Hydrol. Earth Syst. Sci. Discuss., 10, 7291–7324, 2013
www.hydrol-earth-syst-sci-discuss.net/10/7291/2013/
doi:10.5194/hessd-10-7291-2013

Hydrology and Earth System Sciences
Open Access
Discussions

Virtual water trade and development in Africa

M. Konar[1] and K. Caylor[2]

[1]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[2]Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA

Received: 18 May 2013 – Accepted: 23 May 2013 – Published: 6 June 2013

Correspondence to: M. Konar (mkonar@illinois.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A debate has long existed on the relationships between human population, natural resources, and development. Recent research has expanded this debate to include the impacts of trade; specifically, virtual water trade, or the water footprint of traded commodities. We conduct an empirical analysis of the relationships between virtual water trade, population, and development in Africa. We find that increases in virtual water imports do not lead to increases in population growth nor do they diminish human welfare. We establish a new index of virtual water trade openness and show that levels of undernourishment tend to fall with increased values of virtual water trade openness. Countries with small dam storage capacity obtain a higher fraction of their agricultural water requirements from external sources, which may indicate implicit "infrastructure sharing" across nations. Globally, increased crop exports tends to correlate with increased crop water use efficiency, though this relationship does not hold for Africa. However, internal African trade is much more efficient in terms of embodied water resources than any other region in the world. Thus, internal African trade patterns may be compensating for poor internal production systems.

1 Introduction

The debate on the relationship between human population growth, development, and natural resources dates back to Condorcet (1794) and Malthus (1798), and has been contributed to by other classic works (Jevons, 1865; Ehrlich, 1968; Simon, 1980). The now famous wager between Paul Ehrlich and Julian L. Simon centered on population growth and resource scarcity. Recently, this debate has been expanded to include the implications of increased access to natural resources through trade. In particular, recent works focus on water resources embodied in traded commodities (i.e., virtual water trade), and suggest that importing virtual water resources may encourage human

HESSD
10, 7291–7324, 2013

population growth beyond a sustainable limit, eventually diminishing human welfare (D'Odorico et al., 2010; Suweis et al., 2013).

The quantity of resources embodied in international trade has been analyzed for a range of commodities, including land (Fader et al., 2011; Kastner et al., 2012), carbon (Peters et al., 2011), nutrients (Schipanski and Bennett, 2012), and water (Hoekstra and Hung, 2005). In this paper, we focus on freshwater resources embodied in the staple food trade. Trade links water and food systems (Konar et al., 2011), since food production is tightly coupled with water resource availability and use, in a "globalization of water" (Hoekstra and Chapagain, 2008). Our focus is on trade in staple agricultural products, since its impacts on agricultural production and food prices are important in understanding human welfare impacts in developing countries, such as Africa (Hertel et al., 2010).

Recent theoretical research suggests that increasing imports of virtual water resources may cause local human popoulation to grow beyond a sustainable limit, leading to a reduction in local food security (D'Odorico et al., 2010). However, in the economics literature, although a debate does exist, it is fairly well accepted that reliable access to natural resources slows population growth and that open economies improve development objectives (Frankel and Romer, 1999; Winters et al., 2004). For this reason, it has been suggested that trade liberalization can help to improve food security (Dorosh, 2001; Burgess and Donaldson, 2010) and human welfare (Winters et al., 2004). In this paper, we examine the empirical evidence on the relationship between virtual water trade, population growth, and human development, with a particular focus on Africa.

Despite popular conceptions, Africa has a wealth of renewable freshwater resources, estimated at approximately 5400 km^3 per year. This equates to roughly 6800 m^3 per person per year (Odularu, 2009), compared with a per capita annual water availability of 2234 m^3 in China (Hoekstra and Chapagain, 2008). However, water resources are highly variable in both time and space across the African continent and agricultural production is predominantly rain-fed, due to low levels of irrigation infrastructure and dam storage capacity (e.g., approximately 4 % of arable land is irrigated in Sub-Saharan

HESSD
10, 7291–7324, 2013
Virtual water trade and development in Africa
M. Konar and K. Caylor

Africa, compared with a global average of 20 %; FAO, 2009). Consequently, much of African agriculture is particularly vulnerable to weather conditions and climate variability (Rosegrant et al., 2002; FAO, 2011a).

Agricultural yield gains have been much lower in Sub-Saharan Africa than in other world regions (Godfray et al., 2010). For example, maize yields typically attain less than half of their potential throughout the region (Foley et al., 2011). This is largely due to the inadequacies of input and output markets, extension services, and infrastructure (FAO, 2009). Additionally, the Intergovernmental Panel on Climate Change estimates that climate change could cause crops yields on rainfed lands to decrease by 50 % in some African countries, leading them to potentially spend 5–10 % of GDP to adapt to a changing climate. There is an urgent need for agricultural research in Africa, particularly research that focuses on opportunities for adaptation to climate change, yet agricultural research and development spending only grew at an average annual rate of 0.6 % (FAO, 2009).

Reducing risk and vulnerability in agricultural production – especially to extreme weather events and price swings – is necessary to facilitate poverty reduction in Africa, which is one of the Millenium Development Goals of the United Nations. Trade in agricultural products is one way to reduce vulnerability to domestic weather shocks in agricultural production (Burgess and Donaldson, 2010). However, trade in African nations exhibits high sensitivity to price fluctuations, which are anticipated to occur under climate change (Konar et al., 2013). These fluctuations in price and production have direct repercussions for welfare in the importer nations (Hertel et al., 2010).

Since 1980, agricultural imports have grown consistently faster than exports in Africa. Net food imports grew at an average rate of 3.4 % per year between 1980 and 2007 and were primarily comprised of cereals and livestock products (FAO, 2011b). As long as other export sectors generate enough revenue to pay for food imports, this food import dependency may not pose a serious issue. This is because consumers in these countries benefit from the cheap food imports. However, recent spikes in food prices highlight challenges of expanding agricultural production in response to price increases.

HESSD
10, 7291–7324, 2013

Projections to 2050 tend to confirm that African countries will remain dependent upon food imports, making it essential to better understand the impact of imports on food and water security, as well as other development objectives in Africa.

In this paper, we address the following questions using empirical data for African nations: (1) does virtual water trade impact human population and development? (2) Is there a relationship between virtual water trade and food security? (3) What is the relationship between water resources infrastructure and virtual water trade? (4) Does agricultural trade impact crop water use efficiency? Our major findings are that increased virtual water imports do not lead to population growth, but do increase human welfare; increased virtual water trade is correlated with enhanced food security; countries with less dam storage capacity tend to consume a larger fraction of their agricultural water footprint from external sources; and that internal production systems in Africa do not show water use efficiency gains with increased exports, but that internal African trade is the most efficient region in the world. These results suggest that trade may be helping African nations to meet food and water security objectives.

2 Methods

In this section, we describe the national data sets that we use, our calculation of agricultural water use, and how we quantify bilateral virtual water trade flows.

2.1 Cross-sectional data sources

We obtained cross-sectional data from a variety of sources. Population data was collected for each country from 1960–2011 from the World Bank (World Bank, 2012). Human Development Index (HDI) data was collected for each country from 1980–2011 from the United Nations Development Programme (UNDP) (UNDP, 2012). Note that HDI data is available every 5 yr from 1980–2005, but annually from 2006–2011. This is a summary measure of human development. It measures the average achievements

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

10, 7291–7324, 2013

Virtual water trade and development in Africa

M. Konar and K. Caylor

in a country in three basic dimensions of human development: (1) a long and healthy life, as measured by life expectancy at birth; (2) knowledge, as measured by school enrollment and adult literacy; and (3) standard of living, as measured by gross domestic product (GDP) per capita.

