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Water resources transfers through southern African food trade: water efficiency and climate signals

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Abstract
Temporal and spatial variability of precipitation in southern Africa is particularly high. The associated drought and flood risks, combined with a largely rain-fed agriculture, pose a challenge for water and food security in the region. As regional collaboration strengthens through the Southern Africa Development Community and trade with other regions increases, it is thus important to understand both how climate variability affects agricultural productivity and how food trade (regional and extra-regional) can contribute to the region's capacity to deal with climate-related shocks. We combine global hydrological model simulations with international food trade data to quantify the water resources embedded in international food trade in southern Africa and with the rest of the world, from 1986–2011. We analyze the impacts of socio-economic changes and climatic variability on agricultural trade and embedded water resources during this period. We find that regional food trade is efficient in terms of water use but may be unsustainable because water-productive exporters, like South Africa, rely on increasingly stressed water resources. The role of imports from the rest of the world in the region's food supply is important, in particular during severe droughts. This reflects how trade can efficiently redistribute water resources across continents in response to a sudden gap in food production. In a context of regional and global integration, our results highlight opportunities for improved water-efficiency and sustainability of the region's food supply via trade.

Introduction

Rural livelihoods and food production in southern Africa are strongly reliant on rain-fed agriculture, which, coupled with high temporal and spatial rainfall variability, makes the region's economy particularly vulnerable to climate shocks like droughts (Conway *et al* 2015). In addition, agricultural water productivity is low and the sector is by far the most water consuming (77% freshwater withdrawals used for irrigation, (Frenken 2005)). Agriculture is largely based on maize (75% of total cereal production in 2010, (FAO 2015)) but the region's demand for food is growing and diversifying, associated with a slow integration into world's markets, as well as regional integration via the Southern Africa Development Community (SADC), which promotes internal trade (SADC 2005). Global food trade has been shown to save about 10% of global irrigation withdrawals (Dalin *et al* 2012). In southern Africa (here 13 countries corresponding to the SADC members excepting Mauritius and Seychelles, see figure 2), regional heterogeneity in water productivity and availability suggests there is potential for water savings through regional food trade, worthy of further exploration. In addition, strengthening regional and global food trade could improve the resilience of the whole region to localized climate shocks affecting food and water security.

Many southern African economies are subjected to high rainfall variability (Conway *et al* 2009), which has hindered economic growth in the entire region (Barrios *et al* 2010), as well as in particular countries, such as Zambia (Thurlow *et al* 2012) and Malawi (Pauw *et al* 2011) through recurring floods and droughts. One of the longest and most widespread droughts affected the region around 1992, while other events have repeatedly occurred with varying intensity and spatial extent (Rouault and Richard 2005). In addition to these existing risks (Rouault and Richard 2005, CPWF 2003), current water stress is projected to increase under ongoing and future climate change, in important agricultural regions (e.g. Limpopo River basin, (Zhu and Ringler 2012)). For these reasons, ensuring water and food security has been and may continue to be particularly challenging in the region.

A few studies have highlighted the importance of analyzing virtual water trade (VWT) in southern Africa, in particular amongst SADC member states, to explore current and potential associated water savings (Dabrowski *et al* 2009). One study analyzed changes in grain trade and found that promoting water transfers via food trade could be more sustainable and viable than physical transnational transfer schemes (Earle and Turton 2002); others have studied VWT relevance for food security (Earle 2001), and another study found that in 2003, SADC maize trade flows were driven by productivity rather than scarcity of water (Dabrowski *et al* 2009). However, existing work has not explicitly quantified VWT flows (Earle 2001, Earle and Turton 2002) with the exception of one paper (Dabrowski *et al* 2009), which only focused on one commodity for a specific year. Moreover, there is a lack of VWT estimates that include an analysis of temporal changes in water productivity and detailed trade flows. We describe, for the first time, detailed bilateral VWT within southern Africa and with the rest of the world (RoW), and, importantly, account for temporal variation in agricultural water productivity and trade patterns. This enables us to quantify the impacts of socio-economic changes and climate variability on southern Africa's water-food-trade system as linked to the RoW.

In this paper, we combine a hydrological model with historical food trade data to quantify VWT flows with and within southern Africa over the 1986–2011 period. We use state-of-the-art VWC estimates and the longest available record of bilateral international food trade for five major crops and three livestock products. We then analyze changes in water productivity, trade connections and embedded water, and the efficiency of trade in terms of water resources use. Finally, we examine the impacts of temporal climate variability on food supply, and provide insights on the role of trade for climate adaptation. We aim to answer the following questions: (i) how has southern Africa's water productivity, food and virtual water trade evolved between 1986 and 2011? (ii) Has regional or external food trade become more water-efficient during this period? (iii) How significant were the impacts of droughts on agricultural production and water use, and is there evidence for their mitigation via food trade? By addressing these questions, we aim to provide key insights for strategies targeted at improving food and water security in the region.

Data and methods

Virtual water trade

We consider a region composed of 13 southern African countries corresponding to the SADC members—excepting the two island States of Mauritius and Seychelles.

First, we quantify bilateral VWT flows among them and with the other countries. We use bilateral, international trade data for 47 food commodities (see table S1) derived from five major crop (barley, maize, rice, soy and wheat) and three livestock (cattle, pork and poultry) products, from 1986–2011 (detailed trade matrix in (FAO 2015)). These commodities account for about 70% of food supply in southern Africa in 2011 (in calories per capita; food balance sheet in (FAO 2015)).

Virtual water content (VWC) of maize, rice, soy, and wheat is calculated from 1986–2005 with the H08 global hydrological model (Hanasaki 2015), using evapotranspiration (ET) data at 0.5 °and daily resolution (Sheffeld *et al* 2006) and using a recent, state-of-the-art gridded yield (Y) dataset at 1.125 °and annual resolution (Iizumi *et al* 2014), downscaled to the 0.5° resolution by linear interpolation. VWC ($kg_{water}\,kg_{crop}^{-1}$) of raw crop *c* in country *i* and year *y* is calculated as follows: $VWC_{i,c,y} = \overline{ET_{i,c,y}}/Y_{i,c,y}$, where $\overline{ET_{i,c,y}}$ ($kg_{water}\,m^{-2}$) is ET from cropland planted with *c*, averaged over the growing season, and $Y_{i,c,y}$ ($kg_{crop}\,m^{-2}$) is yield of crop *c*, both in year *y* and country *i*. From 2006–2011, maize, rice, soy, and wheat VWC is scaled with annual yield data (crop production data in (FAO 2015)). Harvested areas, including rainfed and irrigated land for 26 crop types, were taken from MIRCA2000 (Portmann *et al* 2010). The H08 model differentiates actual ET across crops within a grid cell using the simulated length of cropping period. Due to data limitations, we estimate VWC of barley and livestock with previous H08 simulations (Dalin *et al* 2012), providing annual data from 1986–2001. From 2002–2011, livestock VWC is kept constant and barley VWC is scaled with annual yield data (crop production data in (FAO 2015)). VWC of processed commodities is then derived from the VWC of raw products, using conversion ratios from (Hanasaki *et al* 2008). All VWC estimates distinguish between green (i.e. soil moisture) and blue (i.e. rivers, reservoirs, and aquifers—via irrigation) sources of water for agricultural production.

