Is irrigation driven by the economic value of internationally traded agricultural products?

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PRELIMINARY WORK. PLEASE DO NOT QUOTE.

Abstract

A recent trend of literature investigates how international trade compensates or accentuates the differences in countries' endowments in water resources and whether trade regulation should be used to improve the use of water resources at the global level. In this paper, we develop a simple model establishing a positive link between the demand for irrigation water of agricultural producers and the international price of irrigated goods. Unlike previous works, that focus on the cost of water resources, we emphasize the price of traded goods as a key element of the shadow value of water used in agriculture. We test our model empirically using data on 159 irrigated crops exported by 183 countries, and find that countries' irrigation behavior is strongly linked to the global price of crops. This indicates that agricultural producers internalize the price of irrigation water. The export price effect is stronger when countries are net exporters of irrigated crops and weaker for internationally traded crops that constitute a pillar of most countries' domestic food security, such as cereals. Our results provide elements for the broader issue of the economically efficient use of water resources in agriculture.

JEL codes: Q17, Q25, F18, N50

Keywords: water resources, virtual water, international trade, agri-food products, irrigation

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1. Introduction

The concept of *virtual water*, introduced in the early 1990s, refers to the volume of water used to produce a good or service. It reveals aspects related to production, consumption, and trade in agricultural goods overlooked by economic (monetary) indicators. Accordingly, the concept of virtual water was rapidly identified as a potential indicator for guiding policy-makers on issues related to water use, water scarcity, and water management in a world where many countries face important water shortages (Antonelli and Sartori, 2014). Extensive recent works conducted by agronomists and geographers have quantified the amount of water used for the production of main agricultural products in different countries of the world (Mekonnen and Hoekstra, 2011a, 2011b, 2016). The amount of virtual water – the *water footprint* – is measured in terms of in cubic meters of water used per kg of produced good (m^3/kg). These works separate the *green water*, that corresponds to the rainfall necessary for the production of one kilogram of each crop, from the *blue water*, that corresponds to the irrigation water brought in surplus on farming plots.

The concept of virtual water is closely associated with international trade. Exporting an agricultural product can be interpreted as exporting the water footprint embedded in that product. Adopting this perspective led to the emergence of the concept of *virtual water trade.* Hoekstra *et al.* (2011) define the virtual water trade flow between two geographical entities as the volume of virtual water that is being transferred as a result of product trade. Following this definition, virtual water trade can be easily computed by combining data on water footprints with data on international trade in agricultural products expressed in physical quantities. For the exporting country, virtual water trade is a way to market its excess water resources. For the importing country, virtual water trade is the water volume saved by choosing to import a good instead of producing it domestically.

The concepts of water footprint and virtual water trade are employed almost exclusively with respect to agricultural products, where water is an essential production input. Pioneer works on these concepts led to the emergence of a recent trend of literature that uses virtual water trade to understand the structure and evolution of the international trade network of agricultural goods and to investigate the link between countries' water resources and their water balance (*e.g.* Antonelli and Sartori, 2014; Debaere, 2014; Gilmont, 2015, Duarte *et al.*, 2016, 2019; Fracasso *et al.*, 2016; Sartori *et al.*, 2017 ; Tuninetti *et al.*, 2017). Some of these studies reveal inconsistencies between virtual water trade and available water resources in net exporting countries, in contradiction with theories of international trade. This questions the efficiency of water management not only at country level, but also on a global scale. For instance, Gilmont (2015) focuses on the agricultural imports of North African and Middle East countries and concludes that increasing the imports of certain food products and concentrating domestic production on crops well adapted to the aridity of their climate would permit these countries to optimize the use of their limited water resources. Virtual water is used here to analyze countries' strategies in terms of adjusting (structuring) their imports to their water endowments and food security objectives.

Other authors advocate the idea that virtual water trade can attenuate international water supply inequities, and can prevent conflicts and wars even more than trade in other strategic goods, such as gas and oil (*e.g.* De Angelis *et al.*, 2017). A previous analysis by Ansink (2010) refutes this line of reasoning, qualifying it as a flawed interpretation of comparative advantage in the production of water-intensive goods. Wickeln (2015) questions more generally the use of virtual water trade and water footprint concepts for formulating policy recommendations. In his opinion, world trade should not be regulated to match countries' virtual water trade with their water resources. Water is only one of the many production inputs used in agriculture, and water-related technologies are so diverse that virtual water is a less relevant indicator of comparative advantage than arable land or irrigated area. Moreover, the water resource is not a global public good, like carbon emissions, and should be managed locally. Hence, the notion of water saved by virtual water trade does not really make sense, and leads to incorrect conclusions, such as consumers from rich countries with high water footprint imports being responsible for the desertification of low-income exporting countries. Overall, Wickeln's analysis highlights that virtual water and water footprints are not helpful indicators of optimal strategies regarding water resources because they lack information on the economic implications of water use (the opportunity cost or the scarcity value of this input).

Still, the drawbacks associated with using these indicators cannot mask the need for a better management of water use in agriculture. Rosegrant (2016) spots that the decline in water resources in various regions of the world threatens the global food security and economic growth, particularly from the perspective of increasing climate change. The author calls for increased investment in research technologies, agricultural systems and water-efficient varieties, as well as for the implementation of country-specific water management public policies adapted to countries' resource availability and economic development prospects. As already mentioned by Novo et al (2009), there is still a lack of policy oriented approaches assessing the trade-offs of implementing a virtual water strategy. We attempt to bridge this gap by providing evidence on the link between the market-induced incentives of economic agents and water use in agriculture.