We obtain a variety of data on agriculture and water resources from the Aquastat Database of the Food and Agriculture Organization of the United Nations (FAO) (Aquastat, 2013). Namely, we obtain information on the dam storage capacity, area equipped for irrigation, and the number of undernourished people, for each country and all available years.

Dam storage capacity is defined as the total cumulative storage capacity of all dams in each country in km^3. The value indicates the sum of the theoretical initial capacities of all dams, which does not change with time. However, the amount of water stored within any dam is likely less than the capacity due to silting. Data on the area equipped for irrigation is from all sources and measured in hectares. The number of undernourished people refers to the condition of people whose dietary energy consumption is continuously below a minimum dietary energy requirement for maintaining a healthy life and carrying out light physical activity. This value is provided per 1000 inhabitants.

Water footprint data was obtained from Hoekstra and Chapagain (2008). Specifically, from this source, we obtain data on crop evapotranspiration (for both national consumption and export), internal agricultural water footprint, external agricultural water footprint, and gross virtual water flows related to trade in crop products.

2.2 Agricultural virtual water content estimates

To obtain national estimates of agricultural water use we utilize the H08 global hydrological model (Hanasaki et al., 2008b,a, 2010), which is a state-of-the-art hydrologic model with human water use. The model runs globally on a $0.5^\circ \times 0.5^\circ$ spatial grid and a daily time step. H08 incorporates energy and water balance closure and consists of six modules: land surface hydrology, river routing, crop growth, reservoir operation, environmental flow requirements, and water withdrawal for human use. We do not go

HESSD
10, 7291–7324, 2013

into detail on the H08 model here, but instead refer the interested reader to Hanasaki et al. (2010).

From the H08 model, we obtain estimates of virtual water content (VWC). VWC is a country-specific estimate of the volume of water used to produce a unit of agricultural output, defined to be 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., $\mathrm{VWC} = \overline{\mathrm{ET}}/Y$ (Hanasaki et al., 2010). We determined the VWC of five crops: barley, corn, rice, soy, and wheat. The VWC of livestock is defined as the water consumption per head [$\mathrm{kg\,head^{-1}}$] divided by the total weight per head [$\mathrm{kg\,head^{-1}}$]. We calculated the VWC of three livestock products: beef, pork, and poultry. From 1986–2001, VWC was calculated using the national crop yield time series data from FAOSTAT (FAOSTAT, 2012) and yearly estimates of $\overline{\mathrm{ET}}$ simulated with the H08 model.

Land use and meteorological data are used to drive the H08 hydrology model. 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 data were fixed to the year 2000 and were re-gridded for consistency with the spatial resolution of the meteorological forcing data. For meteorological data, the H08 model is forced with WATCH data (Weedon et al., 2011), available at a 0.5° spatial resolution at 6 h intervals from 1901–2001. For this reason, H08 estimates of yearly VWC end in 2001.

To obtain yearly estimates of VWC after 2001, we utilize national crop yield statistics from the FAO (FAOSTAT, 2012), following Dalin et al. (2012) and Konar et al. (2012) and according to the equation:

$$\mathrm{VWC}_{\mathrm{e,c,t}} = \frac{\overline{\mathrm{ET}}_{\mathrm{e,c,2001}}}{Y_{\mathrm{e,c,t}}} \quad (1)$$

where the subscripts "e", "c", and "t" correspond to the country of production (and export), the raw crop, and year, respectively. Thus, yearly VWC information is obtained

HESSD
10, 7291–7324, 2013

from the H08 model from 1986–2001 and yearly VWC information is calculated according to Eq. (1) for the 2002–2008 period.

2.3 Bilateral trade data for staple food commodities

We obtain data on the bilateral (i.e., link level) trade (T) of staple food commodities from 1986–2008 from the FAO (FAOSTAT, 2012). Specifically, we obtained trade data on 58 commodities stemming from the unprocessed crop and livestock products for which we have yearly VWC estimates (i.e., barley, corn, rice, soy, wheat, beef, pork, and poultry). Note that these 58 commodities account for over 60 % of global calorie consumption (FAOSTAT, 2012) and embody the majority of virtual water flows (Hoekstra and Hung, 2005; Hanjra and Qureshi, 2010).

A common problem with FAO trade data is that some countries report the final destination country, while others report the first destination. This makes it difficult to distinguish between export and re-export, which may be significant for some trade hubs, such as the United Arab Emirates (US Agricultural Trade Office, 2010). Due to this inconsistency, the virtual water trade of major trade hubs and those that process commodities for re-export may be overestimated in this analysis. In other words, it is impossible to distinguish production and consumption flows in all cases using FAO trade data.

2.4 Quantifying virtual water trade flows and savings

Bilateral trade data, in combination with estimates of VWC, allow us to quantify the virtual water trade (VWT) between two nations e and i in year t by:

$$\mathrm{VWT}_{\mathrm{e,i,t}} = \sum_{a} \mathrm{VWC}_{\mathrm{e,a,t}} \cdot \left[\sum_{x \in a} \frac{p_x c_x}{r_x} \cdot T_{\mathrm{e,i,x,t}} \right] \tag{2}$$

where the subscripts “e”, “i”, “t”, “a”, and “x” denote the exporting country, importing country, year, agricultural item (i.e., unprocessed crop or livestock item), and

HESSD
10, 7291–7324, 2013

commodity, respectively. The VWC of raw crops is transformed into that of a processed commodity by multiplying by the $p_x c_x / r_x$ coefficient, which does not vary in time. Values of r, p, and c are specific to commodity x and are provided for each of the 58 commodities in Appendix A. The price ratio (p) is the ratio between the price of the raw crop and the price of the commodity produced from that raw crop. The content ratio (c) indicates the percentage of a particular processed commodity that originates from the raw crop. The yield ratio (r) quantifies the fraction of the raw crop that goes into the processed commodity (Hanasaki et al., 2010). The notation $x \in a$ indicates the ensemble of commodities that are produced from the raw agricultural item a. $T_{e,i,x,t}$ is the annual trade from exporting country e to importing country i of commodity x in year t.

VWT is measured in $m^3\,yr^{-1}$ and aggregated over all commodities considered in the international food trade. Data on T from the FAO is measured in $tons\,yr^{-1}$ and VWC indicates $kg_{water}\,kg_{crop}^{-1}$. For water, $1\,m^3$ is equivalent to 1000 kg, or one ton, and one liter (or 1/1000 of a cubic meter) weighs 1 kg. So, we obtain virtual water trade flows in m^3 using the conversion: $1\,\text{ton crop} \cdot 1\,\text{kg water}/1\,\text{kg crop} \cdot (1/1000\,m^3\,\text{water})/1\,\text{kg crop} = 1\,\text{ton crop}/1000\,\text{kg crop} \cdot 1\,m^3\,\text{water} = 1\,m^3\,\text{water}$.