VWT flows are obtained by multiplying trade flows by the commodity's VWC in the exporting country, as follows: $VWT_{i,j,c,y} = T_{i,j,c,y}\,VWC_{i,c,y}$; where $VWT_{i,j,c,y}$ (kg_{water}) is the virtual water volume embedded in crop *c* exported from country *i* to country *j*,$T_{i,j,c,y}$ (kg_{crop}) is the weight of crop *c* exported

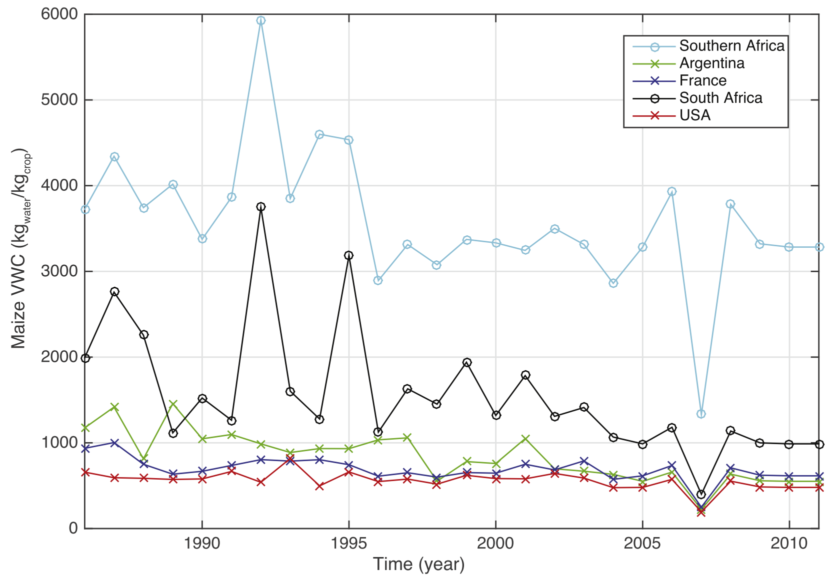

Figure 1. Evolution of maize VWC in southern Africa (average), South Africa, and major trading partners—Argentina, France and the USA—from 1986–2011.

from country i to country j and $VWC_{i,c,y}$ ($kg_{water}\ kg_{crop}^{-1}$) is the VWC of crop c in country i, all in year y.

The water efficiency of trade flows can be measured as global water savings (WS), defined, for a specific trade relationship, as the difference between the volume of water that would be consumed by the importer if it produced the imported food domestically, and the volume of water actually consumed by the exporter to make the exported food. This measure reflects both the volume of food traded through the specific link and the difference in water productivity between the two trade partners and is calculated, for each pair of countries (i, j), commodity c and year y, as follows: $WS_{i,j,c,y} = T_{i,j,c,y} \cdot (VWC_{j,c,y} - VWC_{i,c,y})$.

Climate impacts

Second, we compare the evolution of the food-water-trade system in southern Africa with changes in climatic conditions, using linear regressions. To do so, we create national annual Palmer drought severity index (PDSI, (Palmer 1965)) and precipitation (PRCP) indices. Low PDSI values indicate dry conditions.

We calculate the national annual PDSI index by averaging PDSI data from monthly, 0.5° resolution (Sheffeld *et al* 2006) to annual and national levels. The temporal averaging is done over the approximate maize growing season (October–May included, (Sacks *et al* 2010)) and the spatial averaging is done with weighting 0.5° PDSI by the share of cropland in each cell (cropland information from the 2014 version of (Ramankutty and Foley 1999)). We then compare time-series of the national annual PDSI index with time-series of annual and national VWC, food imports, virtual water imports (VWIs), and agricultural GDP (agriculture's share of gross domestic product (World-Bank 2015)). PDSI corresponding to maize growing season (from October of year y-1 to May of year y) are linearly regressed against dependent variables (Trade, GDP, etc) in year y, as these correspond to after-harvest production.

Similarly, we create a national annual PRCP index, corresponding to 'cumulative rainfall across the growing season', by averaging precipitation data from the most recent, half degree, daily resolution dataset from (Sheffeld *et al* 2006) to annual and national levels. The spatial averaging is done with the same data and methods as for PDSI, and temporally we compute cumulative rainfall.

We then perform linear regression between PRCP and PDSI anomalies (ratio to the mean over the time period) on the one hand and anomalies in VWC, Trade and agricultural GDP on the other hand, for each nation in southern Africa, for the 1986–2011 period. We also linearly regress gridded versions of PRCP and PDSI against gridded maize yields (Iizumi *et al* 2014) (see supplementary information), both with separate regressions for each country and with a panel regression with country fixed effects on the whole dataset—13 countries and 20 years (time frame limited by yield data). To account for precipitation's temporal and spatial variability within a country, we compute two other precipitation indices based on temporal anomalies in each grid cell, by counting the percentage of cells in each country where these anomalies are in the top (WAP(+) – weighted anomaly precipitation) or bottom (WAP(−)) decile of the anomalies distribution over time, as inspired from (Brown 2013). Thus, the WAP(+) (WAP(−)) value associated with each country and year indicates the percentage of grid cells of that country that saw unusually high (low) precipitation in that year. We then

