The Globalization of Virtual Water Flows: Explaining Trade Patterns of a Scarce Resource

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Abstract

The burgeoning literature on embedded or *virtual* water has claimed that water endowments are not a strong indicator in shaping countries' production and trade of food. Because water is only one of the many inputs required in the production of crops and livestock, focus has shifted to "water productivity" - or water footprint. In this paper, we empirically examine these two opposing arguments. Using panel data of bilateral virtual water trade of crops and livestock between 1994 and 2007, we demonstrate that both relative water endowments and productivity have a significant role in shaping bilateral food trade. Our gravity model with high dimensional fixed effects at the country-pair, year and product level shows that exporter-importer asymmetries in water endowments do have a positive effect on virtual water trade, suggesting that the driest countries use food trade as a means to alleviate water scarcity. On the other hand, asymmetries in water footprint have a strong non-linear impact on food trade, mostly because of demand effects. For moderate levels of water footprint asymmetries, and as to be expected, virtual water flows from relatively more to less water-productive countries. But passed a certain threshold, rather than importing goods for which their relative water productivity is low, countries import products that add up to their local production in order to satisfy national demand. In this case, virtual water flows from low to high water productive countries. Our results also support previous findings showing that nearly 80% of food trade occurs between countries with low asymmetries in wealth and population growth. Gravity model control variables support results often cited in the international trade literature.

JEL classification: F14, O13, P28, Q17, Q25, Q27

Keywords: Water Endowments, Water Productivity, Crop Water Requirements, International Trade, Food Security, Gravity

1 Introduction

The claim that the wars of the future will likely occur over freshwater have resonated in policy and even some academic circles. Given that water is crucial for basic survival, irreplaceable, transcends international borders, and often times scarce, it follows that states will take up arms to defend access to a shared river. Yet scholarly research has largely debunked this claim, touting the notable absence of inter-state violence over shared water as an indication of what the future may hold. Several conjectures have been offered to explain the absence of water wars including the cooperation-inducing nature of scarce water and the ingenuity employed by countries to overcome water scarcity. A third explanation, and one that is of particular interest to this investigation pertains to "virtual water" (Allan, 1991). According to Allan, those states experiencing water scarcity import food commodities from abroad. Hence, through trade in virtual (or embedded) water, states are able to preserve their inadequate water resources (resources they would have otherwise needed for their own irrigation) rather than wrangle with fellow riparians over a shared water body. Since 70% of global virtual water flows relate to agricultural crops (Hoekstra, Hung, 2002), many academics have even suggested that virtual water trade be assimilated to food trade (Merrett, 2003).

Virtual water, then, was first interpreted as a strong explanation for the absence of historical conflicts over water, highlighting the opportunity costs of fighting over the resource rather than importing water-intensive commodities. It also conveyed the idea that food trade enabled a more efficient allocation of the water resource around the world, as water-embedded products would flow from water endowed countries to water scarce countries.

Despite the merits of the virtual water-scarcity argument, a new wave of studies highlighted the limited impact of water endowments on food production and trade strategies. Indeed water endowments did not seem to match trade patterns as the main exporters and importers of food and embedded water turned out to be water abundant countries. Furthermore, there were also many examples of water-scarce countries exporting high amounts of virtual water (Ansink, 2010; El Fadel and Maroun, 2003). Moreover, it was established that water endowments, if considered, should be relative to the amount of arable land, a strong determinant of production capacities (Kumar and Singh, 2005).

Instead of highlighting water endowments and scarcity, these studies suggested that a major indicator of food production and export strategies is actually water productivity (the amount of water used to produce a ton of crops or livestock).Water productivity [the inverse of water footprint, as introduced in the Water Footprint Network (WFP) introduced by Hoekstra and Hung (2002) and further elaborated by Chapagain and Hoekstra, 2004] is a complex variable to study and analyze as it is driven by exogenous climatic and soil conditions, as well as a large range of endogenous factors such as economic strength (Turton, 2000), government subsidies, technology, capital, labor and food security policies (Wichelns, 2010, De Fraiture et al., 2004; Novo et al., 2009).

Water footprint figures have been widely used in quantitative studies at a global (Hoekstra and Hung, 2002, 2005; Hoekstra 2003; Chapagain and Hoekstra 2004, 2008 among others) national level (for instance Ma et al, 2006; Verma et al, 2009; Novo et al, 2009, Hoekstra and Chapagain 2007) and product level (among which Chapagain and Hoekstra 2004, Hoekstra 2008c address food trade in general), thus enhancing knowledge about asymmetries in water footprint and the need for better management of our resources. De Fraiture et al. (2003) is among the few studies that empirically showed that cereals are traded from more to less water productive countries in the Middle East region, subsequently resulting in global water saving.

Although the extant literature has examined the water endowment and productivity arguments separately and largely from a qualitative or limited (focusing on specific regions) quantitative fashion, the two arguments have not been subject to cross-national empirical scrutiny on a global scale. In addition, no empirical global study has been conducted on a cross-sector level. This paper empirically sets out to fill that lacuna in the literature. In order to do so, we quantify and compare the impact of water endowments and water productivity on virtual water trade at a global scale and across all sectors related to agricultural production between 1994 and 2007.

Our results demonstrate that virtual water flows are positively correlated with exporter-importer water endowment asymmetries, revealing that the driest countries indeed resort to food trade to alleviate water scarcity as originally conceived by Allan (1991). Moreover, water footprint asymmetries at the product level also matter but with strong non-linear effects. Therefore, and as expected, virtual water flows from relatively more productive to less productive countries, thus responding positively to the theory of comparative advantages and also saving water globally. However, our results indicate that past a certain threshold, high water productive countries import products from relatively low water productive nations. Our data also show that between 1994 and 2007, food trade from more to less water productive countries resulted in saving $4750km^3$ of water which represents around 25% of the total $18700km^3$ of water that were traded during that period. We also find that in terms of water saving, cereal trade is currently the most efficient in the distribution of goods from relatively more to less water productive countries.

Our analysis specifically focuses on bilateral trade so as to identify how asymmetries in endowments and productivity between the exporting and the importing countries shape their food trade strategies, all the while controlling for other essential factors such as asymmetries in wealth, population growth, food prices and other traditional control variables.

We focus our attention mainly on crops and livestock for which water productivity figures, in $m^3.ton^{-1}$, are provided in Chapagain and Hoekstra (2003) and Mekonnen and Hoekstra (2011). Our bilateral flows are taken from the Baci database (Gaulier and Zignago, 2010) and cover food trade between 1994 and 2007 for countries with a population of at least million people. Following a gravity model approach as established in Head and Mayer (2013), we introduce two high dimensional effects at the exporter-product-year and the importer-product-year levels that will capture any yearly country characteristics. The analysis is clustered at the country-pair/year level although it provides the same results as the unclustered analysis.

In the first section below we provide a brief history of the virtual water concept as developed by the literature. We then describe and theoretically justify our data, before explaining our methodology, the results and their interpretation. The last section concludes the paper.

2 Virtual Water: Water Endowments vs Water Productivity

Food (and embedded water) trade was first interpreted as a strong explanation for the absence of historical conflicts over water, highlighting the opportunity costs of fighting over the resource rather than importing water-intense commodities from water endowed countries. This argument was also raised by the international trade literature, suggesting that the probability of war escalation is lower for countries that trade more bilaterally (Martin, Mayer, Thoenig, 2007).

The second interpretation conveyed the idea that food trade enabled a more efficient allocation of water around the world, as water-embedded products would flow from water endowed countries to water scarce countries. This interpretation was of course linked to Ricardo's comparative advantage (1817) and the ensuing Heschker-Ohlin-Samuelson model (1941) on factor endowment in international trade: countries will export products that use their abundant and cheap factor of production and import products that use the countries' scarce factors. Many academics started to empirically test this contention and results were unanimous. However, while the relation between water endowments and virtual water trade patterns seemed to follow this path for cereal trade in certain southern Mediterranean countries (Yang and Zehnder, 2002) or for Spanish grain trade (Novo et al., 2009) such patterns seemed to be confined to a restricted sample of countries only. In fact Yang et al (2003) found that only beneath a certain threshold (less than 2000 m^3 of water per capita per year for a specific country) would a clear negative correlation appear between water endowment and cereal imports[1]. Going even further, De Fraiture et al. (2004) argued that most trade of virtual water actually takes places between water abundant countries, findings that have long been vindicated by the many case and global studies (see the Water Footprint Network).

These results challenged the virtual water approach of the time, suggesting that resource endowments were definitely not a sufficient policy criterion for international trade (Wichelns, 2010) and played a minor role compared to many other inputs and characteristics pertaining to climate, land, labor, capital, politics, economics, history, culture, etc. (Turton 2000, El Fadel and Maroun 200, Warner 2003, De Fraiture et al. 2004, Kumar and Singh 2005, Ansink 2010, Novo et al. 2009, Hoekstra 2010, and many others.). Among others, Earle (2001) and Ansink (2010) both concluded that although virtual water is conceptually based on Heckscher-Ohlin framework, the model performs poorly.

What's more, a large part of the literature empirically showed that certain countries had what seemed as counter-intuitive production and trade strategies related to their water endowments. The famous cases of water-

[1] According to the Falkenmark indicator (1989), a country is considered under water stress if its water availability is less than 1700 m^3 per capita per year. This figure includes daily water requirement (drinking water, sanitation, bathing and food preparation) and embedded water in food, textile, energy, etc.

poor Northern China exporting food to better-endowed Southern China (Ma 2004, Ma et al. 2006, Guan and Hubacek 2007, Liu and Zeng 2012) and flood-prone Eastern India importing food from drier states of the country (Verma et al. (2008)) shed light on the many underlying schemes of food production and trade. In many cases, the issue of food security/self-sufficiency appeared as a main driver for agricultural subsidization, extensive irrigation schemes in dry areas and massive food imports even when water was relatively abundant.

The many questions raised by the relationship between international food trade and water scarcity sparked many studies on virtual water and food production practices. The majority are divided into two main categories. Studies in the first category empirically identify the drivers of food production and food importing/exporting strategies. Arable land has emerged as an essential factor when considering food production (Verma et al. 2005, Wichelns 2010, Kumar and Singh 2005), for example have shown that virtual water trade flows increase with increases in gross cropped area.