Trade-based water savings (WS) is a theoretical measure of how much water is saved through 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. Regional water savings refer to the sum across all trade links within a particular region; global water savings sum all links in the world. We calculate WS by:

$$\mathrm{WS}_{\mathrm{e,i,c,t}} = \sum_{x \in r} CT_{\mathrm{e,i,c,t}} \cdot \left(\mathrm{VWC}_{\mathrm{i,c,t}} - \mathrm{VWC}_{\mathrm{e,c,t}}\right) \quad (3)$$

HESSD
10, 7291–7324, 2013

where the subscripts "e", "i", "c", and "t" indicate exporting country, importing country, commodity, and year, respectively. The notation $x \in r$ indicates the ensemble of countries within region r, which may be all countries for the global calculation.

3 Results and discussion

3.1 Virtual water trade, population, and development

Figure 1 presents the internal African virtual water trade network in the year 2008. Each of the 51 African countries is assigned a unique color and its export trade links are assigned the same color. These export links are then connected to an import nation of a different color. The import trade direction for each link is also indicated by the white gap between the link and the outer ring. For example, the large red link passing through the center of the graph indicates the virtual water export from Algeria to Nigeria.

This network image helps in the visualization of large trade links, major exports, and major importers. From Fig. 1 the virtual water trade from South Africa to Zimbabwe is shown as the largest link in the internal African network. This link represents 0.37 km^3 of virtual water, which is approximately 10 % of the total internal flow. Additionally, South Africa stands out as a major exporter. South Africa exports 1.12 km^3 to other African nations. This is approximately 31% of total internal African trade. Zimbabwe is the major importer of virtual water resources (notice the large white gap associated with Zimbabwe in Fig. 1). Zimbabwe imports 0.66 km^3 of virtual water, approximately 19 % of internal flow.

The total volume of virtual water trade within African countries is 3.59 km^3. The total volume of trade from the rest of the world (ROW) to Africa is 61.67 km^3. The total volume of trade from Africa to the ROW is 1.18 km^3. So, although Africa does not export large volumes of virtual water to the ROW, they trade over twice this volume amongst themselves.

HESSD
10, 7291–7324, 2013

It makes sense that internal African trade is larger than African trade with the ROW, because countries that are close in distance to one another tend to trade more. In the international trade literature, a model often used to assess bilateral trade flows is the gravity model of trade, which states:

$$T_{i,j} = c\frac{M_i M_j}{D_{i,j}} \tag{4}$$

where T is the trade flow, M is the economic mass of each country (typically GDP), D is the distance between i and j, and c is a constant (Tinbergen, 1962). It has been shown that countries that are closer in geographic proximity to one another tend to trade larger volumes of virtual water. In fact, the average distance travelled by a unit of virtual water has decreased by approximately 1000 km between 1986 and 2010 (Tamea et al., 2013).

Recent research suggests that importing virtual water resources may encourage human population growth beyond a sustainable limit, eventually diminishing human welfare (D'Odorico et al., 2010; Suweis et al., 2013). To address this important issue, we consult panel data on population and human welfare. We utilize the human development index (HDI), since it was developed as an indicator of aggregate human welfare (UNDP, 2012). First, we focus on data for African nations and conduct a time average for population, HDI, and virtual water import (VWI), from 1986–2008, since we have bilateral VWI data during this time frame.

We present the relationship between log(population) and log(VWI) for Africa in Fig. 2a. From Fig. 2a, it is clear that log(population) increases in a non-linear way with the log(VWI). In other words, for each percentage increase in VWI there is a non-linear increase in percent population. However, note that this relationship levels off with increasing values of VWI. Thus, although there is a positive correlation between log(population) and log(VWI), the rate of population growth slows with increasing virtual water imports.

HESSD
10, 7291–7324, 2013

To better understand the relationship between human welfare and VWI, we plot HDI against log(VWI) in Fig. 2b. From Fig. 2b, a linear relationship between HDI and log(VWI) is evident. This provides empirical evidence for an increase in human welfare with a percentage increase in VWI. However, this relationship is only a correlation, so no causal information can be inferred. Yet this empirical relatinoship does add another dimension to the current discussion on the relationship between virtual water trade and human development.

Since we only present correlations in Fig. 2, we are unable to distinguish reverse causality. It is possible that higher population levels are leading to increased virtual water imports, rather than virtual water imports leading to increased population. Similarly, enhanced human welfare may contribute to rising VWI, rather than the other way around. In an effort to address this issue with reverse causality, we consider future values of VWI and future values of the variables of interest. Both population and HDI are slow moving variables, so a time lag should exist with current resource access. We select a time windown of ten years into the future. This time window is arbitrary, but should prove long enough to capture changes in these variables, but short enough to allow for analysis with our available data.

In Fig. 3a, we determine the current log(VWI) for each country from 1986–1990. Then, we determine the population growth rate ten years into the future. For example, a single data point represents the log(VWI) of South Africa in 1990 and the population growth rate of South Africa between 1990 and 2000. We plot this relationship for all countries in Fig. 3a. There is a decreasing trend between future population growth rates and percentage increases in current virtual water imports. This relationship indicates that the current virtual water imports of a country are unlikely leading to increased population growth.

Similarly, in Fig. 3b, we determine the current log(VWI) for each country in the world. Then, we determine the HDI of each country in ten years. HDI data is only available every five years between 1985–2006, so this analysis consists of less data points than does Fig. 3a. There is an increasing relationship between future HDI and percentage

HESSD
10, 7291–7324, 2013

increases in current virtual water imports. This relationship indicates a positive correlation between current virtual water imports and future human well-being.

The relationships presented in Figs. 2 and 3 do not demonstrate causality. However, they do highlight that the relationship between virtual water trade, population, and development is likely more complex than previously suggested in the literature. Figure 3 presents an alternative narrative, in which increasing access to freshwater resources through trade tends to slow population growth and enhance human well-being. The idea that access to resources slows population growth, although counter-intuitive, has been documented in the literature for non-trade settings.

3.2 Food security and virtual water trade

There is a debate in the literature on the relationship between trade and food security (Burgess and Donaldson, 2010; D'Odorico et al., 2010; Hanjra and Qureshi, 2010), particularly for African nations (Brown et al., 2009). In this section, we contribute to this discussion by assessing how trade openness impacts food security in Africa. Here, we use the fraction of the population that is undernourished as our proxy for food security.

In economics, the classic definition of trade openness is defined as total trade as a percentage of total economic activity; where total economic activity is typically represented by gross domestic product (GDP). Thus, the classic definition of trade openness is:

$$\mathrm{TO_c} = \frac{\mathrm{Imports_c} + \mathrm{Exports_c}}{\mathrm{GDP_c}} \tag{5}$$

where TO refers to trade openness of country c, imports refers to gross imports of goods and services in value terms of country c, exports refers to gross imports of goods and services in value terms of country c, and total economic activity is proxied with GDP of country c. Thus, TO measures the proportion of economic activity encapsulated in trade. and, for this reason, has also been referred to as the trade share or trade

HESSD
10, 7291–7324, 2013

intensity. Data on trade openness was obtained from the United Nations Conference on Trade and Development (UNCTD) (UNCTD, 2013).

The relationship between the fraction of the population that is undernourished and the classic index of trade openness is presented in Fig. 4a for Africa. This relationship exibits a slight decreasing trend. However, this relationship is insignificant. Thus, the relationship between food security and the openness of a nation to trade is not easy to distinguish utilizing the classic definition of trade openness. This is likely because many of the factors considered in this definition do not directly relate to food production and consumption. For this reason, a definition of trade openness that focuses on the trade in food and embodied water resources would aid our understanding.