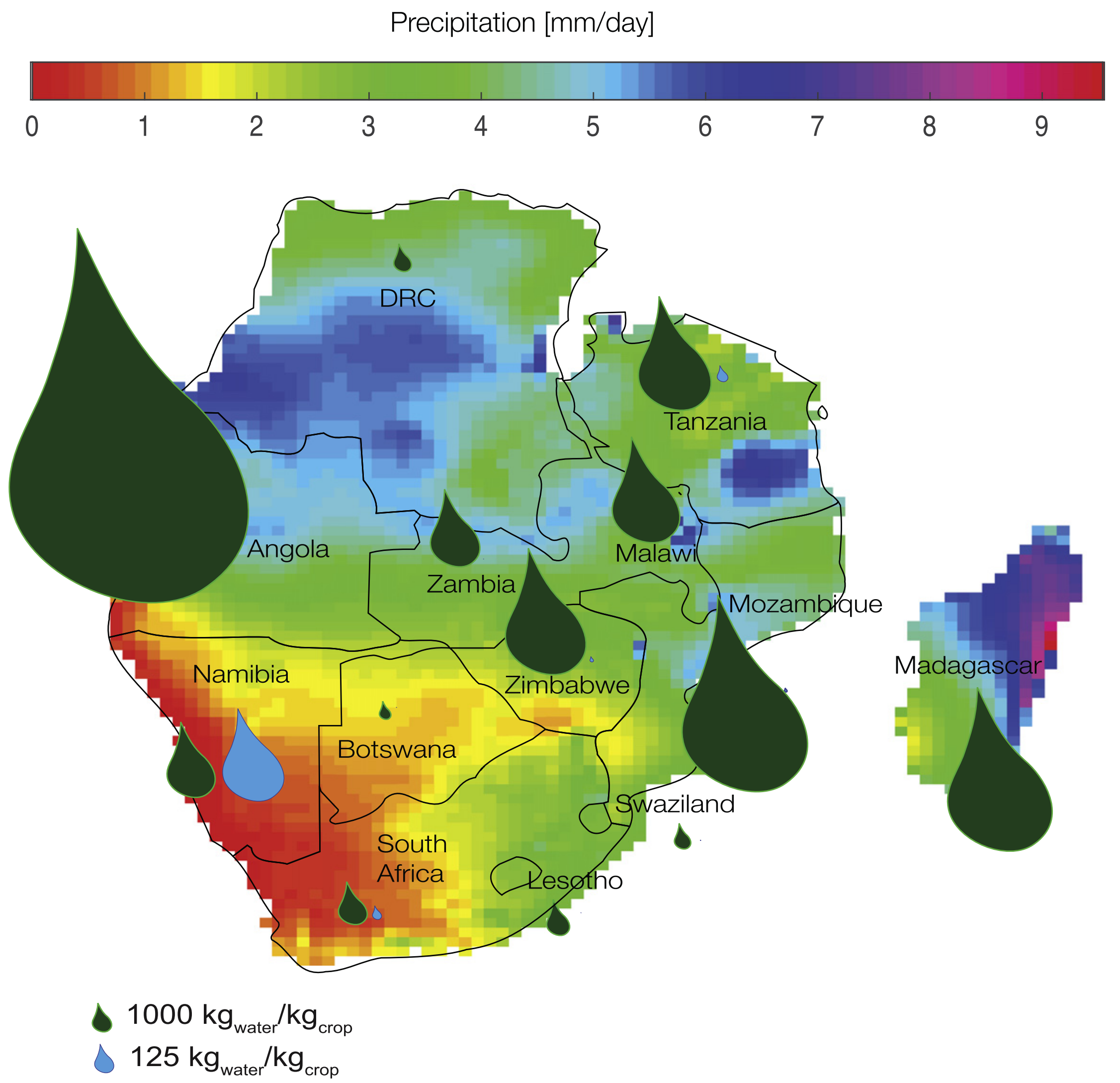

Figure 2. Maize VWC averaged from 1986–2011, by nation and source of water (green: soil moisture, and blue: irrigation). The shading indicates mean growing season (October–May) precipitation.

perform panel linear regression on the entire dataset—13 countries and 27 years—between agricultural GDP, maize VWC, VWI and food imports on the one hand and WAP(+) and WAP(-) on the other hand, with country fixed effects.

Results

Agricultural water productivity

Crop VWC (reflecting the inverse of water productivity) by country shows no clear temporal trend over the study period, but has considerable variability (figures 1, S3). In particular, crop VWC values peak across most of the region in 1992, especially for irrigation-based VWC, reflecting an unusually low crop water productivity, due to the prolonged and widespread drought in southern Africa at the time.

There is also significant spatial variability in crop and livestock VWC across the region. Indeed, over the 1986–2011 period, national mean VWC of crops varies from 1263 to 3977 $kg_{water}\ kg_{crop}^{-1}$, in Botswana and Lesotho, respectively. National mean VWC of maize over the period ranges from 250 to 12 400 $kg_{water}\ kg_{crop}^{-1}$, in Botswana and Angola, respectively (figure 2). Livestock VWC varies between 4000 and 10 000 $kg_{water}\ kg_{meat}^{-1}$, with outliers in Botswana (a maximum of 47 900 in 2000 due to very high pork and poultry VWC). National mean VWC of cattle meat over the period ranges from 2700 to 16 800 $kg_{water}\ kg_{meat}^{-1}$, in DR Congo and Namibia, respectively.

Green water generally dominates VWC over blue water, reflecting the low levels of irrigation in the region (figure 2). The share of irrigation water in crops and livestock VWC is negligible in most countries, except in Namibia, Tanzania, and South Africa.

Food trade

On average in the region, and accounting for the eight main products, a 17% increase in per capita food supply (defined by FAO as the sum of production, net imports, and net stock increase) has occurred over the period, from about 120 to 140 kg/cap/yr. South Africa

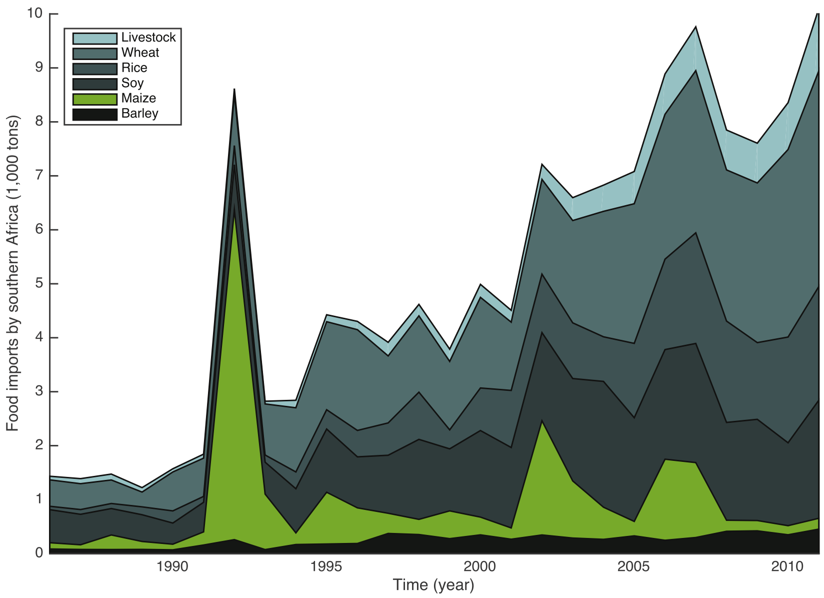

Figure 3. Extra-regional food imports (in thousand tons) by southern Africa from 1986–2011, by product.

has the highest food supply, which increased from 210 to 240 kg/cap/yr over the period.

