pakistan	UK	−0.43	India	UK
3	−0.36	Pakistan	UK	−0.25	India	UK	−0.30	Thailand	RME
4	−0.26	Thailand	RME	−0.23	Thailand	RME	−0.30	Pakistan	UK
5	−0.18	India	RME	−0.08	India	RME	−0.11	India	RME
6	−0.14	RSA	Portugal	−0.08	RSA	Portugal	−0.09	Pakistan	Netherlands
7	−0.13	Pakistan	France	−0.08	RSA	Netherlands	−0.09	RSA	Portugal
8	−0.12	Pakistan	Netherlands	−0.07	Pakistan	USA	−0.08	Thailand	France
9	−0.12	Pakistan	Italy	−0.07	Pakistan	Netherlands	−0.08	India	France
10	−0.12	Pakistan	USA	−0.06	USA	UK	−0.08	Pakistan	USA
Soy									
1	−1.91	Brazil	Spain	−3.01	Brazil	Netherlands	−2.46	Brazil	Netherlands
2	−1.81	USA	Spain	−2.57	Brazil	Spain	−1.90	Brazil	Spain
3	−1.69	Brazil	Netherlands	−1.60	Brazil	Germany	−1.73	USA	Spain
4	−1.40	USA	Canada	−1.55	USA	Spain	−1.17	USA	Canada
5	−1.05	USA	Netherlands	−1.19	USA	Netherlands	−1.10	USA	Netherlands
6	−1.04	Brazil	Italy	−1.17	USA	Canada	−1.08	Brazil	Germany
7	−1.00	Brazil	Germany	−1.15	Brazil	Italy	−0.94	Brazil	Italy
8	−0.83	India	RNA	−0.94	Brazil	Belgium	−0.78	Brazil	Belgium
9	−0.68	Brazil	Belgium	−0.94	Brazil	France	−0.63	Brazil	France
10	−0.68	Brazil	France	−0.75	Brazil	UK	−0.61	India	RNA
Wheat									
1	−1.46	USA	Mexico	−0.92	USA	Mexico	−1.21	USA	Mexico
2	−1.02	USA	Japan	−0.76	Canada	Mexico	−0.81	USA	Italy
3	−0.84	USA	Italy	−0.55	USA	Japan	−0.60	RFSU	Spain
4	−0.75	Canada	Mexico	−0.53	Canada	Japan	−0.53	Russia	Italy
5	−0.62	Canada	Japan	−0.49	USA	Italy	−0.49	Canada	Mexico
6	−0.48	Canada	China	−0.41	RFSU	Spain	−0.32	Canada	Italy
7	−0.40	RFSU	Spain	−0.40	Canada	UK	−0.31	USA	RME
8	−0.39	USA	Spain	−0.36	Canada	China	−0.29	USA	Spain
9	−0.39	Canada	Italy	−0.36	Russia	Italy	−0.27	Russia	Greece
10	−0.34	Russia	Italy	−0.36	Canada	Italy	−0.18	Portugal	Spain

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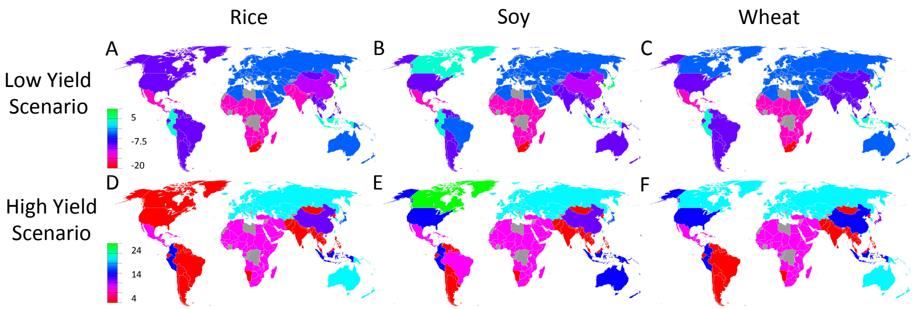

Fig. 1. Maps of yield shocks by country, crop, and scenario. The first row **(A–C)** show the yield shocks for the low-yield scenario; the second row **(D–F)** show the yield shocks for the high-yield scenario. The first column **(A, D)** show yield shocks for rice; the second column **(B, E)** show yield shocks for soy; the third column **(C, F)** show yields shocks for wheat. The colors indicate the percentage change in yield between 2001 and 2030. The legends apply to the entire row. In the low-yield scenario, yield shocks range from −20 % to 5 %; for the high-yield scenario, yield shocks range from 4 % to 24 %.