We define a new index of virtual water trade opennes (VWTO) to mirror the classical definition of trade openness based on financial value. In this way, the relative importance of virtual water trade within a nation is determined, controlling for differences in the size of different countries. Here, we define VWTO to be the total virtual water trade associated with crops divided by the total water use in agriculture. So, VWTO is defined as:

$$\mathrm{VWTO}_c = \frac{\mathrm{VWE}_c + \mathrm{VWI}_c}{\mathrm{ET}_c} \quad (6)$$

where VWTO refers to the virtual water trade opennes of country c, VWE is the gross virtual water export associated with crops for country c, VWI is the gross virtual water import associated with crops for country c, and ET is the total domestic crop evapotranspiration associated with crops in country c. To construct this index we use data collected from Hoekstra and Chapagain (2008).

In Fig. 4b, the relationship between the undernourished fraction and log index of VWTO displays a linearly decreasing relationship for Africa. Note that the values on the x-axis in Fig. 4b are smaller than they are for Fig. 4a. This is because African nations trade relatively small volumes of virtual water resources as a fraction of their domestic agricultural water use, when compared to the fraction of total trade in goods and services as a fraction of total economic activity.

HESSD
10, 7291–7324, 2013

3.3 Virtual water trade and dam storage capacity

Storage of water resources in dams is a way to mitigate against climate variability. Trade in food commodities and embodied water resources represents another opportunity to store water resources in time. African nations have relatively small dam storage capacity, when compared with the rest of the world. This lack in storage makes them vulnerable to climate variability. However, African nations may compensate for having less dam storage through other means, such as trading virtual water resources. In this section, we analyze the relationship between dam capacity and virtual water trade in Africa.

Dam storage capacity in African countries ranges from 0 to 140 km^3. We divide countries into those with 0 to 70 km^3, i.e., "small dam capacity", and those with 70 to 140 km^3, or "large dam capacity". There are 38 countries with small dam capacity and 6 countries with large dam capacity in Africa. After categorizing African nations based on their dam storage capacity, we determine the proportion of a country's agricultural water footprint that originates from external sources. We present a box-whisker plot of this data in Fig. 5.

In Fig. 5, the red horizontal line represents the median of the data. We have also plotted the data mean with a red star. The edges of the box represent the 25th and the 75th percentiles of the data, while the whiskers extend to the most extreme data points that are not considered to be outliers. Data outliers are represented individually by red plus marks.

From Fig. 5 it is evident that countries with a small dam storage capacity consume relatively more water resources from external sources than do countries with large dam storage capacity. However, countries with small storage capacity exhibit high variance in the proportion of water consumption from external sources. This is exhibited by the large spread of the whiskers. Additionally, a few outliers in the distribution consume a much larger fraction of water resources from external sources.

HESSD
10, 7291–7324, 2013

The two data outliers in the small dam storage capacity group are Mauritius and Botswana. Mauritius has the highest external water consumption fraction (63 %), trailed by Botswana at 44 %. Mauritius has a dam storage capacity of 0.09 km^3; Botswana's storage capacity is 0.45 km^3. The data outlier in the large dam capacity pool is Egypt, importing 21% from external sources, with a dam capacity of 168 km^3.

An interpretation of Fig. 5 is that countries with small storage capacity are able to obtain water resources to meet their consumptive demands through trade. The standard interpretation may be that countries with a large fraction of water consumption originating in external sources exhibit food vulnerability. However, we do not take this position. Our intention is not to use Fig. 5 to advocate for more storage.

Instead, it makes sense and may have positive implications that countries with small storage capacity are able to meet their agricultural water needs via external sources. We interpret this as infrastructure sharing. The concept of benefit sharing for large water infrastructure projects exists, but is typically applied in a formal setting to thos organization and individuals directly impacted by a specific project (Skinner et al., 2009). Through trade, countries are able to implicitly share dam infrastructure and the benefits associated with using dams in agricutltural production, such as smoothing climate variability. Sharing infrastructure through trade means that not all countries have to undertake the massive financial and ecological expense associated with building a large dam.

3.4 Crop water use efficiency and agricultural trade

A potential benefit of trade is gains in agricultural water use efficiency. As countries increase agricultural exports, they may become more efficient in the use of factors of production, such as nutrients, labor, machinery, and water. In this section we explore the relationship between trade, agricultural water use, and trade based water savings.

In Fig. 6, we plot the relationship between the log of VWC and the log of total staple crop export. This relationship is shown for all countries in the world in Fig. 6a and just for African nations in Fig. 6b. Globally, water use efficiency increases as crop exports

HESSD
10, 7291–7324, 2013

increase (i.e., VWC decreases, indicating less water is used per unit of crop output). In other words, for each percentage increase in crop export, there is a corresponding decrease in the percentage of water used in crop production at the global scale. However, for African nations, there is no increase in water use efficiency with increased agricultural trade (refer to the flat relationship in Fig. 6b).

Tremendous opportunities exist to improve crop yields in Africa. Improved management of nutrient and water inputs has been suggested as a means to close "yield gaps" in Africa (Foley et al., 2011). Although agricultural production in Africa falls short of its potential, it is possible that some other facet of the agricultural systems is compensating for diminished yields. We investigate the possibility that the agricultural trade system within Africa demonstrates efficiences unseen in its production system.

Figure 1 shows the virtual water trade that takes place solely amongst African nations for the year 2008. This internal trade of food commodities represents 3.59 km^3 of virtual water resources. This is the second smallest internal trade of all world regions (i.e., only Oceania trades less virtual water internally, with a volume of 1.08 km^3; refer to Table 1). Although internal African trade is small, particularly relative to its land area, its trade based water savings are average, with a volume of 9.14 km^3 saved.

Trade based water saving (WS) is a theoretical measure of how much water is actually used to produce traded commodities, compared with the water that would have been used had the importing nation produced the food themselves, maintaining all other factors equal. A trade links "saves" water resources when the food exporter uses less water to produce the crop output than the importer nation theoretically would have used. The volume of water saved is then calculated as this difference in VWC multiplied by the volume of food traded between countries. To quantify regional savings, all the trade links of a particular region are summed to obtain an estimate of internal trade based savings.

Not all trade links save water. Trade often occurs between nations in which the importer could have produced the commodity with less water than the exporter used. This is because trade occurs for many reasons other than for water resources. Although

HESSD
10, 7291–7324, 2013

trade does not occur due to water resources, it is useful to understand if particular trade links and the trade system as a whole is efficient in terms of water resources or not. Internal African trade loses 0.44 km^3 per year.

The ratio of a region's internal WS to its total trade and water losses provide an estimate of its trade based water efficiency. Internal African savings are 2.5 times higher than total African trade. African WS amount to over 20 times more than losses. These numbers are significant when compared with other regions of the world. Internal African trade exhibits the most efficient regional virtual water trade system by far. Globally, the ratio of savings to trade is 0.57 and the ratio of savings to losses is 5.20. However, this global average includes Africa, with values high above other world regions (refer to Table 1). When Africa is exclused from the average, the ratio of global savings to trade drops to 0.14 and the ratio of global savings to losses falls below 2.

Figure 7 presents a network representation of efficiency in African agricultural trade. Trade based losses as shown in Fig. 7a and savings in Fig. 7b. Note that the regional graphs are not scaled by the volume of water. To properly scale the African networks, the regional savings network provided in Fig. 7b would need to be 20 times larger than the regional loss network provided in Fig. 7a. This scaling would make the regional loss network indistinguishable, so we indicate the fact that the water savings network is 20 times larger in text.