Regional food trade (among southern African countries) shows a generally increasing temporal trend, but with significant inter-annual oscillations. Similar growth (figure S2) and inter-annual variability is observed for the region's agricultural production. Maize strongly dominates these trade flows over the 1986–2011 period, but the relative importance of wheat has increased since 2000 (figure S4).

Extra-regional food trade, between southern Africa and the RoW, is an order of magnitude larger than regional trade, in both directions (figures 3 and S5). While extra-regional exports remained relatively constant (although with major fluctuations), imports by southern Africa have significantly increased with time, from around 1.5 thousands tons in the late 1980s to 10 thousands tons in 2011 (figure 3). These imports, with similar contributions from wheat, rice, soy, and maize, are more diverse than regional trade and extra-regional exports, dominated by southern African maize. The drought of 1991–1992 is clearly reflected in the trade figures. Imports by southern Africa increased more than four-fold from 1991–1992, and decreased by three-fold from 1992–1993 (figure 3), reflecting the peak that helped fill the drought-induced supply deficit in 1992. Simultaneously, exports by southern Africa dropped from 1991 to 1992 (by about 90%), and then increased 12-fold directly after (from 1993 to 1994; 0.29 to 3.5 million tons of food commodities), leading to the highest export level by far after the drought recovery (figure S5).

Virtual water trade

The evolution of regional VWT is similar to that of regional food trade. Indeed, given the definition of VWT, if VWC shows no clear trend over time, then food trade and VWT will have similar trends. The dominance of maize is also maintained while converting trade to obtain VWT volumes (figure S8).

This similarity is also observed between southern Africa extra-regional food and virtual water exports (figures 6(b)). However, the evolution of southern Africa VWIs from outside the region differs from that of food imports (figure 3). Indeed, in this case, trade flows are multiplied by VWC in the RoW, which must have evolved differently than in southern Africa. For example, the peak in VWI imports in 1992 (figures 6(a) and 4) is relatively less important than the corresponding peak in food imports. This may be due to a different set of nations exporting to the region during this crisis, that may have produced maize more water-efficiently than the usual suppliers of southern Africa. Indeed in 1992, the dominant maize flour trade partner is the USA (with a maize VWC of 540 $kg_{water}\ kg_{crop}^{-1}$), followed by Brazil (1847 $kg_{water}\ kg_{crop}^{-1}$), France (804 $kg_{water}\ kg_{crop}^{-1}$) and Italy (931 $kg_{water}\ kg_{crop}^{-1}$). In 1993, maize imports are also dominated by the USA, but this country produced maize with a higher VWC than in the previous year (817 $kg_{water}\ kg_{crop}^{-1}$, figure 1), followed by Brazil (1841 $kg_{water}\ kg_{crop}^{-1}$), Italy (896 $kg_{water}\ kg_{crop}^{-1}$), and Portugal (1580 $kg_{water}\ kg_{crop}^{-1}$). So the major explanation for different patterns in VWI and food imports in 1992 seems to be France exporting crisis maize produced relatively more water-efficiently, and USA (the dominant exporter) having a better water productivity in 1992 than 1993.

Water savings via food trade

WS induced by regional food trade are mainly driven by maize trade, reflecting that more water productive