Studies in the second category rely on case studies to understand water consumption patterns and analyze their efficiency regarding water endowments and alternative opportunities offered by international trade (El Fadel and Maroun 2003, De Fraiture et al. 2004, Dabrowski et al 2008, Novo et al. 2009). A main contribution to this literature is brought by the Water Footprint Network (WFP) introduced by Hoekstra and Hung (2002) and further elaborated by Chapagain and Hoekstra (2004) following the FAO crop water requirements (1998). By developing an indicator of water productivity which is the amount of water required to grow crops (and livestock) in $m^3.ton^{-1}$, the WFP network offers an essential insight into our water consumption patterns from the various drivers of food production[2]. Such a variable actually varies within countries and across regions and depends on a wide range of exogenous and endogenous conditions: climate, soil, know-how, technology, government subsidies, history, culture, etc. The availability of water productivity figures is extremely powerful as it indicates, beyond water endowments, countries' strenghts and weaknesses in their food production. Chapagain and Hoekstra (2003) and Mekonnen and Hoekstra (2011) provide water footprint figures for crops and livestock, averaged between 1996 and 2005. As of today, no study

[2]The water footprint of nations indicates the amount of virtual water consumed in a year by a country, with a distinction made on the origin of the embedded water: national water (internal water footprint) or foreign water (external water footprint)

has provided yearly data, although water footprint is expected to vary over the years with specialization, climate change and capital stock/technology accumulation. [3]

To date, the literature has made the following conclusion regarding virtual water. On the one hand, water endowments play a minor role in shaping food and virtual water trade and are not an appropriate policy criterion for determining virtual water flows. That being said, trade in food does allow for water savings on a global scale. As such water savings are the unintended by-product of trade from water-efficient to less water-efficient countries (De Fraiture et al. (2004), Dabrowski et al (2008), etc.). Food trade strategies are thus a tool to mitigate the stress caused by scarcity of water, as originally suggested by Allan (1997), although virtual water should be considered in a bigger picture, within a larger analysis of other virtual inputs being exported alongside the water resource.

3 Methodology

3.1 Dependent variable: Bilateral flows of embedded water

This paper considers yearly water content of bilateral trade flows between 1994 and 2007 at the product level in $m^3.ton^{-1}$ as our dependent variable. Our study covers 179 countries, 2113 products from 25 different trade sectors. All of the countries have at least 1 million inhabitants so as to reduce the effect of specific local conditions of small countries on the analysis (see Yang et al. 2003). To compute our dependent variable, we follow the method

[3]The WFP is efficient in indicating, to a certain extent, countries' dependence on water in the global system and developing more coherent water consumption use patterns. The WFP also encourages the distinction between types of water: blue (surface and ground water), green (water stored in soils or that temporarily stays on top of the soil or vegetation) and grey (freshwater pollution). Such distinctions have been subject to critics (Wichelns, 2010) because of the difficulty of properly isolating them: surface water interchanges with groundwater, and deep infiltration can contribute to shallow and deeper aquifers. Nevertheless this typology is important as it enables a better understanding of local conditions: for instance water-rich countries benefit from higher availability of "green water" which alleviates the need to irrigate (blue water) because of favorable natural conditions (soil, climate, etc.).

developed by the Water Footprint Network which consists of multiplying international trade flows by their associated virtual water content (or water productivity). Although trade flows vary every year, the virtual water content of crops across countries is fixed, as computed by Chapagain and Hoekstra (2003) and Mekonnen and Hoekstra (2011).

Trade in Virtual Water Data

Bilateral trade flows in tons are taken from the BACI dataset, as developed in the CEPII report by Gaulier and Zignago (2010). They provide data at the highest level of product disaggregation, 6 digits Harmonized System (HS) code from 1994 to 2007. The original data come from the COMTRADE database of the UN Statistical Division and were harmonized for more than 200 countries since 1994.

BACI is very convenient in dealing with missing data because of its reconciliation methodology[4]. Indeed, missing values of bilateral trade for a specific product can occur if one or both of the countries fail to report their trade flows. BACI takes advantage of the double information on each trade flow to provide a unique "reconciled" value for each flow reported at least by one of the partners. The only true missing values are those concerning trade between two non-reporting countries [5]. Therefore this dataset is very useful in analyzing international trade of non-reporting countries such as many African countries.

Also, and similar to COMTRADE, BACI does not report zero values of trade because of computational issues. Furthermore, a missing observation is considered as a zero when at least one of the trading partners reports its trade to the UN. If both partners are not reporting, the missing observation is considered a true missing value.

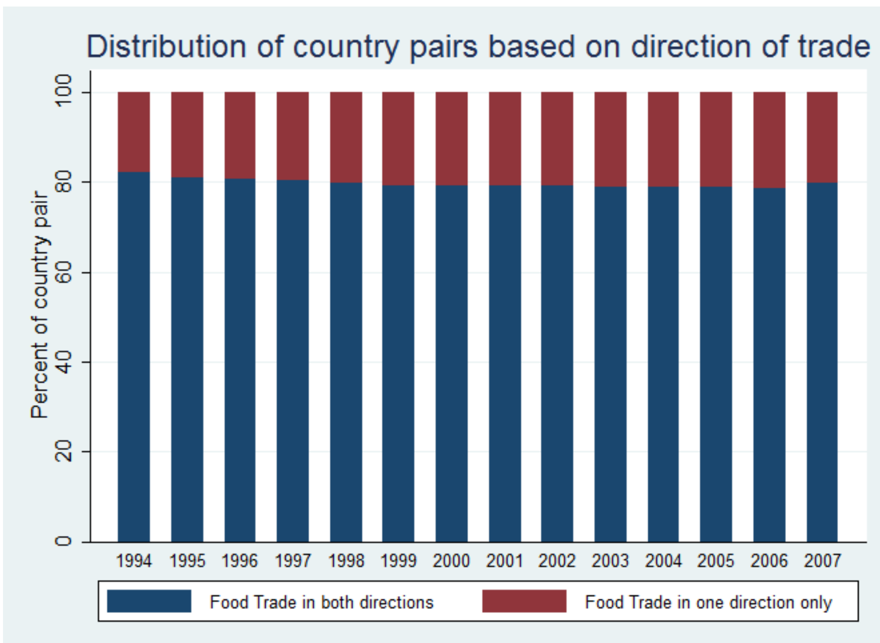
Our dataset for this article will distinguish directions of trade: observations consist in reported trade flows of a particular product p from exporter i to importer j at year t. Figure 1 shows the distribution of country pairs according to the direction of trade. Roughly 80% of country pairs, as established by the BACI data, trade food between each other and account for over 85% of virtual water exports every year. Out of the country pairs that

[4]Reconciliation provides an explanation for the discrepancy between the import and export statistics of trading partners by identifying conceptual reasons for them and explaining differences in data collection and processing. See United Nations (2004)

[5]See Gaulier and Zignago (2010) for more detailed explanations

trade in both directions, 16% actually trade the same product; when this is the case, both trade flows still appear as two discrete observations between the partners, once for when country i is the exporter and once when it is the importer.

Figure 1: Distribution of country pairs according to direction of trade



Virtual Water Content - or Water Footprint of traded products

Water productivity figures are taken from Mekonnen and Hoekstra (2011), whereby they compute the green, blue and grey water footprint of crops an for crops. Chapagain and Hoekstra (2003) compute the same water footprint but for livestock. Most recent studies (Chapagain et al. 2006a; Yang and Zehnder, 2007) on water footprint have made a point of distinguishing between the blue (volume of surface and groundwater consumed or evaporated as a result of the production of a good), green (rainwater which is consumed) and grey water (volume of freshwater required to assimilate the load of pollutants based on existing water quality standards). [6] In this paper, we do

[6]The relevance of dividing empirical estimates of virtual water flows into blue, green

not make the distinction between water types for two reasons: one pertains to the issues around the economic interpretation of green vs blue water; the other relates to computational issues as the current 3 million observations would be tripled.

Mekonnen and Hoekstra (2011) provide national water productivity figures for 146 crops disaggregated at the 6-digit HS level, averaged over the period 1996 to 2005. We use their data for 146 crops - which correspond to 102 different sub-categories (HS4) of 18 major crops (HS2) - and 144 livestock products (HS6). See appendix for a more detailed description of the crops and livestock products we cover in this analysis.

The water footprint of livestock as computed in Chapagain and Hoekstra (2003) considers the total embedded water content of their feed and the volumes of drinking and service water consumed during their lifetime. It is assumed that a livestock product exported from a country is entirely produced in that country (the animal feeds, drinks and lives only in the producing country).

3.2 Bilateral independent variables

The gravity model specified in the next section will account for unobserved time varying country-product effects, thus capturing any country specific variations between 1994 and 2007. The explanatory variables are strictly at the dyadic level and reflect both the international relations and the international trade literature. They are built as ratios to emphasize relative asymmetries between importer and exporter. We begin with our main variables of interest: water endowment and water productivity. We then proceed to identify other important variables in the model.

Asymmetries in water per hectare of land endowments

In order to capture the effect of resource endowment asymmetries, we include the ratio of actual renewable water resources per ha of land for our

and grey components has been questioned (Wichelns, 2010) because the methodology is not based on a conceptual framework able to guide policies. It has been suggested that the opportunity cost of green water is smaller than that of blue water (Yang et al., 2006; Aldaya et al. 2008, 2010) while Wichelns argues this interpretation can be overturned according to local country characteristics.

country pairs, following the reasoning that when access to arable land increases, the ability for a country to use its water resource and raise livestock or produce crops increases (Kumar and Singh, 2004). Actual renewable water resources per year are taken from the FAO Aquastat dataset and arable land data is provided by the World Bank indicators[7].

Total renewable water resources are the sum of Internal Renewable Water Resource (IRWR)[8] and External Renewable Water Resource (ERWR)[9]. Although the IRWR is roughly fixed across time, the ERWR can vary with time. Total water resources thus decrease over time because of population increase (which decreases water per capita) and political or climatic events changing the ERWR.

We include a squared term to account for non-linear effects of resource asymmetries on virtual water trade and to identify whether excessive asymmetries might affect bilateral trade of food. Yang et al. (2002) and Wichelns (2010), for example, claim that the significance of water scarcity over food trade is strongest for water-scarce countries. In the result tables, the variables will be displayed as $RatioWaterLand$ and $RatioWaterLand^2$ where:

$$RatioWaterLand = \frac{WaterpLand_{it}}{WaterpLand_{jt}}$$

We hypothesize that virtual water exports will be positively correlated with water per land asymmetries, supporting the literature which has demonstrated that a country's ability to produce is largely determined by its amount of arable land and water availability (Kumar and Singh 2004).