The largest links in the savings and losses networks can be seen in Fig. 7. The trade of food from Mozambique to Malawi amounts to trade based water losses of 0.14 km^3, which is approximately 32 % of total internal African losses (refer to Fig. 7a). From Fig. 7b it is evident that trade from South Africa to Zimbabwe comprises the majority of the internal savings. The trade of food from South Africa to Zimbabwe is responsible for saving 4.85 km^3, or approximately 53 % of total internal African savings. Although this trade link dominates internal savings, the internal African network is still much more efficient than the global average without it.

Thus, crop yields in Africa are low and present a major opportunity for future food production. Crop yields do not show efficiency gains with trade in Africa, though they

HESSD
10, 7291–7324, 2013

do at the global scale. However, regional trade within Africa does demonstrate high levels of trade based water saving and efficiency, with values far exceeding the global average. Since the African trade network is much more efficient in terms of embodied water resources than any other region in the world, internal African trade patterns may be compensating for poor internal production systems.

4 Conclusions

We contributed to the recent debate on the implications of increasing access to natural resources through trade for human population growth and development. To do this, we conducted an empirical analysis of panel data for Africa. We focused on Africa because this region has long been the subject of development debates. Additionally, this region is vulnerable to climate variability, due to small water storage capacities. Africa has been highlighted as an important focal point for increasing agricultural productivity.

We found that virtual water imports are unlikely leading to higher population growth rates. However, current virtual water imports are correlated with future increases in human development. Similarly, as a country becomes more open to virtual water trade, it experiences decreases in undernourishment, which we use to proxy food security gains. Of note, food security showed no correlation with the classic measure of trade openness in financial terms, but exhibited a strong relationship with the index of virtual water trade openness that we developed in this paper.

Countries with relatively large dam storage capacity consume less water resources from international sources. Although countries with small storage capacity consume more water from abroad, this does not indicate food vulnerability. Rather, these countries are accessing storage capacity through trade, in what can be thought of as infrastructure sharing. Implicitly sharing infrastructure through trade is efficient, in terms of minimizing the direct financial cost of building more dams, as well as the often heavy environmental and social costs of dam building.

HESSD
10, 7291–7324, 2013

Globally, countries tend to increase their crop water use efficiency as they export more crops. However, countries in Africa do not exhibit this trend. This confirms findings in the literature that yield gaps exist in Africa and that increasing internal agricultural production is a major challenge for the future. Despite low crop yields, regional agricultural trade in Africa exhibits high efficiency in terms of embodied water resources. African trade based efficiences are on the order of ten times higher than the global average. Thus, the agricultural trade system within Africa may be compensating to some extent for low levels of domestic productivity.

Acknowledgements. We would like to thank the data sources for making the data available, without which this project would not be possible.

References

Aquastat: Aquastat Database, Food and Agriculture Organization of the United Nations (FAO), http://www.fao.org/nr/water/aquastat/main/index.stm, last access: 15 April 2013.

Brown, M., Hintermann, B., and Higgins, N.: Markets, climate change, and food security in West Africa, Environ. Sci. Technol., 43, 8016–8020, 2009.

Burgess, R. and Donaldson, D.: Can openness mitigate the effects of weather shocks? Evidence from India's famine era, American Economic Review: Papers and Proceedings, 449–453, 2010.

Condorcet, M.: Esquisse d'un tableau historique des progrés de l'espirit humain, Chez Agasse, Paris, 1794.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., and Rodriguez-Iturbe, I.: Evolution of the global virtual water trade network, P. Natl. Acad. Sci., 109, 5989–5994, doi:10.1073/pnas.1203176109, 2012.

D'Odorico, P., Laio, F., and Ridolfi, L.: Does globalization of water reduce societal resilience to drought?, Geophys. Res. Lett., 37, L13403, doi:10.1029/2010GL043167, 2010.

Doll, P. and Siebert, S.: Global modeling of irrigation water requirements, Water Resour. Res., 38, 8.1–8.10, doi:10.1029/2001WR000355, 2004.

Dorosh, P.: Trade liberalization and national food security: Rice trade between Bangladesh and India, World Development, 29, 673–389, 2001.

HESSD
10, 7291–7324, 2013

Virtual water trade and development in Africa

M. Konar and K. Caylor

Ehrlich, P.: The Population Bomb, vol. 208, Ballantine Books, New York, 1968.
Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., and Cramer, W.: Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade, Hydrol. Earth Syst. Sci., 15, 1641–1660, doi:10.5194/hess-15-1641-2011, 2011.
FAO: How to feed the world 2050: High-level expert forum, The special challenge of Sub-Saharan Africa, Rome, 12–13 October 2009.
FAO: Climate change, water and food security, Food and Agriculture Organization of the United Nations (FAO) Water Reports 36, 1st Edn., Rome, 2011a.
FAO: Why has African become a net food importer? Explaining Africa agricultural and food trade deficits , Trade and Markets Division, Rome, 2011b.
FAOSTAT: Food and Agriculture Organization of the United Nations (FAO), http://faostat.fao.org/, last acces: 15 November 2012.
Foley, J., Ramankutty, N., Brauman, K., Cassidy, E., Gerber, J., Johnston, M., Mueller, N., O'Connell, C., Ray, D., West, P., Balzer, C., Bennett, E., Carpenter, S., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., and Zaks, D.: Solutions for a cultivated planet, Nature, 478, 337–342, doi:10.1038/nature10452, 2011.
Frankel, J. and Romer, D.: Does trade cause growth?, Am. Econom. Rev., 89, 379–399, 1999.
Godfray, H., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., and Toulmin, C.: Food security: The challenge of feeding 9 billion people, Science, 327, 812–818, doi:10.1126/science.1185383, 2010.
Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 2: Applications and assessments, Hydrol. Earth Syst. Sci., 12, 1027–1037, doi:10.5194/hess-12-1027-2008, 2008.
Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing, Hydrol. Earth Syst. Sci., 12, 1007–1025, doi:10.5194/hess-12-1007-2008, 2008.
Hanasaki, N., Inuzuka, T., Kanae, S., and Oki, T.: An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model, J. Hydrol., 384, 232–244, doi:10.1016/j.jhydrol.2009.09.028, 2010.