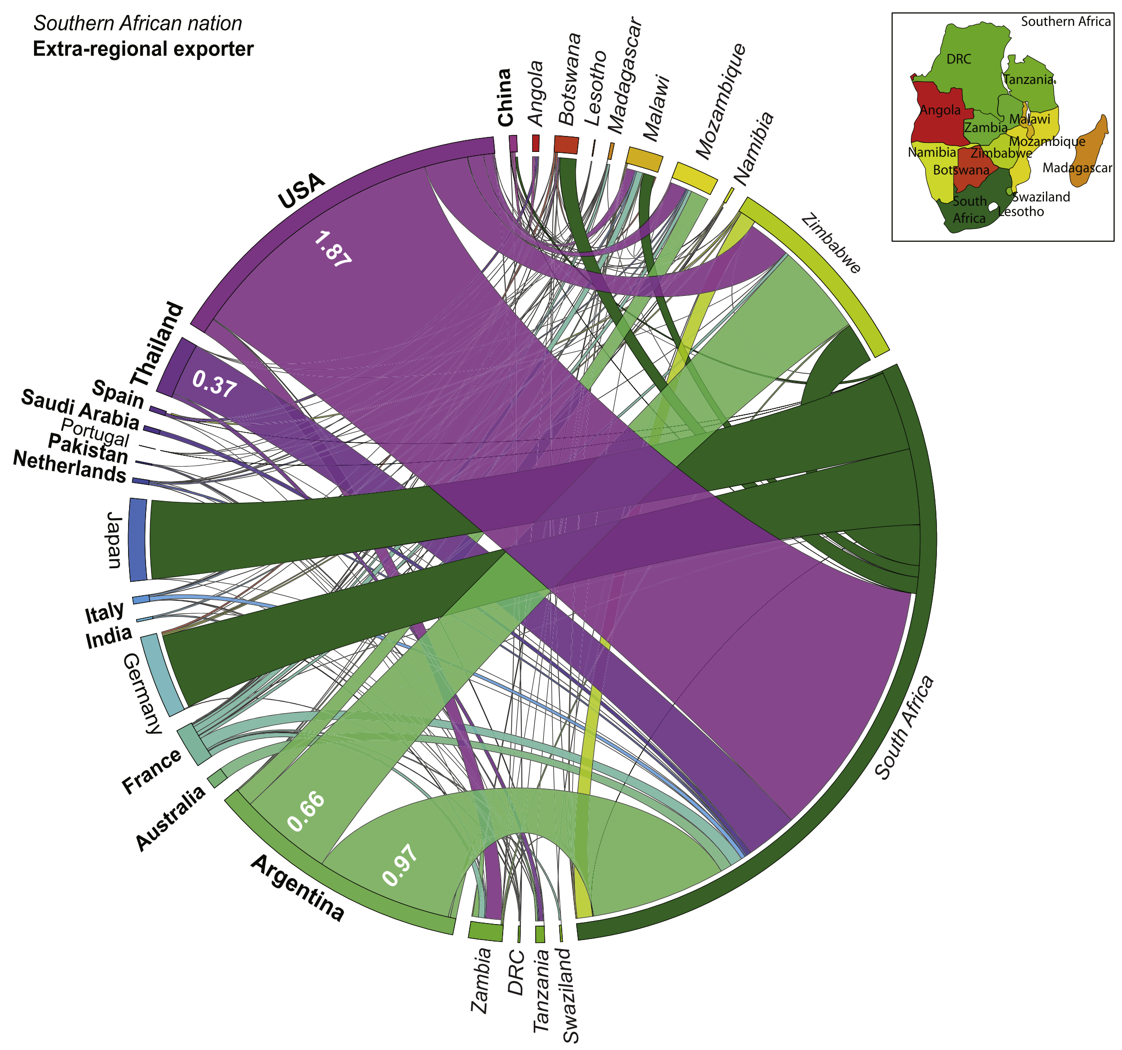

Figure 4. Additional virtual water trade flows (in km^3) with southern Africa in 1992 compared to 1991. Note the important additional virtual water imports from the USA (2.5 km^3) and Argentina (1.8 km^3), which contributed to alleviate drought impacts in southern Africa. The link color indicates the exporting country and the map provides a key to the color scheme for southern African countries. Center graph produced with software by (Krzywinski 2009).

countries export maize to less productive places in the region. There is no significant trend in WS over the 1986–2011 period, but an upward shift in the mean occurred in 2000. The peak WS was reached in 2005, with about 5.6 $km^3\ y^{-1}$, followed by a large drop to 0.3 km^3/y in 2007 (figure S9). Rice and wheat trade induces losses of blue water resources (WS of about -0.1 $km^3\ y^{-1}$ in 2011, figure S10).

WS induced by extra-regional food trade are more homogeneously distributed across commodities. However, we observe several years in which maize trade strongly dominates savings: 2008–2009, 2005–2006, 2002, and, in particular, 1992, where maize trade induced more than 3 km^3 WS, while these savings remain below 1.5 $km^3\ y^{-1}$ and often below 1 km^3 in other years. WS from all southern African food trade have been increasing since 2000, with major contributions from maize, wheat, and livestock trade (figure 7(a)). In 2011, maize, soy, wheat, and poultry trade have saved most water, largely from green sources (figure 7(b)).

Climate, food and virtual water trade fluctuations

We compared time-series of the national annual PDSI and PRCP indices with time-series of annual and national VWC, food imports, VWIs, and GDP; as well as PDSI and PRCP with gridded maize yield in each country using linear regressions.

Drought: The linear relationship between PDSI and maize blue VWC is negative for all southern African nations (except Tanzania), suggesting that irrigation use per unit crop increases (i.e. higher blue VWC) with drought severity (i.e. lower PDSI). However, only four cases are statistically significant at the 10% confidence level, including Namibia (largest R^2 of 0.45, table S5), one of the driest and most irrigation intensive countries. Maize green VWC also increases with drought severity (table S6), with a statistically significant linear relationship for Namibia, Angola and Madagascar (figure S14).

The nature of the relationship between PDSI and national food (crop and livestock) imports varies (i.e. negative and positive slopes, table S9). Food imports are found to increase with drought severity only for Angola, South Africa, Tanzania, Namibia and Lesotho, and the linear relationship is only statistically significant in Tanzania, at the 5% confidence level (with R^2 of 0.15).

Similarly, the relationships between PDSI and VWI are weak, and the sign of the slope varies across nations (table S7).

Weak relationships are found between PDSI and national agricultural GDP (table S10) for most countries; with the exception of Angola (slope 1.01, R^2 0.24 and statistically significant at the 1% confidence level), Namibia (slope 0.66, R^2 0.59 and statistically significant at the 1% confidence level) and Zambia, where agricultural GDP decreases strongly with drought severity.

The positive linear relationship between PDSI and maize yield (table S15), reflecting drought-induced yield decline and improved productivity in wetter years, is statistically significant only in Zimbabwe (R^2 0.12) and Madagascar (R^2 0.24) (figures S11, S12).

Rainfall: For most countries, we observe a negative relationship between PRCP and green VWC, indicating that rainfall-based ET per unit crop is lower (i.e. rainwater productivity is higher) in wetter years. The relationship is statistically significant in six countries, and best for Mozambique (R^2 0.33), Namibia (R^2 0.26, figure S13) and Malawi (R^2 0.23). The panel regression between WAP(−) and green maize VWC, with country fixed effects, leads to similar results over the whole region, showing a positive influence of WAS(−) (i.e. low rainfall) on green VWC, with high statistical significance ($p < 10^{-6}$) and a R^2 of 0.75.

The relationship between PRCP and agricultural GDP is positive for most countries (higher rainfall relates to larger GDP), and significant at the 1% level for Namibia and Zimbabwe (with R^2 of 0.29 and 0.31, respectively). The panel regression between WAP(−) and agricultural GDP, with country fixed effects, leads to similar results over the whole region, showing a negative influence of WAS(−) on agricultural GDP, with statistical significance at the 10% confidence level ($p < 0.10$) and a R^2 of 0.68.

Gridded, cumulative PRCP shows a strong, statistically significant positive linear relationship with gridded maize yield, indicating that wetter years correspond to higher yields, only in Zimbabwe (table S14). $R^2 = 0.21$, table S14. However, panel regression between gridded precipitation and gridded maize yield, with country fixed effects, results in a more significant positive effect, with $p < 0.001$ and $R^2 = 0.34$ (figure S16).

The linear relationship between PRCP and food imports is only statistically significant in Angola, where imports decrease with more abundant rainfall. Panel regression with country fixed effects leads to no significant relationship between WAS(−) and food or virtual water imports.

Discussion

Spatial and temporal variability of regional water productivity, food trade, and water savings

The region-wide low agricultural water productivity could be improved, and while current food trade patterns save water resources, regional trade could become more water-efficient through targeted agricultural improvements in wetter countries.