Asymmetries in water footprints

Differences in water productivity are central to production and trade strategies, as virtual water is argued to flow mostly from highly water productive to less water productive countries (De Fraiture et al., 2004). Chapagain and Hoekstra (2003) and Mekonnen and Hoekstra (2011) provide the water footprint for most of the crops considered in this study and we control

[7] Visit http://www.fao.org/nr/water/aquastat/dbase/index.stm and http://data.worldbank.org/indicator

[8] Long-term annual flow of rivers and recharge of aquifers generated from endogenous precipitation.

[9] resources not generated in the country, including inflows from upstream countries, border lakes and/or rivers; takes into account the quantity of flow reserved by the upstream or downstream country through formal or informal agreements.

for relative values of water footprint for a specific crop/livestock product p between the exporter and the importer. We also include the squared term of productivity ratios for the same reasons as above. In the regression tables, they will be displayed as $RatioWFP$ and $RatioWFP^2$ where:

$$RatioWFP = \frac{WFP_{ip}}{WFP_{jp}}$$

Unfortunately water footprint figures are not available for every product being traded in our database, hence our analysis is restricted to trade for which we do have information about water productivity which is about 77% of our total flows.

We hypothesize that the ratio of water footprint for a specific product should be negatively correlated with virtual water exports, thus supporting the fact that virtual water flows from relatively more productive to less productive countries. Indeed, as the ratio of water footprint between the exporting and importing increases, this means that the exporting nation is consuming more water to produce a unit of the good than what the importer would have, had it produced the good itself.

3.3 Control Variables

Since two countries are likelier to be trading a specific product in a given year if they were already trading the previous year, we include a dummy "Existing Trade" for whether the product was already being traded the year before between countries i and j. We should expect the coefficient on this variable to be strongly significant and positive.

Economic and Demographic controls

Growing populations is one of the main drivers for increasing water withdrawals and food import (Rosegrant and Ringler, 2000; Liu et al., 2008). We account for relative increase in population by including the ratio of increase in population between years t and t-1 of the exporting over the importing country. We also control for non-linear effects of asymmetries in population growth by including the squared term of this ratio. These variables will be displayed as $RatioPopEvol$ and $RatioPopEvol^2$ where:

$$RatioPopEvol = \frac{pop_{it}-pop_{it-1}}{pop_{it-1}} / \frac{pop_{jt}-pop_{jt-1}}{pop_{jt-1}}$$

Our hypothesis is that countries with high population rate of increase will need to either increase production if they have the means to do so, decrease exports and/or increase imports to satisfy national demand. This could translate into a negative correlation between the ratio of population rate of increase and virtual water exports.

Because economic power will play a role in a country's ability to engage in virtual water trade (Turton, 2000; Hoekstra, 2010 and others), asymmetries of wealth of can be measured by the ratio of GDP per capita, as in Dinar and Dinar (2011). Indeed, food trade is subject to particularly high trade costs thus excluding certain developing countries (Hoekstra and Hung, 2002; Reimer, 2012, etc.).

The ratio of GDP per cap will be displayed as $ratioGDPcap$ and $ratioGDPcap^2$ where:

$$ratioGDPcap = \frac{GDPcap_{it}}{GDPcap_{jt}}$$

We also control for asymmetries in food price indices, which are a measure of the food purchasing power parity as provided by the FAO, where:

$$RatioPriceindex = \frac{FoodPPP_{it}}{PPP_{it}} / \frac{FoodPPP_{jt}}{PPP_{jt}}$$

Given that the wealthiest countries in the world are among the largest exporters of virtual water, we can hypothesize that virtual water exports will increase along with the ratio of wealth between the exporting and the importing country. The question will be whether such a positive correlation can be sustained as asymmetries in wealth increase up to a point where the importing country is necessarily among the poorest in the world and can be financially excluded from food trade.

Traditional controls from Gravity Models

Trade costs are also proxied in the international trade literature by many different variables, among which distance, contiguity, language and common colonizer. These factors are referred to as multiateral resistance terms (Anderson and van Wincoop, 2003) and are inherent to gravity models (Tinbergen 1962). We control for them with data taken from Head, Mayer and Ries (2010).

Regional Trade Aggrements (RTA) have been shown to promote peaceful relations by increasing the opportunity costs of conflicts. Past and current political affinities are accounted for by a dummy variable for the existence of Regional Trade Agreements (RTA) between countries as in Head et al (2010).

3.4 Product vs Sectoral-level analysis

The analysis of our trade dataset can be accomplished at different levels of disaggregation: the product level (most disaggregated) or sectoral level (less detailed). Because we specifically want to study the role of water endowments and water productivity in determining virtual water flows, and since Water Footprints figures are presented at the product level, our dependent variable also needs to be at the product level. Nevertheless analyzing the data at the sectoral levels provides detailed insights regarding the types of products being traded and our consumption of water resources.

Table 1 provides summary statistics for the variables of interest. The dependent variable, Virtual Water exports, is at the dyadic-year-product level. The explanatory variables are all country-pair andyear specific, apart from contiguity, common colonizer, common language and distance which are fixed over time.

Table 1: Summary statistics

Variable	Mean	Std. Dev.	Min.	Max.	N
lnXWFP_i	10.447	3.527	-5.149	31.191	2899756
RatioWaterLand	5.773	31.908	0	6287.918	2971919
ratioGDPcap	4.005	9.803	0.003	301.928	2759199
ratioWFP	1.232	2.179	0.002	253.764	2158841
LagTrade	0.806	0.395	0	1	3224620
BilateralTrade	0.659	0.474	0	1	3224620
RatioPopEvol	3.583	52.083	-2380.994	4204.476	3091441
RatioPriceindex	1.008	0.314	0.231	4.33	2689286
contig	0.132	0.339	0	1	3063777
comcol	0.045	0.207	0	1	3063777
comlang_off	0.197	0.398	0	1	3063777
dist	5203.31	4369.028	114.637	19650.135	3063777

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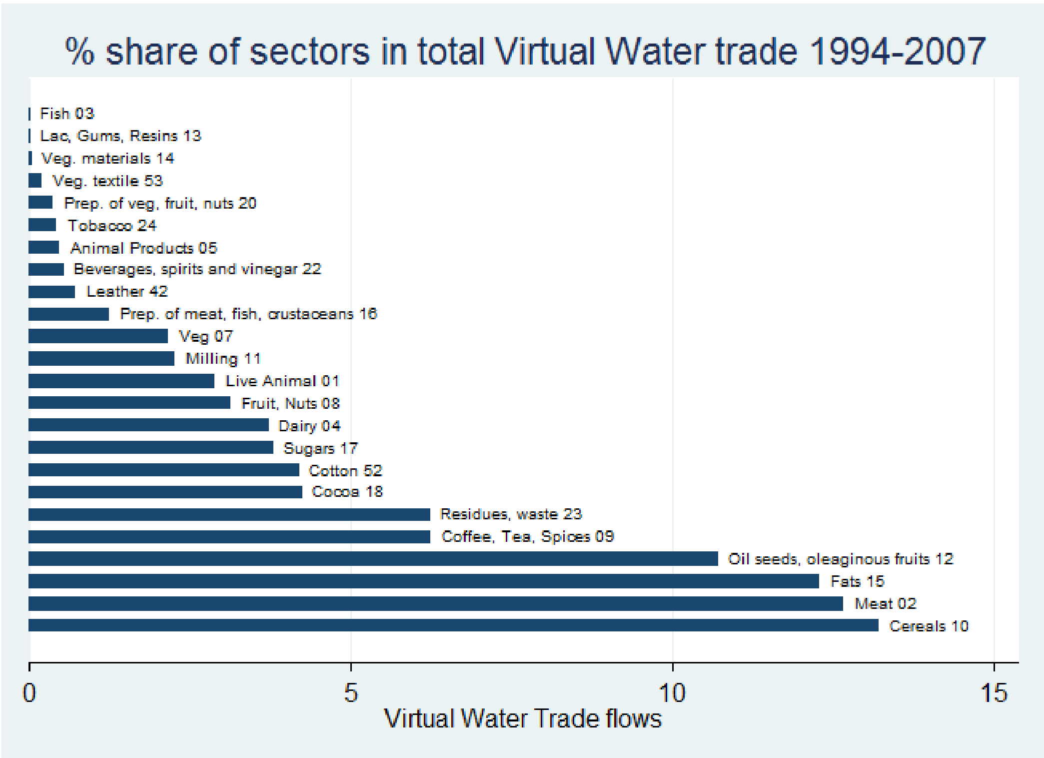
... table 1 continued

Variable	Mean	Std. Dev.	Min.	Max.	N
rta	0.301	0.459	0	1	3063777

Food sectors are not equally responsible for water withdrawal around the world. Figure 2 shows the distribution of our complete trade flows between 1994 and 2007 according to sectors. Products from the Cereal (HS10), Meat (HS02), Fats (HS15) and Oil Seeds (HS12) sectors are the most traded between 1994 and 2007 and represent just a little less than 50% of all bilateral trade flows.

Figure 2: Share of Trade Flows according to food sector between 1994 and 2007



Given the availability of water footprint data in $m^3.ton^{-1}$for both the exporter and the importer as well as quantities in *tons*, we are able to compute the counterfactual amount of water that would have been used if the importer had produced locally rather than import. The difference between the real and the counterfactual water footprint gives us the amount of water saved or additionally consumed through trade. Figure 3 shows the distribution of global water savings as a percentage of total water traded between 1994 and 2007, and according to sectors.