Hanjra, M. and Qureshi, M.: Global water crisis and future food security in an era of climate change, Food Policy, 35, 365–377, 2010.
Hertel, T., Burke, M., and Lobell, D.: The poverty implications of climate-induced crop yield changes by 2030, Global Environ. Change, 20, 577–585, 2010.
Hoekstra, A. and Chapagain, A.: Globalization of water: Sharing the planet's freshwater resources, Global Environ. Change, 1–224, 2008.
Hoekstra, A. and Hung, P.: Globalisation of water resources: international virtual water flows in relation to crop trade, Global Environ. Change, 15, 45–56, 2005.
Jevons, W.: The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines, Macmillan & Co., London, 1865.
Kastner, T., Rivas, M., Koch, W., and Nonhebel, S.: Global changes in diets and the consequences for land requirements for food, P. Natl. Acad. Sci., 109, 6868–6872, doi:10.1073/pnas.1117054109, 2012.
Konar, M., Dalin, C., Suweis, S., Hanasaki, N., Rinaldo, A., and Rodriguez-Iturbe, I.: Water for food: The global virtual water trade network, Water Resour. Res., 47, W005520, doi:10.1029/2010WR010307, 2011.
Konar, M., Dalin, C., Hanasaki, N., Rinaldo, A., and Rodriguez-Iturbe, I.: Temporal dynamics of blue and green virtual water trade networks, Water Resour. Res., 48, W07509, doi:10.1029/2012WR011959, 2012.
Konar, M., Hussein, Z., Hanasaki, N., Mauzerall, D. L., and Rodriguez-Iturbe, I.: Virtual water trade flows and savings under climate change, Hydrol. Earth Syst. Sci. Discuss., 10, 67–101, doi:10.5194/hessd-10-67-2013, 2013.
Malthus, T.: An essay on the principle of population, J. Johnson, London, 1798.
Monfreda, C., Ramankutty, N., and Foley, J.: Farming the planet, Part 2: The geographic distribution of crop areas and yields in the year 2000, Global Biogeochem. Cy., GB1022, doi:10.1029/2007GB002947, 2008.
Odularu, G.: Conceptual explanation of virtual water trade and lessons for Africa, J. Develop. Agr. Econom., 1, 162–167, 2009.
Peters, G., Minx, J., Weber, C., and Edenhofer, O.: Growth in emission transfers via international trade from 1990 to 2008, P. Natl. Acad. Sci., 108, 8903–8908, doi:10.1073/pnas.1006388108, 2011.

Ramankutty, N., Evan, A., Monfreda, C., and Foley, J.: Farming the planet, Part 1: The geographic distribution of global agricultural lands in the year 2000, Global Biogeochem. Cy., GB1003, doi:10.1029/2007GB002952, 2008.
Rosegrant, M., Cai, X., and Cline, S.: World water and food to 2025, 1st Edn., International Food Policy Research Institute, Washington, DC, 2002.
Schipanski, M. and Bennett, E.: The influence of agricultural trade and livestock production on the global phosphorus cycle, Ecosystems, 15, 256–268, doi:10.1007/s10021-011-9507-x, 2012.
Siebert, S., Döll, P., Hoogeveen, J., Faures, J.-M., Frenken, K., and Feick, S.: Development and validation of the global map of irrigation areas, Hydrol. Earth Syst. Sci., 9, 535–547, doi:10.5194/hess-9-535-2005, 2005.
Simon, J.: Resources, population, environment: an oversupply of false bad news, Science, 208, 1431–1437, doi:10.1126/science.7384784, 1980.
Skinner, J., Niasse, M., and Haas, L., eds.: Sharing the benefits of large dams in West Africa, Natural Resource Issues No. 19, International Institute for Environment and Development, London, UK, 2009.
Suweis, S., Rinaldo, A., Maritan, A., and D'Odorico, P.: Water-controlled wealth of nations, P. Natl. Acad. Sci., 110, 4230–4233, doi:10.1073/pnas.1222452110, 2013.
Tamea, S., Allamano, P., Carr, J. A., Claps, P., Laio, F., and Ridolfi, L.: Local and global perspectives on the virtual water trade, Hydrol. Earth Syst. Sci., 17, 1205–1215, doi:10.5194/hess-17-1205-2013, 2013.
Tinbergen, J.: An Analysis of World Trade Flows, in: Shaping the world economy, Twentieth Century Fund, New York, 1962.
UNCTD: Statistical Database, United Nations Conference on Trade and Development, http://unctadstat.unctad.org, last access: 10 April 2013.
UNDP: International Human Development Indicators, United Nations Development Programme, http://hdrstats.undp.org/en/tables/ (last access: 10 April 2013), 2012.
US Agricultural Trade Office: Gulfood 2010 Briefing, www.gulfoodusapavilion.com/Files/ATO%20Dubai%20briefing.ppt (last access: 15 March 2013), 2010.
Weedon, G., Gomes, S., Viterbo, P., Shuttleworth, W., Blyth, E., Osterle, H., Adam, J., Bellouin, N., Boucher, O., and Best, M.: Creation of the WATCH forcing data and its use to assess global and regional reference crop evapotranspiration over land during the 20th century, J. Hydrometeorol., 12, 823–848, doi:10.1175/2011JHM1369.1, 2011.

Winters, L., McCulloch, N., and McKay, A.: Trade liberalization and poverty: The evidence so far, J. Econom. Literat., 42, 72–115, 2004.
World Bank: The World Bank Databank, http://databank.worldbank.org/data/ (last access: 15 April 2013), 2012.

HESSD
10, 7291–7324, 2013

Virtual water trade and development in Africa

M. Konar and K. Caylor

Table 1. Regional virtual water trade, savings, and losses in km^3 for 2008. Regional African trade is the second smallest and savings are approximately average. However, note that the ratio of internal savings to trade in Africa is 2.55, while the global average without Africa is 0.14. Surprisingly, the ratio of African savings to losses is 20.77, while the global average, exlusive of Africa, is 1.74.

	Trade [km^3]	Savings [km^3]	Losses [km^3]	Savings: Trade	Savings: Losses
Africa	3.59	9.14	0.44	2.55	20.77
North America	57.73	20.54	3.34	0.36	6.15
South America	44.43	6.20	5.83	0.14	1.06
Asia	75.70	10.11	20.23	0.13	0.50
Europe	46.84	9.34	3.56	0.20	2.62
Oceania	1.08	0.02	0.26	0.02	0.08
World	38.23	9.23	5.61	0.57	5.20

HESSD
10, 7291–7324, 2013

Virtual water trade and development in Africa

M. Konar and K. Caylor

Table A1. List of commodities and the yield ratio (r), price ratio (p), and content ratio (c); reproduced from Hanasaki et al. (2010).

Crop commodities	r	p	c	Livestock products	r	p	c
Wheat	1	1	1	Cattle meat	0.6	0.61	1
Flour of wheat	0.78	0.97	1	Offal of cattle, edible	0.32	0.38	1
Bran of wheat	0.22	0.024	1	Fat of cattle	0.04	0.0024	1
Macaroni	0.78	0.97	1	Meat-cattle boneless (beef and veal)	0.6	0.61	1
Germ of wheat	0.025	0.01	1	Cattle, butchered fat	0.04	0.0024	1
Bread	0.78	0.97	0.71	Preparation of beef	0.4	0.61	1
Bulgur	1	1	1	Pig meat	0.7	0.88	1
Rice, paddy	1	1	1	Offal of pigs, edible	0.12	0.12	1
Rice, husked	0.72	1	1	Fat of pigs	0.06	0.006	1
Milled husked rice	0.72	1	1	Pork	0.49	0.88	1
Rice, milled	0.65	0.95	1	Bacon and ham	0.49	0.88	1
Rice, broken	0.65	0.95	1	Pig, butchered fat	0.06	0.006	1
Bran of rice	0.07	0.049	1	Pork sausages	0.49	0.88	1
Rice, bran oil	0.013	0.049	1	Prepared pig meat	0.49	0.88	1
Cake rice bran	0.057	0.049	1	Lard	0.06	0.006	1
Rice, flour	0.65	0.95	1	Chicken meat	0.53	0.95	1
Rice, fermented beverages	0.48	0.95	0.36	Offal and liver of chicken	0.022	0.014	1
Barley	1	1	1	Fat liver prepared (foie gras)	0.022	0.014	1
Pot barley	0.46	0.76	1	Chicken meat canned	0.53	0.95	1
Barley, pearled	0.46	0.76	1	Fat of poultry	0.022	0.013	1
Bran of barley	0.54	0.24	1	Fat of poultry, rendered	0.022	0.013	1
Barley flour and grits	0.46	1	1				
Malt	0.78	1	1				
Malt extract	0.78	1	0.8				
Beer of barley	0.78	1	0.14				
Maize	1	1	1				
Germ of maize	0.115	0.18	1				
Flour of maize	0.8	0.75	1				
Bran of maize	0.085	0.068	1				
Maize oil	0.04	0.18	1				
Cake of maize	0.075	0.18	1				
Soybeans	1	1	1				
Soybean oil	0.19	0.35	1				
Cake of soybeans	0.76	0.65	1				
Soya sauce	0.76	0.65	0.17				
Maize, green	1	1	1				
Maize for forage and silage	1	1	1				