Maize water productivity in southern Africa has not significantly improved from the mid-80s to the 2000s, similarly to that of major trade partners (e.g. USA, Argentina, France). However, it is much lower than in the RoW (around 3500 $kg_{water}\,kg_{maize}^{-1}$ in the region versus 1880 $kg_{water}\,kg_{maize}^{-1}$ globally) and in other sub-tropical regions (e.g. 1200 $kg_{water}\,kg_{maize}^{-1}$ in Morocco and 830 $kg_{water}\,kg_{maize}^{-1}$ in Argentina, figure 1), even in South Africa, the most water productive country of the region (around 1600 $kg_{water}\,kg_{maize}^{-1}$). Low yields are the main reason for these high VWC values (only 2000 kg ha^{-1} in southern Africa versus 4300 kg ha^{-1} globally—on average over the period), which are exacerbated by high rates of potential ET (Hulme *et al* 1996). In southern Africa, large yield gaps still remain to be filled. Mueller *et al* (2012) found yields are limited by insufficient nutrient and water inputs, or by low nutrient only, in large parts of the region's northeastern area.

Agriculture is centered in the drier, water stressed South (e.g. South Africa and Swaziland), while the more water abundant North still has low production capacity. Paradoxically, crops' virtual water content is lower in dry regions (figure 2), due to a more developed agricultural sector, supported by relatively stable and mature economies favoring significantly higher yields. So even though trade currently occurs from dry to humid areas, it saves water resources at the regional scale, because more water abundant countries have lower agricultural water productivity. Indeed, regional food trade induces WS for the region (from 0 to 5.5 $km^3\,y^{-1}$), which are largely driven by maize trade (figure S9) from more to less water productive countries. In 2011, savings were 2.5 km^3, accounting for 16% of irrigation withdrawals in southern Africa around 2007 (FAO 2014).

Importantly, however, the main exporting nations like South Africa, Botswana or Namibia are more water stressed than importing nations and thus water has much higher opportunity costs (e.g. for urban, mining, electricity generation and environmental uses). At the regional level, it might then be judicious to improve agricultural water productivity in northeastern, wetter countries, such as Mozambique, Malawi, Tanzania and Madagascar, and to promote exports to drier areas of the region, so that scarcer water resources can be saved for higher value uses or environmental flows. Such changes require, among other things, improvements in local agricultural management and facilitation of regional trade. Important

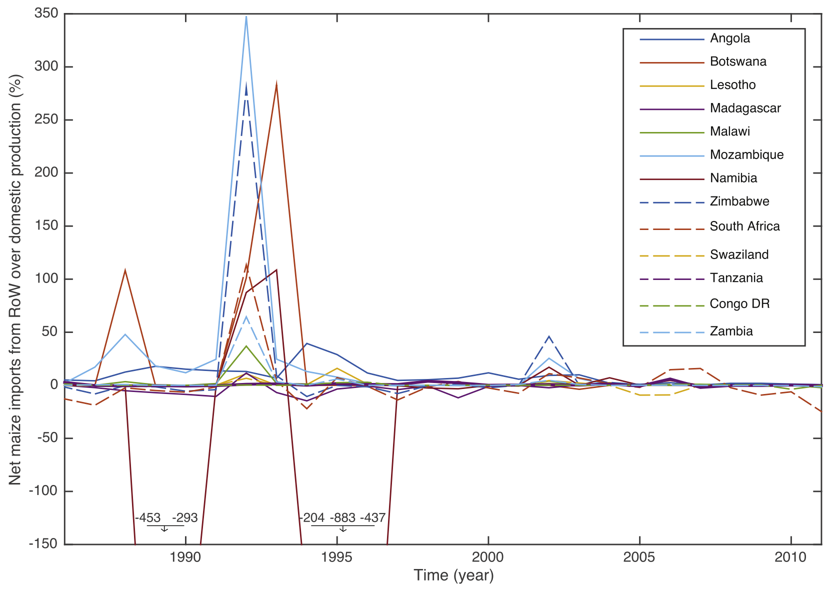

Figure 5. Ratio (in %) of net maize imports from outside southern Africa to domestic maize production, for each of the 13 southern African countries from 1986–2011. Note the relatively important extra-regional imports in 1992 for most countries.

barriers for improving agricultural production and water productivity are low levels of economic development and political instability. Regional crop production has grown more slowly than population since 1986 (figure S2). However, GDP grew rapidly from 2003, and the region's GDP per capita has more than doubled in 26 years (World-Bank 2015). In addition, irrigation capacity in the Zambezi river basin, which crosses most northern SADC countries, is planned to increase four fold by 2050 (Cervigni *et al* 2015), which should contribute to enhance crop yields in this basin. Trade facilitation among member countries is one of the priorities of the SADC for regional integration. Efforts are ongoing to reduce major existing trade barriers, such as regulations, tariffs, and lack of reliable transportation infrastructure (Engel *et al* 2013, Ondiege *et al* 2013), notably via the Protocol on Trade (SADC 2005), including facilitation of customs processes and a regional infrastructure plan for the transport sector (SADC 2012). Even though at least 85% of trade is duty-free in the SADC since 2008 (Engel *et al* 2013), the region is still one of the least active free trade areas in the world, with only 0.01% of crop production exported regionally, versus 1% in the North American Free Trade Area (for raw maize, rice, soybeans and wheat in 2011 (FAO 2015)).

Spatial and temporal variability of extra-regional food trade, virtual water trade, and water savings

Crop production in the region has been highly variable—including a marked decline in 1992—with no clear trend until around 2005, and then grew by 40% from 2006 to 2011. Often to compensate for low output, southern Africa has been a net importer of food and virtual water from outside the region (figures 3 and S5). Indeed, while extra-regional imports have rapidly grown (tons of food imports multiplied by 7 from 1986–2011), much faster than regional GDP and population, exports have remained constant or declined slightly, as they only surpassed 1986 levels in a few years (e.g. 1994 and 2011, figure S2).

The dependence of southern Africa on other regions for its food supply has shown considerable fluctuations. Maize imports from the RoW are relatively large compared to domestic production, and this ratio is very large across the region in 1992 (net imports from RoW accounting for up to 350% of domestic production, figure 5), and, less so, in 2002. This indicates that extra-regional trade played a major role in providing maize to southern Africa during these dry years. Some of the growth in extra-regional food trade has been facilitated by the end of the protectionist apartheid regime in 1994 in South Africa, which joined the World Trade Organization in 1995. Trade barriers such as tariffs have been progressively lifted since then (Edwards and Alves 2005). This will enable to further leverage the potential of trade to alleviate food crises (Tschirley and Jayne 2010). Trade liberalization was found to facilitate buffering of food production declines via international imports (e.g. between Bangladesh and India (Dorosh 2001)); more generally, open borders moderate inter-annual variability of staple food prices and consumption (Zambia case (Dorosh *et al* 2009)).