Figure 3: How Sectors contribute to saving water through international trade between 1994-2007

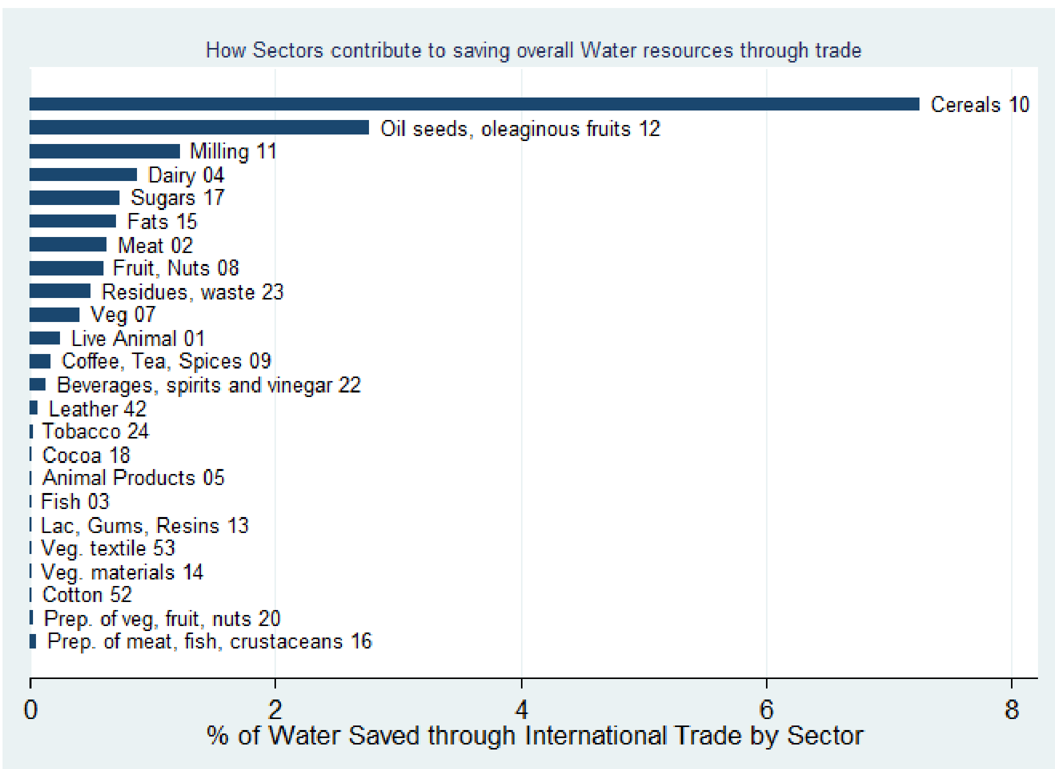


Figure 3 shows that on average, between 1994 and 2007, the sector for which inter-state trade saved the most water globally is cereals, relieving water withdrawals for slightly more than 7% of the total amount of virtual water trade. This result is similar to De Fraiture et al. (2004), who find that in 1995 global crop water use in cereal production would have been higher by 6% had it not been for international trade. Out of 18700km^3 of embedded water being traded between 1994 and 2007, cereal importers have saved around 1350km^3 of water that would have otherwise been depleted. The second sector for which trade has contributed to water savings is "Oil seeds and oleaginous fruits", for which the amount of water saved corresponds to an average of 2.7% relative to total virtual water traded between 1994 and 2007.

4 Econometrics Methodology

We perform our analysis of bilateral virtual water flows at the product-dyad-year level and so our gravity model needs to address several issues.

First of all, our dyads will display strong heterogeneity, exacerbated by unobserved factors such as political affinities, history, culture, or distance that will affect the level of trade and be correlated with the explanatory variables. Therefore the econometric analysis needs to account for unobservable country-pair effects and potential heteroskedaticity.

Second, missing values of zero trade flows can either come from failure of the exporter or importer to report trade or simply from non-existence of trade between two countries at a given year and for a given product.

We will control for country heterogeneity by using a gravity model with two time-varying effects: one at the exporter-product-year level and one at the importer-product-year level. Our time-varying country-product effects will control for all omitted variables that are cross-sectionally specific, such as variations in national economic indicators, political shocks, relations with other countries excluding the trading partner etc. Our explanatory variables on the other hand will be strictly bilateral and cover time varying and constant characteristics such as distance, contiguity, language, culture, Regional Trade Agreements, etc.

We estimate country's i export volume of embedded water to country j as:

$$lnXWC_{ijpt} = \alpha_0 + \alpha_{ipt} + \alpha_{jpt} + \beta_{ijpt} Z_{ijpt} + \epsilon_{ijpt}$$

where i is the exporter country, j the importer country, p is the traded product at year t $\in$ [1994;2007]. Our dependent variable XWC_{ijpt} is the water content of exports from country i to j for product p at year t, expressed in $m^3.ton^{-1}$. The 1 x k row vector Z_{ijpt} comprises all of our explanatory bilateral variables. We assume here that the slope coefficients are constant across country pairs and over time.

The intercept has three parts: α_0 which is common to all years and all dyads; α_{ipt} which is specific to product p, year t in country i and α_{jpt} which is specific to product p, year t in country j.

The error term ϵ_{ijpt} is assumed to be normally distributed with zero mean and constant variance for all observations. It is also assumed that the errors are pairwise uncorrelated.

5 Regression results

We use the command reg2hdfe to estimate our linear regression model with two high dimensional fixed effects provided by Guimaraes and Portugal (2010).

Table 2 displays results for OLS analysis, with the second regression being clustered at the exporter-year-sector level. The clustered analysis covers 1,630,621 observations, over 27921 groups[10].

We also performed the regression without the quadratic terms to observe the linear effects of our variables on virtual water exports (see Appendix for regression table) and obtained similar results.

The results for the non-clustered regression show that all our coefficients are highly significant at the 1% level except for the quadratics effects of the water per land and the population ratios. But both our variable of interest, asymmetries in water per hectare of land and asymmetries in water footprints, have significant and non-linear effects on virtual water exports at the product level. On the other hand, water per land asymmetries and food purchasing power ratios lose their non-linear effect in the clustered regression but remain positive at a 5% significance level.

Figure 4 plots the predicted values of virtual water exports according to the ratio of water endowments per ha of land and according to non-clustered

[10]We ran the regressions with many different clusters and got similar results for all coefficients, apart from the quadratic term of the ratio of food price indexes which lost its significancy.

Table 2: Linear regression with two high dimensional fixed effects

	(1) Log of VW exports		(2) Log of VW exports	
$RatioWaterLand$	0.001***	(0.000212)	0.001**	(0.000330)
$RatioWaterLand^2$	-0.000000511*	(0.000000221)	-0.000000511	(0.000000317)
WFP_ratio	-0.0546***	(0.00355)	-0.0546***	(0.00644)
WFP_ratio^2	0.000383***	(0.0000361)	0.000383***	(0.0000700)
$LagTrade$	1.100***	(0.00697)	1.100***	(0.0112)
$BilateralTrade$	0.164***	(0.00678)	0.164***	(0.0105)
$GDPcap\_ratio$	0.0114***	(0.00138)	0.0114***	(0.00261)
$GDPcap\_ratio^2$	-0.000103***	(0.0000151)	-0.000103***	(0.0000268)
$PopEvol\_ratiol$	0.000418***	(0.000107)	0.000418**	(0.000152)
$PopEvol\_ratio^2$	-0.000000173*	(6.85e-08)	-0.000000173	(9.31e-08)
$FoodPriceindex\_ratio$	-1.475***	(0.290)	-1.475**	(0.570)
$FoodPriceindex\_ratio^2$	0.0966	(0.0594)	0.0966	(0.112)
$Contig$	0.925***	(0.00880)	0.925***	(0.0184)
$ComCol$	0.250***	(0.0176)	0.250***	(0.0348)
$ComLang$	0.228***	(0.00802)	0.228***	(0.0151)
$lndist$	-0.804***	(0.00487)	-0.804***	(0.0112)
RTA	0.257***	(0.00905)	0.257***	(0.0200)
N	1554651		1554651	
R^2	0.696		0.696	
adj. R^2	0.561		Cluster	exporter-sector-year
F	5.149		Nb. of groups	26714
df_m	478120			
df_r	1076530		478121	

Standard errors in parentheses

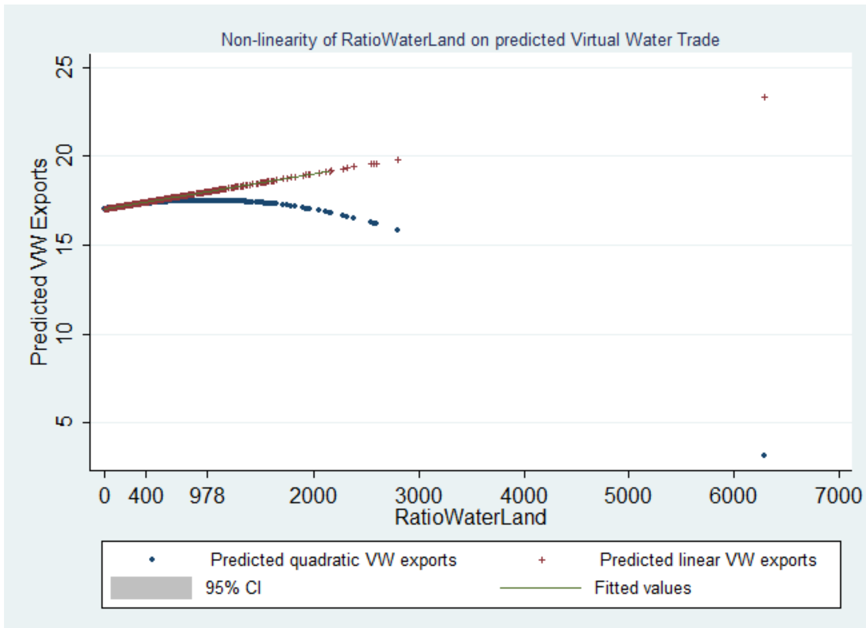
Unit of study is country_pair year product

Unit of study is country-pair year product

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

and clustered results. The non-clustered results show a small non-linear effect while the clustered results only show linear effects.

Figure 4: Non-linearity of water per land asymmetries on predicted values of virtual water exports



Regarding water endowment asymmetries, for small values of $\Delta RatioWaterLand$, the effect on virtual water exports can be computed as follows:

$$log(VWexp) \approx 0.001 * RatioWaterLand - 0.000000511 * RatioWaterLand^2) \quad (1)$$

$$\Delta log(VWexp) \approx 100*(0.001-2*0.000000511*RatioWaterLand)\Delta RatioWaterLand \quad (2)$$

In interpreting the results, there are two important questions related to relative endowments and virtual water exports that we should answer. First, are virtual water exports sensitive to relative water endowments, and if so, in what way? Second, are relatively better-endowed countries necessarily exporters of virtual water to relatively less-endowed trading partners?

Figure 4 already suggests an answer to our first question. Nations seem to export more virtual water to their trading partners as their relative water-per-land endowment increases, up to a certain threshold of 978 in the case of non-clustered. In that sense, water endowment asymmetries are fostering virtual water trade rather than constraining it. Beyond that threshold, the large asymmetries between exporter and importer endowments start having a negative impact on virtual water trade. But because the significance on the quadratic term is at 10% in the non-clustered regression and too weak in the clustered model, we consider it as negligible. The impact of water per land asymmetries on water exports is thus positive.