HESSD
10, 7291–7324, 2013

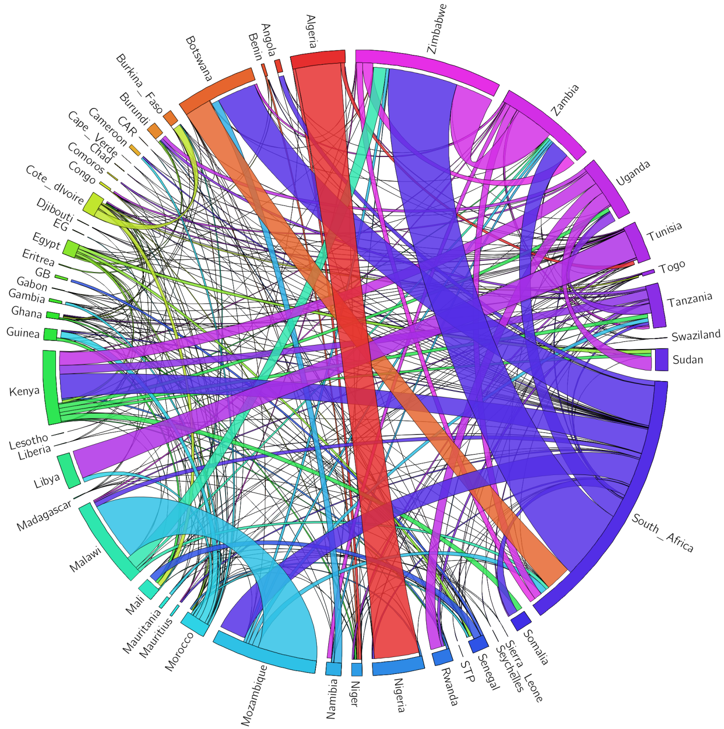

Fig. 1. African virtual water trade network. Each of the 51 African nations included in this graph is assigned a color. Trade links are assigned the same color as the country of export. Trade direction is indicated by the white gap between the trade link and the country of import. The total volume of virtual water trade within African countries is 3.59 km^3. The dominant link is that from South Africa to Zimbabwe, with a volume of 0.37 km^3 of virtual water. South Africa is the major exporter of virtual water resources, sending 1.12 km^3 to other African nations. Zimbabwe is the major importer of virtual water resources, importing 0.66 km^3. "CAR" indicates Central African Republic, "EG" indicates Equatorial Guinea, "GB" indicates Guinea-Bissau, and "STP" indicates Sao Tome and Principe.

HESSD
10, 7291–7324, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

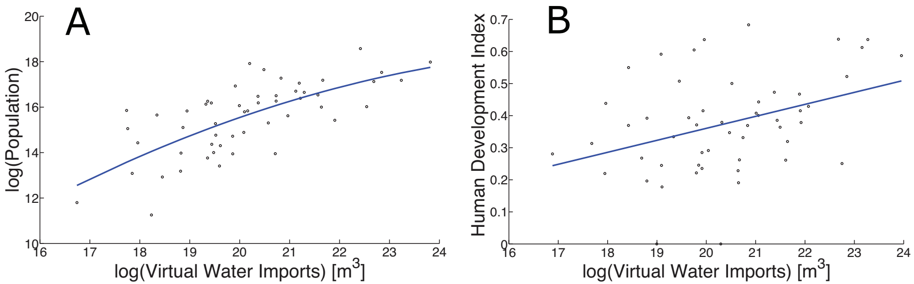

Fig. 2. Relationships for human population and development with virtual water imports (VWI) in Africa. **(A)** log(Population) against log(VWI) exhibits an increasing non-linear relationship. Note that the growth rate slows with increasing virtual water imports. **(B)** Human development index (HDI) against log(VWI) exhibits an increasing linear relationship. Each point represents the national time-average of available data between 1986 and 2008.

HESSD
10, 7291–7324, 2013

Virtual water trade and development in Africa

M. Konar and K. Caylor

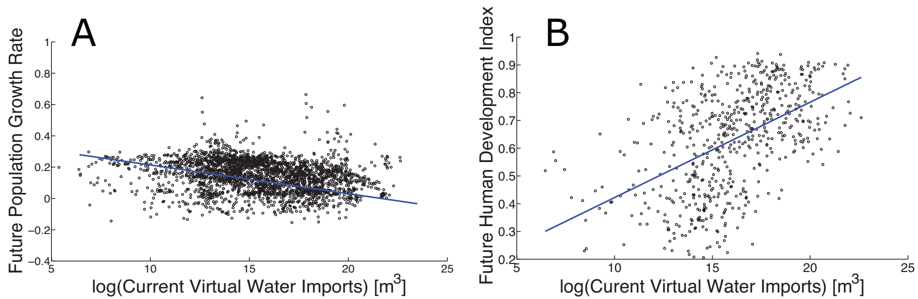

Fig. 3. Lagged global relationships for human population and development with virtual water imports (VWI). **(A)** Future population growth rate against current log(VWI) shows a linearly decreasing trend. **(B)** Future HDI exhibits a linearly increasing trend with current log(VWI). The time lag used is 10 yr.

HESSD
10, 7291–7324, 2013

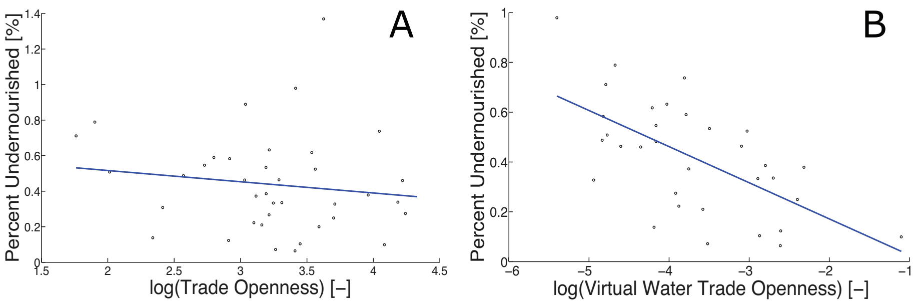

Fig. 4. Relationship between the fraction of the population that is undernourished and **(A)** the classic definition of trade openness based on financial value (i.e., USD); and **(B)** the index of virtual water trade openness.