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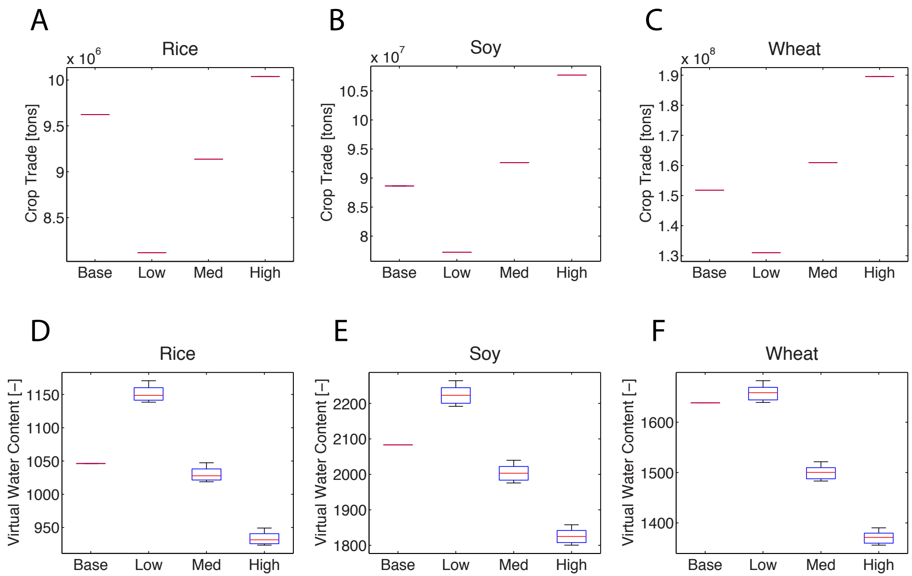

Fig. 2. Total crop trade [metric tons] and mean virtual water content (VWC) [dimensionless] by crop and yield scenario. **(A–C)** illustrate the total crop trade and **(D–F)** illustrate the mean VWC. The x-axis in each plot indicates the yield scenario: "Base" indicates the baseline scenario, "Low" indicates the low-yield scenario, "Med" indicates the most-likely scenario, and "High" indicates the high-yield scenario. Box-whisker plots are provided in **(D–F)** for values of VWC across outcomes of the global climate models (GCMs). Box-whisker plots indicate the median data value (red line), the quantiles of the data (blue box), and any data outliers (red stars). Note that the volume of the wheat commodity trade is the largest of the commodity trades.

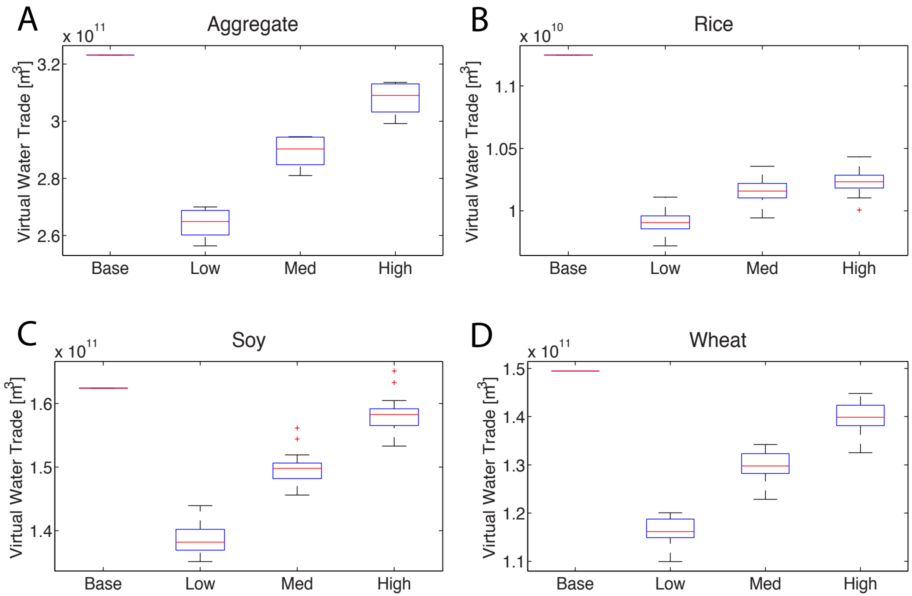

Fig. 3. Total virtual water trade (VWT) by commodity trade and yield scenario. **(A)** Total VWT associated with the trade of rice, soy, and wheat commodities; **(B)** Total VWT associated with the rice commodity trade only; **(C)** Total VWT associated with the soy commodity trade only; and **(D)** Total VWT associated with the wheat commodity trade only. The x-axis in each plot indicates the yield scenario: "Base" indicates the baseline scenario (i.e. 2001), "Low" indicates the low-yield scenario, "Med" indicates the most-likely scenario, and "High" indicates the high-yield scenario. All future climate change scenarios are for the year 2030. Box-whisker plots for each yield scenario indicate the median data value (red line), the quantiles of the data (blue box), and any data outliers (red stars).