In terms of quantitative effects, the coefficients on water endowments variables ratio take on very low values in (1) because our dependent variable is at the product level which is the most disaggregated one. The slope diminishes as the ratio approach the maximizing value 978: a one standard deviation (s.d) increase in the x value from 10 to 41.908 (10+31.908) increases virtual water exports by about 3.1%; a one s.d. increase when the asymmetry is already high, at 700, close to the maximizing value, will still increase virtual water exports but at a lower rate of 2%.

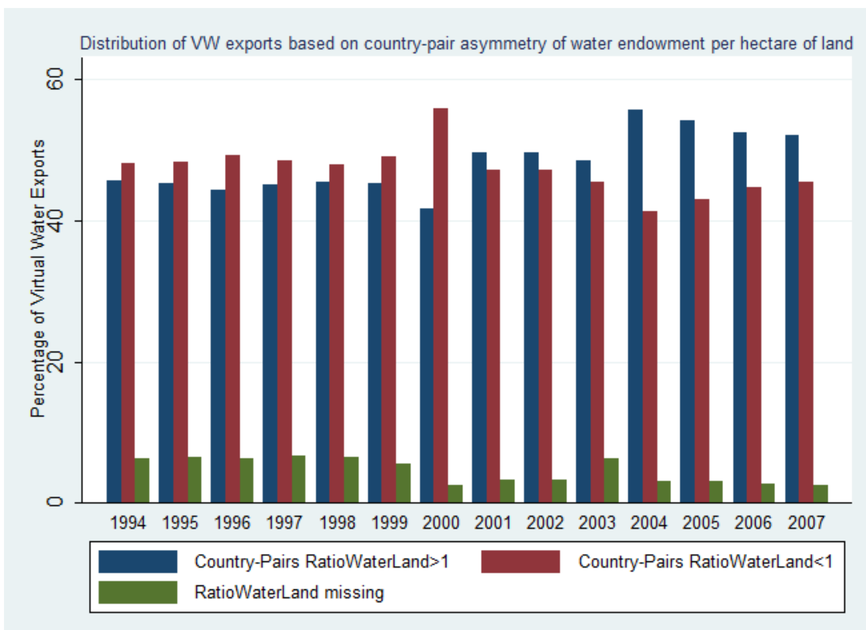
Also, the threshold of 978 is very high: indeed, the data shows that only 10% of country-pairs have water-per-land ratios superior or equal to 17.5. In fact, most of the country-pairs with asymmetries between 700 and 1600 will involve importers among the countries in the world experiencing high scarcity: Saudi Arabia, Algeria, Tunisia and Lybia. Their imports will be highly diversified and come from such countries as Chili, Congo, Ecuador, Malaysia, Peru, New Zealand or Singapore. Among these countries, Ecuador Malaysia, Congo, Chili and New Zealand are among the richest countries in water per capita and in water per land, hence the exceptionally high water-per-land ratio.[11]. The highest ratios of water per hectare of land are actually between New Zealand and Libya and Singapore and Lybia, with ratios of over 2000[12]. But because of trade diversification, trade among countries with high endowment asymmetries make up for a very small fraction of total virtual water trade.

[11]The case of Singapore stands out, as it is among the poorest countries in water per capita but among the richest in water per hectare of land. Furthermore, Singapore's exports are built up by the fact that the nation re-exports around 70% of its food imports, mainly dairy products, frozen poultry and poultry parts.

[12]The outlier value of over 6000 is between Papua New Guinea and Saudi Arabi, which account for only one observation in our dataset, for one trade flow in 1995.

Because the coefficient of the quadratic term is significant only at the 10% level, and given that only a very small proportion of water exports occur between countries with extremely high differences in water-per-land endowments, we can infer that the effect of water asymmetries on virtual water is positive overall. Appendix C shows the result table when performing regressions without the quadratic terms. The coefficient on RatioWaterLand is very significant and positive: a one standard deviation increase in water endowment asymmetries increases virtual water exports by 1.9%.

Figure 5: Percentage of virtual water exports according to country-pair water endowment asymmetries



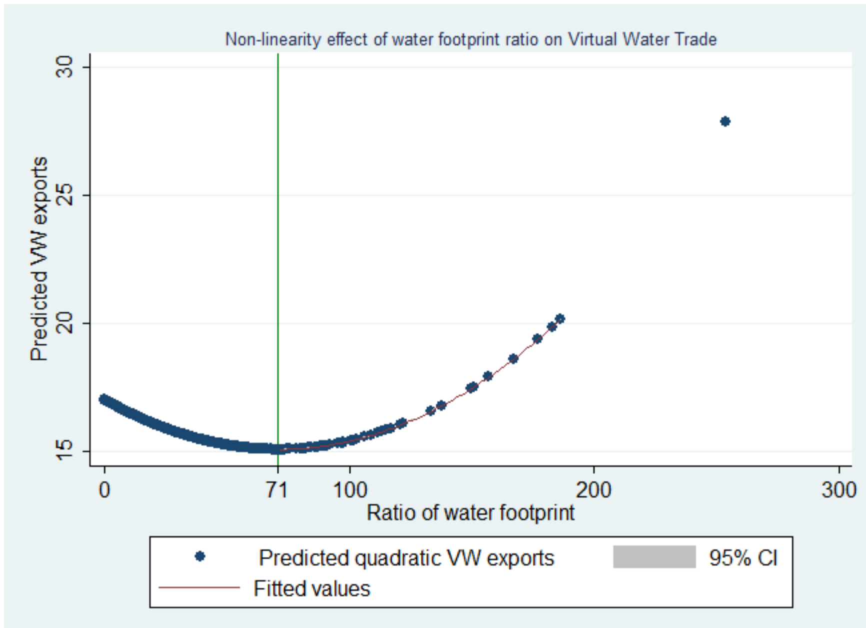
Further statistics and figure 5 also show that, to the extent of data availability, virtual water exports are almost proportionally exchanged between countries with water-per-land ratios above and below one (45% have a water-per-land ratio below one). This is easily explained by the fact that because 80% of our country-pairs trade in both directions, depending on the direction of the flow, the same country-pair can have two different water per land ratios: one that is lower than 1, and one over 1, its inverse. So in figure 4, country pairs trading in both directions are represented at least twice, once below 1 and once above[13]. These figures show that relatively less-endowed countries are as likely as their better-endowed counterparts to be exporting virtual water.

Both these results are important: first, that water asymmetries have an overall positive effect on virtual water exports; second, that relatively less-endowed countries are exporters as much as their relatively better-endowed trading partner. Indeed, the results bring nuance to the claims that most virtual water trade takes place between water "abundant" countries (De Fraiture et al, 2004). Relative abundance sheds a new light on how we perceive trading partners: for instance, Argentina is 1.3 times more abundant in water-per-land than Mali, but the latter is 1.7 times more abundant than France. Yet France is a much larger exporter than Mali because of a significance of other factors (economic, geographic, historical, institutional, etc.). Therefore, the terme "abundance" needs to be utilized with caution.

We now turn to the analysis of the coefficients of relative water footprints at the product level. Water footprint is the inverse of water productivity - meaning that the higher our exporter-importer ratio of water footprint for a specific product, the more water the exporting country uses to produce a unit of the product and so the less water productive. Figure 6 plots the predicted values of virtual water exports according to values of asymmetries in water footprints.

[13]One observation for each product they trade, unidirectionally; they will appear more than one time if they trade more than one product.

Figure 6: Non-linearity of water footprints on predicted values of virtual water exports



According to our results, the water footprint ratio at the product level has a strongly significant non-linear effect on virtual water exports both in the non-clustered and clustered models. The variable is fixed for each country-pair and product across years and the effects can be seen through the equation:

$$log(VWexp) \approx (-0.0546 * RatioWFP + 0.000383 * RatioWFP^2)$$

and so:

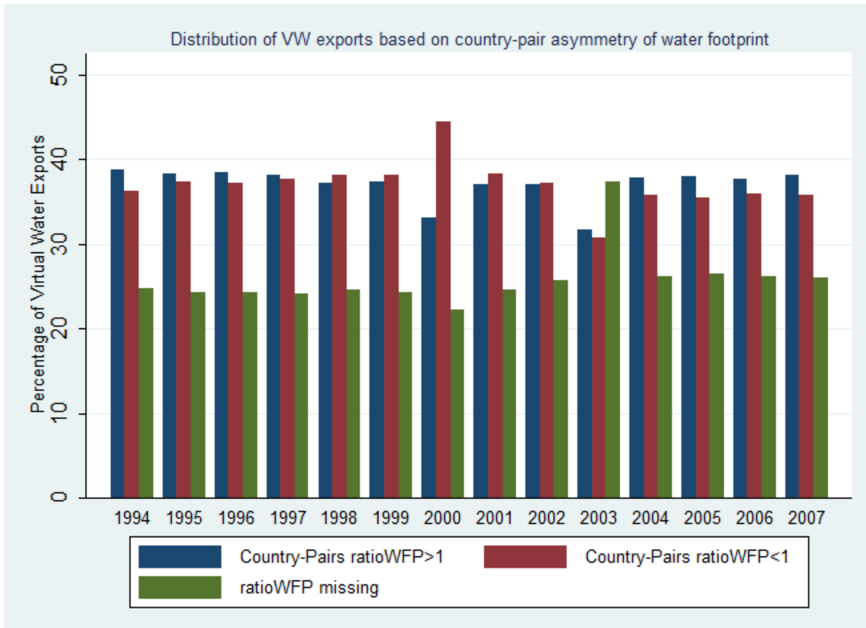
$$\Delta log(VWexp) \approx 100 * (-0.0546 + 2 * 0.000383 * RatioWFP)\Delta RatioWFP$$

The quadratic function is decreasing in water footprint asymmetries until the threshold value of 71, after which it increases. On the left side of 71, a one standard deviation increase in water footprint asymmetries from 10 to 12.179 (10+2.179) will decrease virtual water exports of the product by 10% which is a very strong decreasing effect. The slope decreases along with asymmetries: a one standard deviation change from 30 to 32.179 decreases virtual water exports by 6%.On the right side of the curve, a one s.d. increase in water footprint ratios from 100 increases virtual water exports by 5%.