HESSD
10, 7291–7324, 2013

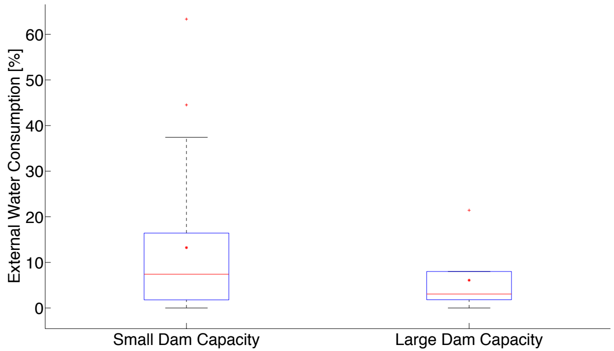

Fig. 5. Box-whisker plot of the external water consumption [%] vs. the total storage capacity of each African nation. Small dam capacity is defined to be between 0 and 70 km^3; large dam capacity is between 70 and 140 km^3. The red horizontal line represents the median, while the mean is plotted with a red star. The edges of the box represent the 25th and the 75th percentiles of the data, while the whiskers extend to the most extreme data points that are not considered to be outliers. Data outliers are represented individually by red plus marks. Note the right skewed distribution of countries with a small dam capacity.

HESSD
10, 7291–7324, 2013

Virtual water trade and development in Africa

M. Konar and K. Caylor

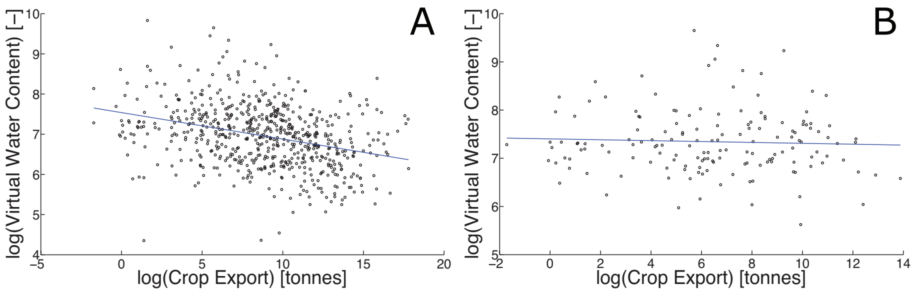

Fig. 6. Relationship between log VWC and log crop export for **(A)** the world and **(B)** Africa. Note that water use efficiency in agriculture increases (i.e., VWC decreases) in percentage terms with percentage increases in crop export for the world **(A)**. However, the relationship between log VWC and log crop export is flat for Africa **(B)**.

HESSD
10, 7291–7324, 2013

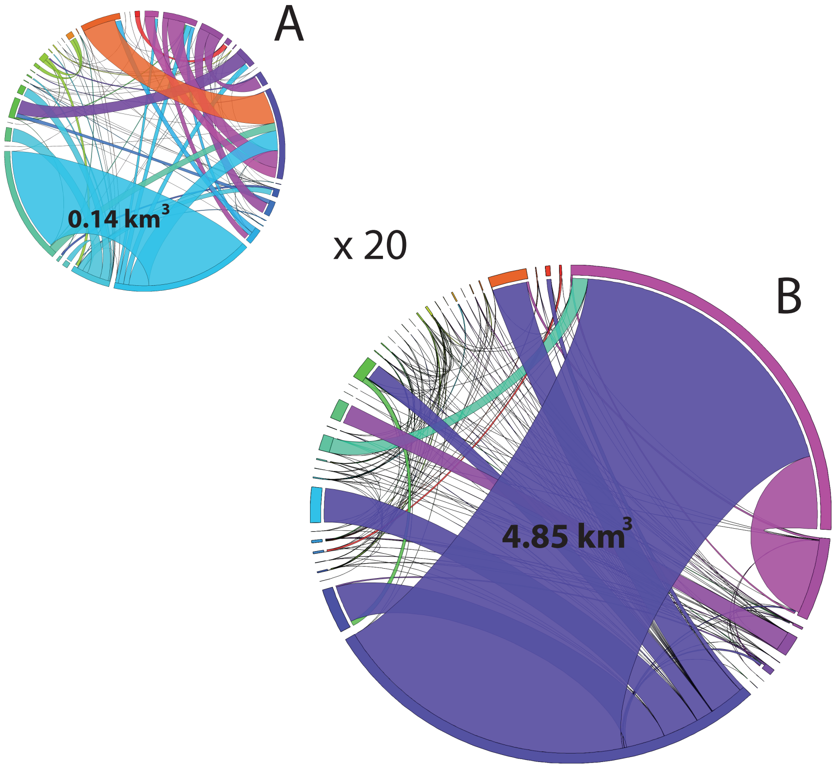

Fig. 7. Internal African **(A)** trade based water losses and **(B)** trade based water savings. Note that the regional graphs are not scaled by size, since internal African savings are approximately 20 times greater than losses. The largest link in **(A)** is that from Mozambique to Malawi, which amounts to trade based water losses of 0.14 km^3, approximately 32 % of total losses. The largest link in **(B)** is that from South Africa to Zimbabwe, responsible for saving 4.85 km^3, or approximately 53 % of total savings.

HESSD
10, 7291–7324, 2013

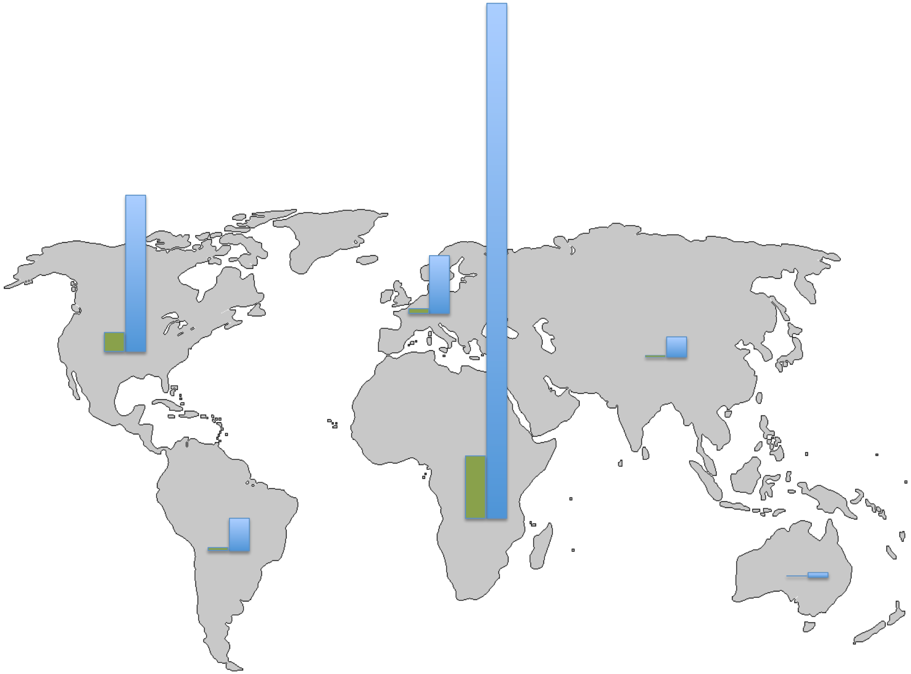

Fig. 8. World map displaying the ratios of regional water savings to trade and losses. The green bars indicate the water savings to trade ratios and the blue bars illustrate the water savings to losses ratios. Values of the regional ratios can be found in Table 1. Note that internal African trade is the most efficient in the world.

HESSD
10, 7291–7324, 2013