Trade flows with and within southern Africa have shown positive and increasing water efficiency, leading to important savings. This is mainly due to rising imports from relatively more water productive foreign nations (e.g. the USA and Argentina), as well as to water-efficient regional trade. These savings occur despite food trade patterns being largely influenced by non-water factors, such as prices, labor costs, arable

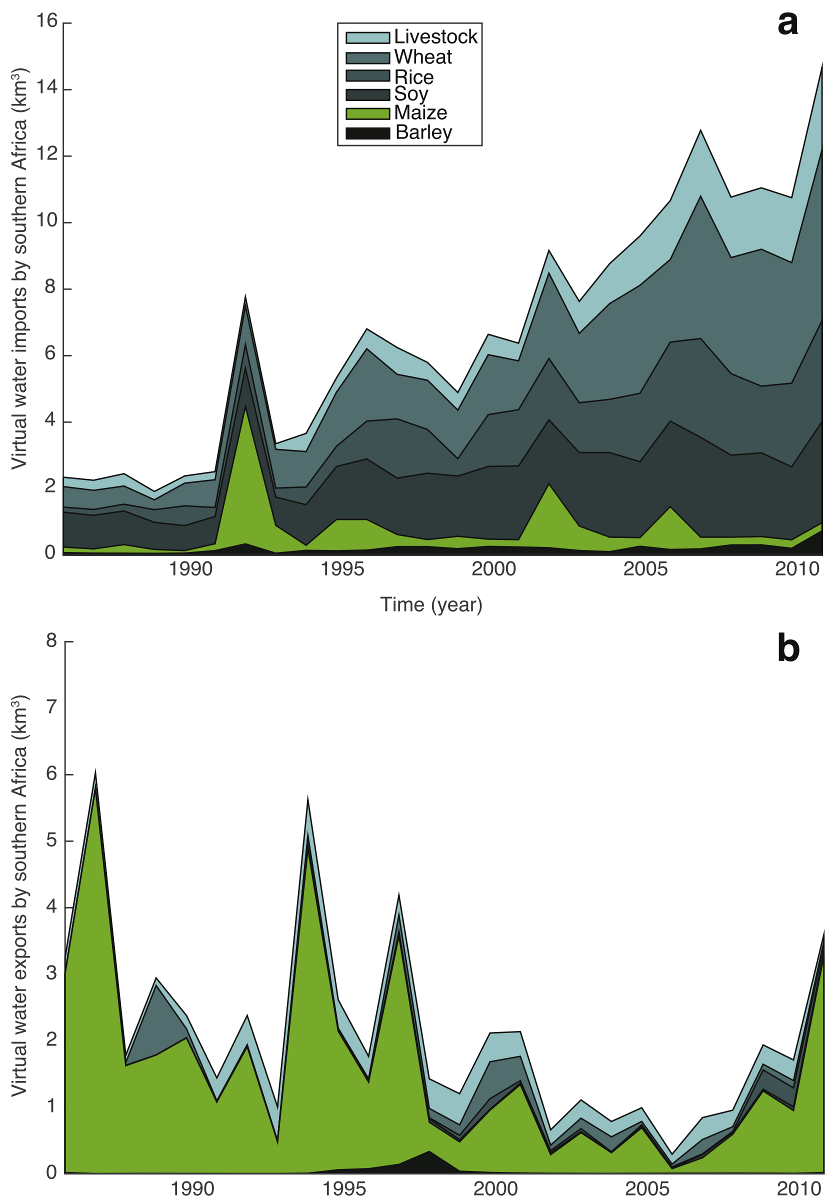

Figure 6. Extra-regional virtual water imports (a) and exports (b) by southern Africa from 1986–2011 (in km^3). Note the peaks in 1992 and 1994, respectively, and the importance of maize in virtual water exports.

land availability, etc. Food trade has induced from about 0 to 15 km^3 y^{-1} of WS over the period, peaking at 35 km^3 in 1992 (figure 7(a)). In recent years, the share of global WS induced by livestock, soy and wheat trade have been increasing to reach nearly 5 km^3 y^{-1} each (figures 7(a), (b)). Importantly, even more water resources are actually saved in southern Africa due to extra-regional food imports. Because these resources correspond to all the water that would be consumed for producing the imported goods locally, and not just to the difference in water productivity between southern African nations and RoW trade partners, as is accounted for in WS.

The imprint of extreme regional drought and climate variability

During the 1986–2011 period, the five driest years in the region—in terms of precipitation from October in previous year to May in current year—were 2005, 1991–1992 and 1994–1995 (table S2, figure S1). The 1991–2 and 1994–5 two year dry spells are linked to a strong and a moderate El Niño event, respectively (Rouault and Richard 2005). Important linkages between southern Africa rainfall patterns and the occurrence of El Niño/La Niña events have been shown (Nicholson and Kim 1997, Usman and Reason 2004). The severe 1991–1992 drought affected most of the region, where agricultural production significantly declined. Maize yields were more than halved (2170 in 1991 to 790 kg ha^{-1} in 1992 on average in Botswana, Lesotho, Namibia, South Africa and Swaziland (FAO 2015)) to reach the lowest production recorded in this group of countries between 1986 and 2011. This yield decline directly affected crop water productivity—especially for irrigation water—and also had indirect consequences, such as a sudden rise

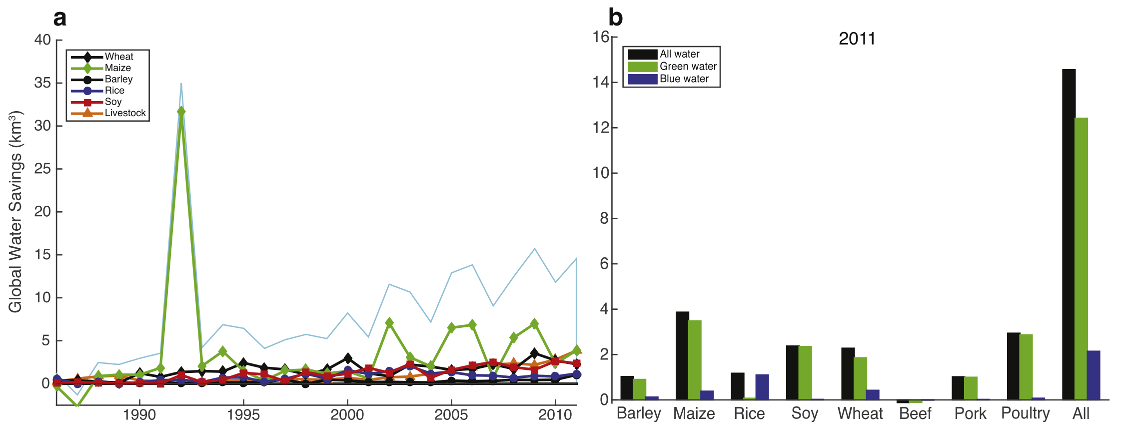

Figure 7. Total water savings (in km^3) induced by food trade within southern Africa and with the rest of the world, by product, each year from 1986–2011 (a) and by source of water in 2011 (b).