We hypothesized that countries will trade products for which they have a higher water footprint, hence for which $ratioWFP = \frac{WFP_{ip}}{WFP_{jp}} < 1$. As a matter of fact, about 40% of trade flows are between countries with a water footprint ratio lower than 1 and the rest are roughly divided between missing water footprints and water footprint ratios higher than 1 (30% and 30%). If we consider only the existing data on water footprints, then 57% of trade flows are between countries with a water footprint ratio lower than 1. This in fact means that, to the extent of data availability, our hypothesis is validated for more than half of our sample. Countries with more efficient water use strategies for a particular product export virtual water to less efficient countries per the same product.

Figure 7 represents the percentage of virtual water exports in quantity according to whether country-pairs have a water footprint ratio above or below 1. The figure shows that 35% to 45% of virtual water exports flow between countries with water footprint ratios below 1 (exporting country more water-efficient), while 33% to 38% of them are accounted for by above 1 water footprint ratio trading partners. Considering only the existing data, above and below 1 water footprint ratio country-pairs each account for half the virtual water exports in total, although below 1 water footprint country-pairs account for 57% of products traded. This is because the amount of trade increases along with the asymmetries in water footprint.

Figure 7: Percentage of virtual water exports according to country-pair water footprint asymmetries



The left side of the curve shows that the quantitiy of virtual water embedded in a product and exported from a relatively less to a relatively more water-efficient country decreases as the productivity gap increases in favor of the importing country. In short: because there is a negative correlation between asymmetry of water footprint and virtual water exports, then virtual water flows from relatively more to relatively less productive countries. This is in line with most of the literature, and mostly De Fraiture et al. (2004) and Novo et al. (2009).

The non-linearity of the water footprint ratio, however, suggests that countries with relatively higher water footprints for certain products still export them to countries where production would have been less water-consumptive. This is counter-intuitive in terms of comparative advantage as suggested in the existing literature. Furthermore, the threshold value of 71 is again very high. Only 309 flows are reported to be between countries who have water footprint ratios above 71, representing only 0.014% of the sample. That is negligible, yet the quantities of exports are sufficiently high for the coefficients to stay significant and change signs. Because there are few country-pairs on the right of the curve, we can easily distinguish them and try to understand the change of sign.

Figure 8: Percentage of virtual water exports according to country-pair water footprint asymmetries

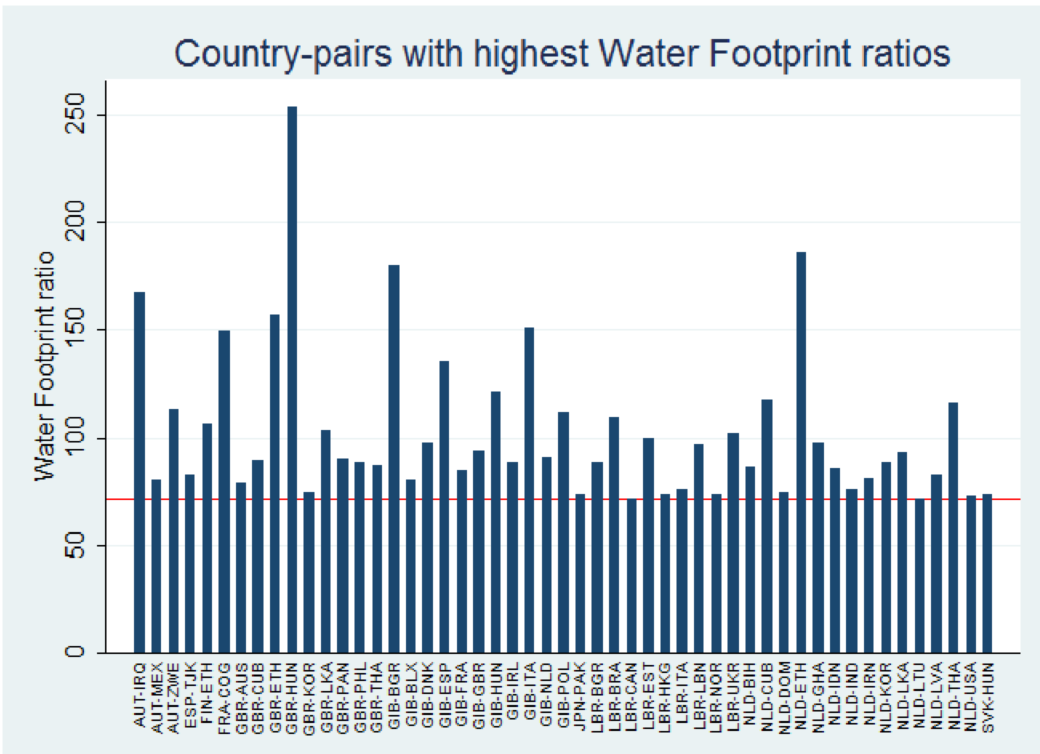


Figure 8 shows the country-pairs with the highest levels of exporter over importer water footprints. The labels on the x-axis have been changed in order to identify trends: the country-pairs are to be read in "importer-exporter" format. There are 5 main nations which import products for which they are over 71 times more water productive than the exporter: Austria, Great-Britain, Gibraltar, Liberia and The Netherlands. Apart from Liberia, these countries are developed, western countries who are also known to be exporters of virtual water because of water availability and abundance of capital, labor and technology. That being said, some are relatively small nations with good water availability per capita but less available land (The Netherlands, Gibraltar, Austria) or have historically favored industries over agriculture (Great-Britain). In particular, Western diets and increasing populations have thus compelled these countries to import foods to satisfy local increasing demand to supplement local production. Liberia, on the other hand, is among the 10 least developed countries in the world and imports over 90% of its staple food as it benefits from international food aid programs. Because of the country's specialization in rubber plantations, it manages to export a great deal of derived animal products (HS41, Raw Hides, Skins and Leather).

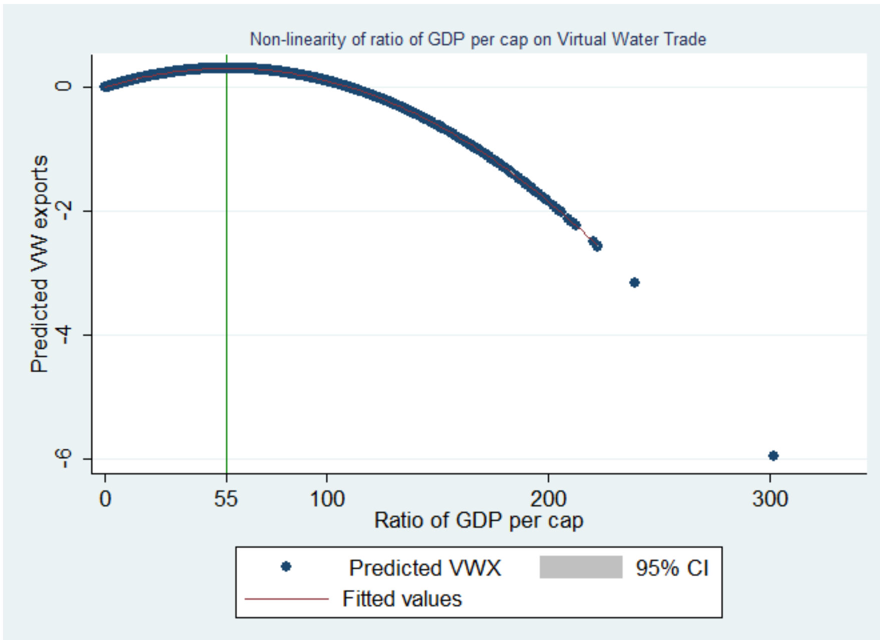
Furthermore, among the products imported by Austria, Great-Britain, Gibraltar, Liberia and The Netherlands from much less productive countries, around 55% are from the HS7 sector, "Edible Vegetables" which as mentioned earlier is the most popular sector in international food trade, and 20% from the HS16 sector, "Edible Preparations of Meat, Fish, Crustaceans, etc.". The rest are roughly from sectors HS4, HS8, HS9 and HS17 (see Appendix A for more detailed information).

5.1 Time-varying and fixed control variables

Our time-varying control variables include ratios of wealth, population growth and food price indexes. Our fixed controls include the typical international trade dummy variables for contiguity, common colonizer, common language, distance and the existence of Regional Trade Agreements (which over our time span of 13 years can be almost considered as non-varying).

GDP per capita is considered as a measure of wealth (Dinar and Dinar (2011)) which is bound to be correlated with the ability to engage in trade and investment in agricultural production. Wealthy nations are generally large exporters and importers of food - but remain net exporters of virtual water, whereas relatively poorer nations are often net virtual water importers. Our results show that asymmetries of wealth have a non-linear effect on virtual water exports, with an inverted u-shape with a high distribution of observations on the right of the threshold value 55. Figure 9 shows the distribution of predicted virtual water exports according to values of GDP per capita ratios.

Figure 9: Non-linearity of wealth asymmetries on predicted values of virtual water exports



On the left side of the curve, virtual water exports increase along with wealth asymmetries. On this part of the curve, a change in wealth asymmetry from 10 to 20 induces an increase in virtual water exports of approximately 8.6%, a very strong effect. The slope then decreases around the value of 55 and then becomes increasingly negative according to:

$$log(VWexp) \approx 0.0114 * RatioGDPcap - 0.000103 * RatioGDPcap^2$$

and so:

$$\Delta log(VWexp) \approx 100*(0.0114+2*0.000103*RatioGDPcap)\Delta RatioGDPcap$$

What our results suggest is that virtual water does flow from relatively wealthier to poorer countries, but only up to such an extent. Above an asymmetry of 55, food exports from wealthy to very poor countries will decrease. Summary statistics show that 90% of our country-pairs actually have GDP per capita ratios underneath 10. Country-pairs with above 10 and beyond asymmetries in GDP per capita generally involve developed or emerging nations as exporters and among the poorest nations as importers, mostly from the African continent. Above the threshold of 55, virtual water exports decrease because countries are financially excluded from food trade. This is also in line with De Fraiture et al. (2003) who find that most food trade occurs between rich countries – we find that 90% of food trade occurs between countries whose wealth asymmetry does not go beyond a ratio value of 10.