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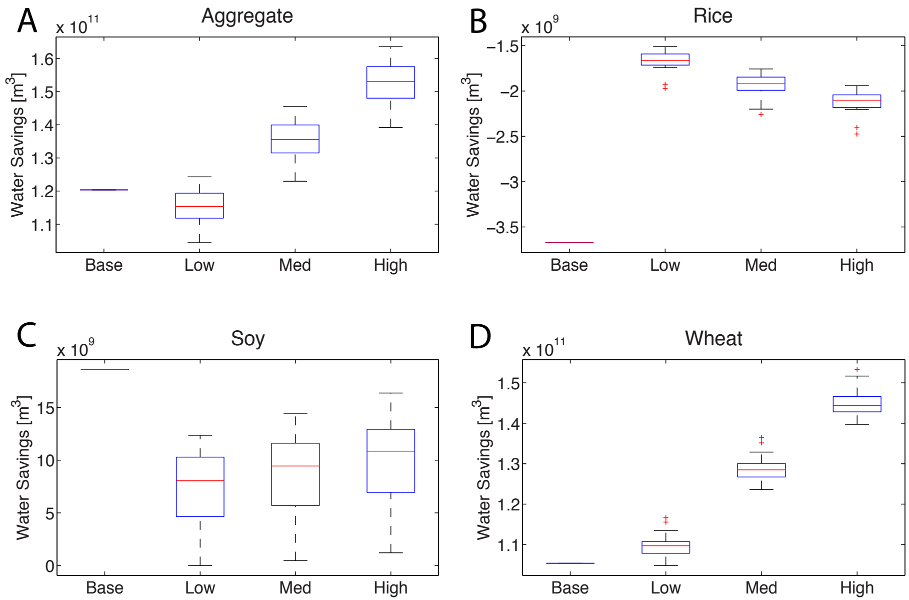

Fig. 4. Global water savings (GWS) by commodity trade and yield scenario. **(A)** GWS associated with the trade of rice, soy, and wheat commodities; **(B)** GWS associated with the rice commodity trade only; **(C)** GWS associated with the soy commodity trade only; and **(D)** GWS associated with the wheat commodity trade only. Definitions follow Fig. 3.

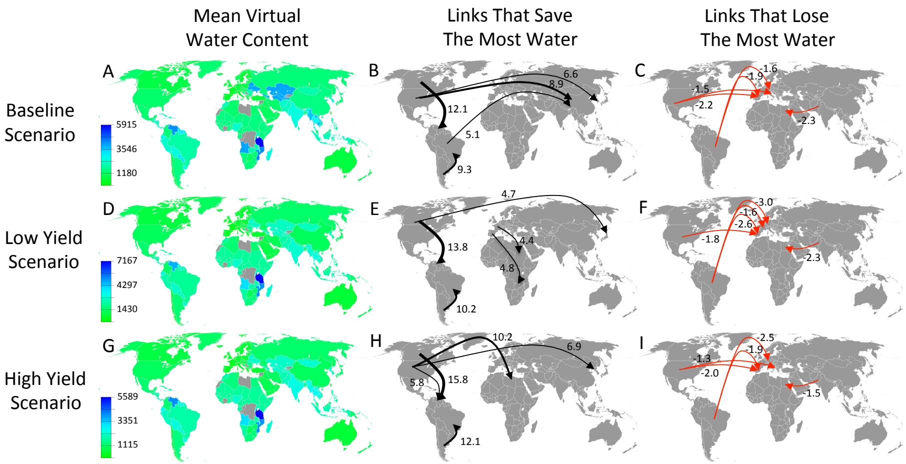

Fig. 5. Maps of virtual water content (VWC) and the links that save and lose the most water by scenario. **(A, D, G)**: Maps of VWC averaged across crops. The color of each country illustrates the water-use efficiency (i.e. VWC, total evapotranspiration per unit of crop) of each country. **(B, E, H)** The 5 links that save the most water are provided in black. **(C, F, I)** The 5 links that lose the most water are provided in red. Note that the width of the arrows has been scaled according to the volume of virtual water either saved or lost with each link. The volume of water [billions m^3] saved or lost with each trade link is displayed. The first row **(A–C)** illustrates the baseline scenario (i.e. 2001); the second row **(D–F)** illustrates the low-yield scenario; the third row **(G–I)** illustrates the high-yield scenario. All future climate change scenarios are for the year 2030.

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