in extra-regional food imports (figures 3, 4) which alleviated the production deficit (figures 5), and a peak in WS via trade (figure 7(a)), reflecting a large difference between water productivity of southern Africa and its trade partners.

Interestingly, the rise in VWI (figures 6(a), 4) from the RoW is relatively smaller than the rise in corresponding food imports (figure 3). This difference is due to an increase in water productivity of the region's trading partners. Indeed, maize yields in North America show a local maximum in 1992, which makes the VWC coefficient used to multiply food imports into VWI smaller in that year. This polarization of yield change across the two regions in 1992 (decrease in southern Africa and increase in North America) led to important and water-efficient maize trade. Indeed, the largest WS induced by extra-regional trade over the whole period was reached in 1992 ($35\,km^3\ y^{-1}$, figure 7(a)). This exemplifies how trade can redistribute food across continents in a water efficient way, in response to a sudden gap in food production and water productivity. These findings highlight the water saving benefits of food trade during crises, adding to the food supply and security benefits found in this study and in the food security literature (Dorosh *et al* 2009, Schmidhuber and Francesco 2007).

A strong re-bound of extra-regional exports from southern Africa in 1994 followed the major drought (figure S5), due in part to a particularly high regional crop production in 1993 and 1994 (FAO 2015). Extra-regional export peaks generally follow those in regional crop production, however, the export peak after this drought is relatively larger than the one in production. Internal trade also increased significantly in 1994 (figure S4), and was particularly water-efficient, as that year saw high WS induced by internal trade ($1.5\,km^3\ y^{-1}$, figure S9), reflecting that relatively more water-productive countries exported to less water-productive ones. Again, enhanced trade openness allowed the region to benefit from trade. Indeed, the economic return of boosting regional trade and extra-regional exports more than usual (larger rise than that in production) may have helped reduce the drought's economic impact.

To a lesser extent, drought induced yield decline, alleviated by rising extra-regional imports, is observed during the milder 1995 drought. At this time, southern African maize yields fell even more sharply (from 2713 in 1994 to $1380\,kg\,ha^{-1}$ in 1995), but still exceeded 1992 maize production. While the imprint of the 1991–1992 drought is clear, the effects of other droughts and inter-annual climate variability are much less notable at the regional and national levels.

In terms of inter-annual climate variability, our findings indicate that wetter years correspond to lower irrigation and rainwater consumption per unit crop (VWC_{blue} and VWC_{green}, resp.), i.e. higher water productivity (tables S5 and S11). While precipitation and PDSI indices show a positive linear relationship with gridded maize yield, indicating that wetter years correspond to higher yields, the correlation is not statistically significant for most countries (table S14), except in Zimbabwe and Madagascar (figures S15 and S12). The relationship between crop yields and climate extremes are indeed very complex, even in locations with very high resolution climate data, such as the USA (Troy *et al* 2015), and may be obscured at coarser scales of aggregation.

Relationships between PRCP and PDSI on the one hand, and food imports and VWI on the other hand are mostly not significant. This indicates that other factors are also driving food trade and VWT. Linear regressions against agricultural GDP indicate statistically insignificant influence of climate (at national and annual scales) on the agro-economy in most of southern Africa, except for Namibia and Angola. The clear imprint of the 1991–1992 drought suggests relationships may be nonlinear. The relationship between climate and agricultural GDP is strongest when using panel regression between agricultural GDP and the

WAS(−) index ($p < 0.1$, $R^2 = 0.68$), which accounts for the extent of a country receiving lower than average precipitation. Discrepancies may also result from data limitations and quality issues. For example, precipitation data are limited by the decline in monitoring of rain gages in southern Africa since the late 1980s (Willmott *et al* 1994).

Conclusion

Southern Africa is largely a net importer of virtual water resources through food trade, with rapidly increasing imports from outside the region (by a factor of 10 from 1986–2011). Most trade flows go through two main regional hubs: South Africa and Zimbabwe. Food production and consumption is dominated by maize, but external imports are increasing and diversifying.

Agricultural water productivity is generally low in southern Africa compared to other sub-tropical regions, primarily due to low yields. Even the most water productive countries, like South Africa, have potential to increase crop yields via additional water and/or nutrient inputs. Despite greater atmospheric evaporative demand, substantial yields make agricultural water productivity higher in driest countries of the region. As these nations export food to more humid, less water productive areas, trade leads to WS at the regional level. However, this system is likely unsustainable because productive exporters rely on increasingly scarce water resources. Improvements of water productivity coupled with agricultural expansion in more humid countries could lead to a more optimal use of the region's water resources, conditional on enhanced regional North–South trade.

The role of the RoW for southern Africa food supply is important, in particular during extreme events, when extra-regional imports have alleviated drought-induced productivity shocks. Significant impacts of severe extreme events (e.g. 1992 and 1995 droughts) are observed on yield, water use, trade and WS. Water-efficient post-drought trade has also been used to compensate some economic losses. Whilst the imprint of a major drought in 1991–1992 is clear, the effects of other droughts and inter-annual climate variability on food production, trade and water productivity are much less notable at the regional and national levels. It is thus unclear how much the impacts of milder, more localized droughts are alleviated via regional trade.

We have quantified important evolutions in the water and food systems of southern Africa as linked to international trade. The impacts of trade liberalization and climate extremes are observed in the VWT dynamics. Importantly, imports to compensate food deficits and exports to recover from drought-induced production shocks have both been from more to less water productive areas, highlighting the role of trade in driving efficient allocation of resources. However, the particular regional context—with water scarcity in major exporting countries—threatens the sustainability of internal food production and trade. This needs to be accounted for in future regional level decisions regarding water, agriculture and trade.

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