Since population growth is a major factor placing pressure on the withdrawal of water resources, production and import of food, we include the relative rate of population increase from one year to another allowing us to compare the level of strain on each trading partner. According to our results, the relation between predicted virtual water exports and ratio of population rate of increase follows:

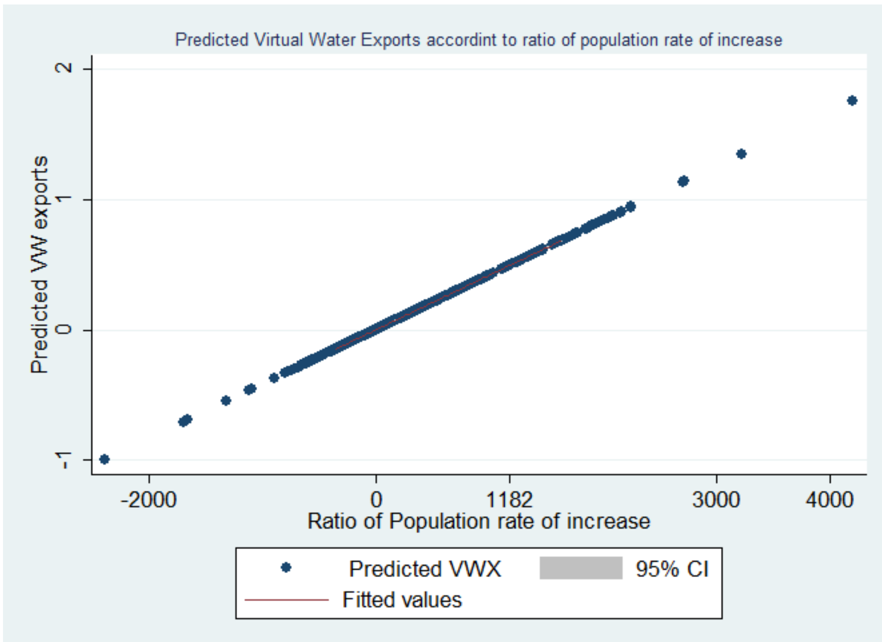
$$log(VWexp) \approx 0.000418 * RatioPopEvol$$

and so:

$$\Delta log(VWexp) \approx 100 * 0.000418 \Delta RatioPopEvol$$

Figure 10 depicts predicted virtual water exports according to the ratio of population rate of increase.

Figure 10: Predicted Virtual Water exports according to ratio of population rate of increase

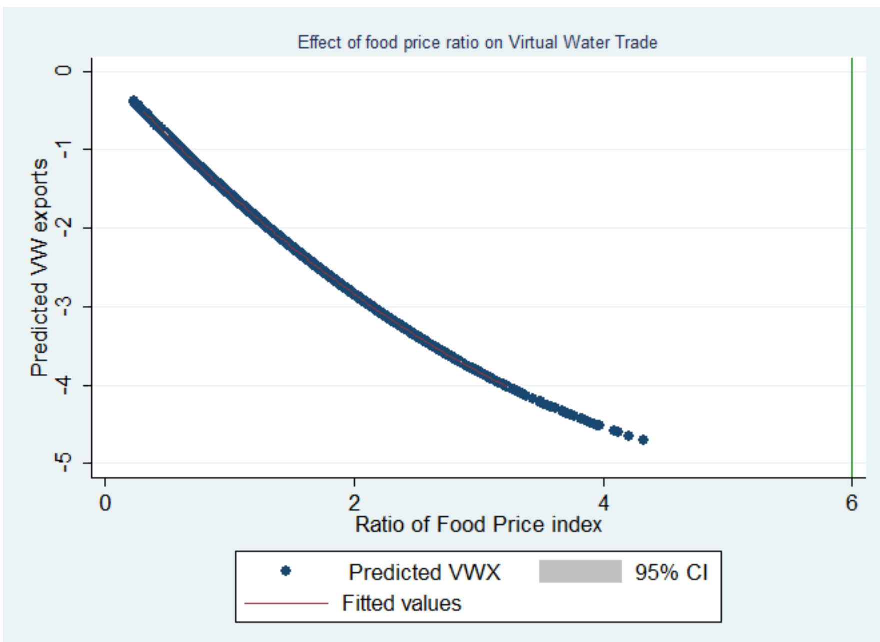


The rationale behind population increase is that the higher the rate of increase, the higher the national demand for food. Producing countries may have the means to increase production, decrease exports and/or increase imports in order to satisfy local demand. On the other hand, water-land scarce countries are bound to increase imports if they cannot respond to increase in population. One could expect the coefficient on this variable to be negative: the higher the increase of population in the exporting country relative to the importing country, the less virtual water exports.

Measures of food price indices provided by the FAO are the ratio of the food purchasing power parity (FPPP) to the general PPP. They help capture the importance of food in the overall consumption basket and take the highest values for the least developed countries.

The coefficient on the linear term is significant at the 10% level and negative. This is clearly visible on the graph, where the effect of food price ratio on virtual water trade is basically linear and our observations never reach the threshold of 6, at which predicted virtual water exports reach their lowest level. In fact, because the highest values of the food price index are reached for the least developed countries, it is intuitive that high exporting-importing food price ratios have a decreasing effect on virtual water exports. It is in line with quantitative studies that show how poorer countries are generally net virtual water importers rather than net exporters.

Figure 11: Effect of food price ratio on predicted values of virtual water exports



The gravity controls behave according to expectations in the extant literature on international trade. Indeed, contiguity, common colonizer and common language are all highly significant and positively correlated with the exports of virtual water.

If the exporting and importing countries are contiguous, virtual water exports of products almost double as they increase by 93.5%. Having been colonized by the same nation will also increase virtual water exports (in our analysis by 25%), which is in line with the results of Head, Mayer and Ries (2010). Sharing a common language increases virtual water exports by 23.2%. As predicted by international trade theories, a 1% increase in distance between the exporting and importing countries decreases virtual water exports of a product by 0.8%. The positive effect of Regional Trade Agreements on virtual water flows is also supported by the literature (Martin, Mayer and Thoenig, 2012).

6 Sectoral Analysis

The sectoral analysis was conducted by sub-sampling our data according to HS2 categories of products, further described in Appendix A. The model used is the same as the one used for the analysis of the entire sample; the dependent variable is still at the product, country-pair and year level, although the number of observations per sample is reduced to the number of trade flows belonging to the same sector. Table 3 displays the results of the coefficients for our two main variables of interest, asymmetry in water endowments and in water footprints. In bold are the coefficients that are significant at the 10% level and stronger.

The results show important inter-sectorial differences in the way they relate to endowment and productivity asymmetries. First of all, certain sectors lose sensitivity regarding those two variables: 8 (12) out of 23 sectors display significant coefficients. Second, for the coefficients that are non-linear, the squared term is almost always very weak. It is interesting to interpret these results all the while having figures 2 (% share of sectors in total trade) and 3 (how sectors contribute to saving water through international trade) in mind because of the underlying hypothesis:

- The most traded sectors involve the largest food producers in the world, who also happen to be the most water abundant nations, hence suggesting a higher sensitivity of trade regarding asymmetries in water endowments. This hypothesis is true up to a certain extent – although the world's richest countries in water are among the biggest food producers, many nations with moderate or scarce water resources are still producing agricultural goods and exporting them. This is due to short-term economic incentives and food security policies fostered by government subsidies.

- The most water saving sectors are the ones where the amount of embedded water actually exported is lower than what would have been used by the importing country had produced the good locally. As this

Table 3: Linear regression with two high dimensional fixed effects - Sector analysis

	Variables				
Sectors	Intercept	RatioWL	$(RatioWL)^2$	RatioWFP	$(RatioWFP)^2$
Live Animal 1	16	**0.00256*****	**-0.00000174***	-0.150	0.0208***
Meat 2	18	0.000634	-0.000000418	0.00789	0.0232*
Fish 3	15	-0.00180	0.0000165	-0.0952	-0.00334
Dairy 4	17	**0.00176****	-0.00000114	**-0.519*****	**0.0262*****
Animal Prod. 5	17.58	-0.000578	1.087	0.644	-0.218**
Vegetables 7	15.4	0.000617	0.000000644	**-0.0466*****	**0.000323*****
Fruits, Nuts 8	16.7	**-0.00375****	0.00000327	**-0.0541*****	0.000458
Coffee, Tea, Spices 9	17.5	0.0157	-0.000147	**0.0753****	**-0.00106****
Cereals 10	18.5	**0.0213*****	**-0.000101****	**-0.197***	0.00608
Milling 11	16.5	0.00746	-0.0000105	**-0.122****	**0.00311***
Oil Seeds 12	17.3	-0.00304	0.0000225	-0.0552	0.00333**
Lac, Gums, Resins 13	16.5	-0.00170	-0.000222	-0.235	0.199*
Veg. Materials 14	19.7	-0.383	0.00760	1.707	-0.232
Fats 15	18.3	**0.0259****	-0.0000711	**-0.305*****	**0.00559***
Prep. of meat, fish 16	16.5	**0.00316***	-0.00000190	**0.216****	**-0.00806***
Sugars 17	17.6	0.000930	-0.00000591	0.465	-0.0186
Cocoa 18	20	0.103	-0.00254	11.80	-1.847
Prep. of Veg. 20	15.9	0.00153	-0.00000174	-0.0265	0.000448
Beverages 22	15.7	0.00341	-0.0000193*	-0.0783	0.00396
Food Waste 23	20.35	**0.0624****	**-0.000524*****	**-3.993*****	**0.399*****
Tobacco 24	18.9	**0.00863*****	**-0.0000170*****	**-0.159***	0.00646
Raw Skins 41	18	0.000201	0.000000146	**1.066*****	**-0.107****
Leather 42	16	-0.0000856	0.000000315	**3.060*****	**-0.232*****
Cotton 52	15	0.0195	-0.0000505	-0.874	0.110
Other Veg. Text. 53	22	-0.0197	0.000296	0.182	-0.0132

difference increases, so does the amount of water saved. Hence the intuition that those specific water saving sectors should be sensitive to water footprint asymmetries.

Among the top six traded sectors which each represent over 5% of total virtual water trade between 1994 and 2007, three display significant coefficients for the water endowment asymmetry variable. These sectors are: Cereals (HS2 10), Food waste (HS2 23) and Fats (HS2 15). The first two display non-linear coefficients, suggesting that relatively more water abundant countries will export to relatively less water rich nations until a certain threshold of asymmetry. Above that threshold, exports in cereal will drop because of the economic weaknesses of the country involved and their inability to participate in trade because of trade costs. Figure 12 shows the predicted virtual water exports by sectors according to water endowment asymmetries. The figure only shows the sectors for which the coefficients in table 3 are significant. We can see that the two sharpest slopes are indeed for the Cereal and Food Waste sectors.

The relationship between bilateral exports of cereals and water endowment asymmetries are as follow:

$$log(VWexp) \approx (0.02123{*}\text{RatioWaterLand}{-}0.000101 * RatioWaterland^2)$$

and so for small values of $\Delta RatioWaterland$:

$$\Delta log(VWexp) \approx 100 * (0.02123 - 0.000202 * RatioWaterland)\Delta RatioWaterland$$

The quadratic function of bilateral exports of cereals first increasing in water per land asymmetries until a treshold of 105, above which only 7% of our trade flows in cereals are located. Below this threshold, a one standard deviation increase from an asymmetry ratio of 20 to 37 (20+17) generates an increase in bilateral flows of embedded water of 25% which is a very strong effect. This effect decreases as we approach the threshold: a one standard deviation increase in water per land asymmetries from 85 to 102 would increase bilateral flows of virtual water in cereal trade by only 4%.

Figure 12 also shows that apart from Cereals and Food Waste, bilateral exports in other sectors have a very flat slope: their sensitivity to water per land asymmetry is very weak. This is an interesting result because it gives perspective to the importance of water endowments relative to food trade.

On the other hand, even if the quadratic effects are moderately strong, sectors seem to be much more sensitive to water footprint asymmetries. This

Figure 12: Predicted Virtual Water exports by sector according to Water per Land ratio

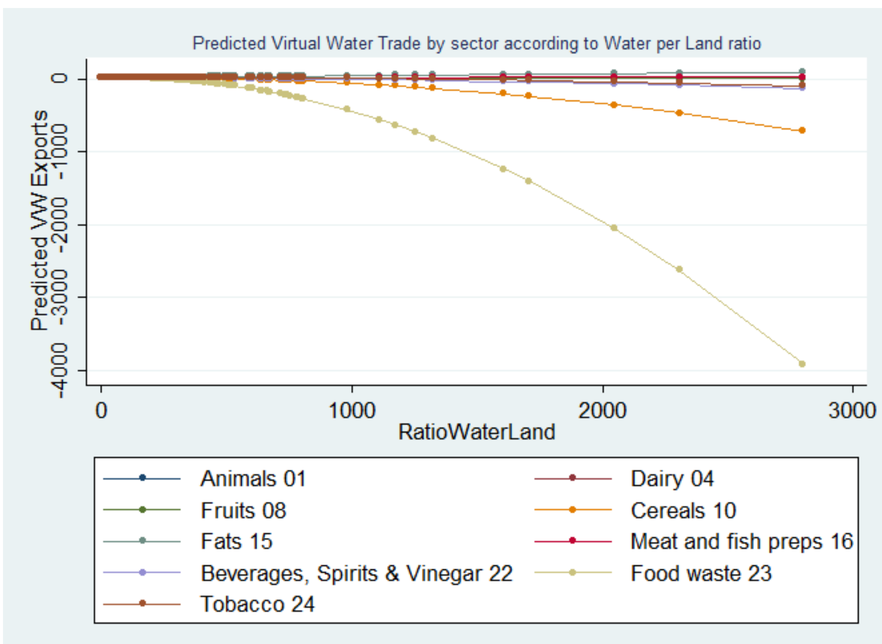
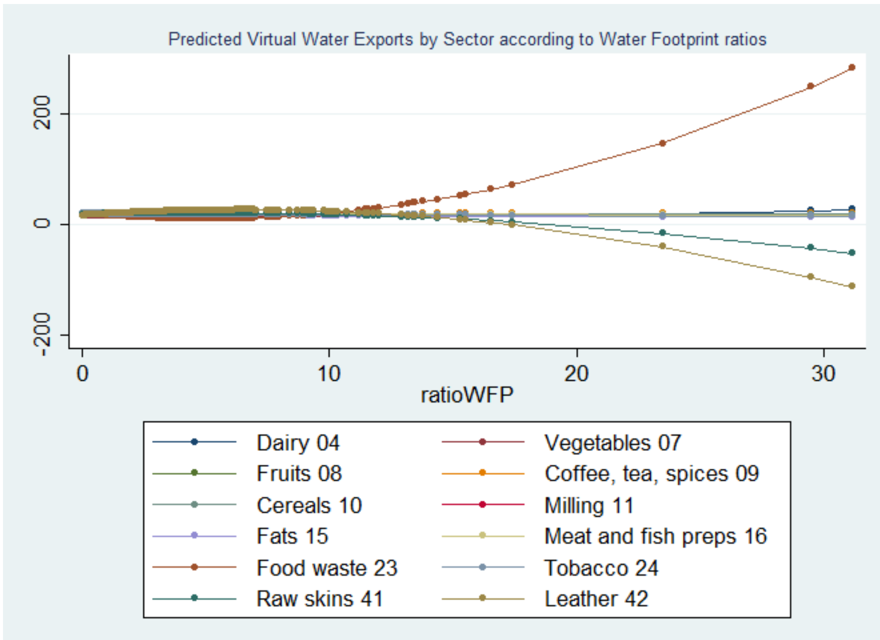


Figure 13: Predicted Virtual Water exports by sector according to Water Footprint ratios



is shown in figure 13, which displays the predicted virtual water exports by sectors according to water footprint asymmetries. The figure only shows the sectors for which the coefficients in table 3 are significant.

Virtual Water exports in the Cereal sector no longer display a non-linear relationship regarding the x-axis which represents water footprint ratios. The relationship is the following:

$$log(VWexp) \approx (-0.197 * ratioWFP)$$

and so:

$$\Delta log(VWexp) \approx 100 * (0.02123)\Delta RatioWaterland$$

A one standard deviation increase in water footprint ratio will increase bilateral exports of products by $100 * (1.47 * 0.02123) \approx 3\%$, which is a weak effect. On the other hand, Food Waste (HS2 23), Raw Skins (HS2 41) and Leather (HS2 42) have important non-linear coefficients.

7 Conclusion

This paper addresses virtual water and food trade from a different perspective than most of the existing literature. First of all it takes a bilateral rather than an unilateral perspective on food trade, enabling an in-depth analysis on exporter and importer caracteristics and asymmetries.

Second, and closely linked, is the inter-disciplinary approach of this analysis and model which allows for the examination of specific economic, political or climatic factors that might influence food production and trade rather than limiting the analysis to water-related variables.

Lastly, because it quantifies the effects of asymmetries in water endowments and productivities on virtual water exports, it allows for a comparison of the influence of these two important variables on food trade - all other things being equal. The paper shows that the countries experiencing high water scarcity resort to food trade to alleviate water paucity. This finding empirically validates earlier theories about virtual water trade. Our results also validate more recent explanations for virtual water trade (that of comparative advantage), but up to a point. In other words, more water efficient countries export food to less water efficient countries yet beyond a certain threshold, virtual water flows from relatively less water efficient countries to more water productive countries.

Increasing knowledge about *virtual* water flows, endowments and productivity should help countries implement more efficient use of their water resources for agricultural, industrial and individual consumption. Nevertheless, because most agricultural sectors across the globe are highly subsidized, it seems unfeasible that governments may wish to stop producing basic crops because of low water productivity. But such information can be valuable in order to foster innovation and technology use to increase crop yield and decrease water footprint. It can also help famers get a better sense of which crops to cultivate.

One of the main challenges remains that of data collection for enhanced computations of water footprint values. Water footprint measurements mainly constitute a mixture of climatic and soil characteristics data (e.g. soil, land, evapotranspiration, temperature, etc.). But productivity is also endogenous to the economic, political and historical strengths of a country and these factors should also be considered by the model.

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Appendices

A World Customs Organization - HS Nomenclature 2012

- HS01 - Live animals
- HS02 - Meat and edible meat offal
- HS03 - Fish and crustaceans, molluscs and other aquatic invertebrates
- HS04 - Dairy products; birds' eggs; natural honey; edible products of animal origin, not elsewhere specified or included
- HS05 - Products of animal origin, not elsewhere specified or included
- HS07 - Edible vegetables and certain roots and tubers
- HS08 - Edible fruit and nuts; peel of citrus fruit or melons
- HS09 - Coffee, tea, mat and spices
- HS10 - Cereals
- HS11 - Products of the milling industry; malt; starches; inulin; wheat gluten
- HS12 - Oil seeds and oleaginous fruits; miscellaneous grains, seeds and fruit; industrial or medicinal plants; straw and fodder
- HS13 - Lac; gums, resins and other vegetable saps and extracts
- HS14 - Vegetable plaiting materials; vegetable products not elsewhere specified or included
- HS15 - Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes
- HS16 - Preparations of meat, of fish or of crustaceans, molluscs or other aquatic invertebrates
- HS17 - Sugars and sugar confectionery

- HS18 - Cocoa and cocoa preparations
- HS20 - Preparations of vegetables, fruit, nuts or other parts of plants
- HS22 - Beverages, spirits and vinegar
- HS23 - Residues and waste from the food industries; prepared animal fodder
- HS24 - Tobacco and manufactured tobacco substitutes
- HS41 - Raw hides, skins and leather
- HS42 - Articles of leather; saddlery and harness; travel goods, handbags and similar containers; articles of animal gut (other than silk-worm gut)
- HS44 - Wood and articles of wood; wood charcoal
- HS52 - Cotton
- HS53 - Other vegetable textile fibres; paper yarn and woven fabrics of paper yarn

B Regression results - no quadratic terms

Table 4: Linear regression with two high dimensional fixed effects

	(1) lnXWFP_i		(2) y	
RatioWaterLand	0.000645***	(0.000110)	0.000645***	(0.000151)
WFP_ratio	-0.0244***	(0.00214)	-0.0244***	(0.00336)
$GDPcap\_ratio$	0.00299***	(0.000699)	0.00299*	(0.00149)
$ExistingTrade$	1.103***	(0.00697)	1.103***	(0.0112)
$PopEvol\_ratio$	0.000206***	(0.0000611)	0.000206*	(0.0000839)
$FoodPriceindex\_ratio$	-0.943***	(0.0637)	-0.943***	(0.126)
$Contig$	0.934***	(0.00879)	0.934***	(0.0186)
$ComCol$	0.247***	(0.0176)	0.247***	(0.0349)
$ComLang$	0.232***	(0.00802)	0.232***	(0.0152)
$lndist$	-0.816***	(0.00484)	-0.816***	(0.0114)
RTA	0.260***	(0.00904)	0.260***	(0.0200)
N	1554651		1554651	
R^2	0.696		0.696	
adj. R^2	0.560		Cluster	exporter-sector-year
F	5.144		Nb. of groups	26714
df_m	478114			
df_r	1076536		478115	

Standard errors in parentheses

Unit of study is country_pair year product

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$