Standard international trade models incorporate traditional factors of production such as capital, labor and land, but do not account for countries' water endowments. A commonly invoked argument of this state of the art is that the markets for water are thin or lacking. Therefore, the economic value of the water used in agricultural production is rarely addressed in the trade literature. For example, Debaere (2014) uses a Heckscher-Ohlin framework and shows that water is a source of comparative advantage, although it affects international production and trade patterns (specializations) to a less extent than traditional production factors (capital and labor). Still, he reveals an unsustainable use of water in water-scarce countries, while water-abundant countries treat water as a free good. The recent work by Afkhami *et al.* (2018) combines water (matched with arable land) and capital (both human and physical) in a Heckscher-Ohlin model and shows that water-scarce developing countries may specialize in water-intensive crops because they lack capital to specialize in non-agricultural sectors.

The price of virtual water is remotely addressed in the above-mentioned works. Tuninetti *et al.* (2017) use the average country-level agricultural production costs to value virtual water of internationally trade agricultural and food products. Novo *et al.* (2009) use the shadow price or scarcity value of irrigation (blue) water to compute the economic value of virtual water in the case of Spain. Authors recommend the use of other socio-economic indicators to improve the assessment of the real opportunity cost of water. Fracasso *et al.* (2014, 2016) include the price of irrigation water in their analysis of virtual water trade determinants, but do not find a robust effect. Instead of considering the cost of water in agricultural production, in the current paper, we focus on the opportunity price of irrigation water. Precisely, we use the price of agricultural and food products in international markets.

More specifically, we question whether a country's irrigation choices depends on the expected revenue from exporting the irrigated crops. By answering this question, we provide elements for the broader issue of the link between the use of water resources in agriculture and the market value of produced agricultural goods. One of our contributions is specifically aimed at directly linking the volume of virtual water traded to the price of the agricultural products, for all unprocessed products and world countries for which the data are available. This analysis sheds light on how the established international trade patterns influence the choice of agricultural products that benefit from irrigation and the more or less intensive use of irrigation water in agricultural production in different regions of the world.

The paper is structured as follows. In the next section, we develop a simple model linking the use of irrigation to the export price of goods and other determinants. Section 3 summarizes the data we used for the empirical validation of our model. The main estimation results are presented and discussed in section 4. In section 5, we investigate the specific case of products for which countries are net exporters and for cereals. Our main findings are resumed in section 6.

2. The economic productivity (shadow value) of irrigation water

In this section we use a simple model to establish a link between the demand for irrigation water of agricultural producers and the international price of irrigated goods. Unlike previous works, that analyze the relationship between countries' water resources and their virtual water trade only in volume terms (quantities), we emphasize the price of traded goods as a key element of the shadow value of water used in agriculture.

The reference analytical framework employed by most existing studies is that of a standard Heckscher-Ohlin trade model with water resources as an additional production factor. This model predicts that countries with large water endowments should specialize in water-intensive agricultural products and export the latter, while countries facing water scarcity should specialize in products adapted to arid climates and import water-intensive commodities. However, previous studies provide many examples of countries that deviate from this result

(Antonelli and Sartori, 2014; Debaere, 2014; Gilmont, 2015). Thus, the water-scarce Jordan and Morocco are major exporters of tomatoes, a water-intensive agricultural product. Similarly, cotton − another water-intensive agricultural commodity − accounts for a large share of the exports revenues of arid Central Asian countries. All these specializations arise due to an intensive use irrigation.

Since irrigation is costly, we expect that countries privilege irrigating crops with a higher expected revenue, *i.e.* agricultural goods that can be sold at a higher price on international markets. An empirical confirmation of this statement would indicate that producers internalize the irrigation cost. On the contrary, the rejection of a positive link between the decision to irrigate and the export price of agricultural goods would point to the fact that agricultural producers consider irrigation as a complementary public good.

Since water (W) is an essential factor for the production of any agricultural good, we consider a production function embedding this factor along with other production factors combined, for simplicity, under a single composite factor (X). The composite factor comprises the generic factors labor and capital, as well as agriculture-specific factors, arable land and inputs (including seeds, fertilizers, pesticides, *etc.*). With a Cobb-Douglass production function, the amount of good k produced in country i is:

$$y_{ik} = f(X_{ik}, W_{ik}) = X_{ik}^{1-\alpha_k} \cdot W_{ik}^{\alpha_k} , \qquad (1)$$

where X_{ik} and W_{ik} are the necessary amounts of composite factor and, respectively, water, to produce y_{ik} units of product k, and $0 < \alpha_k < 1$.[1] Parameter α_k reflects how water intensive is product k in country i.

As in a standard Heckscher-Ohlin trade model, we assume fixed factor endowments for all countries:

$$\bar{X}_i = \sum_k X_{ik} \ ; \quad \bar{W}_i \geq \sum_k W_{ik} \ ,$$

perfect factor mobility across sectors (within each country), but none at the international level (across countries). These assumptions lead to factor price equalization in each country. Let c_i and r_i represent the marginal cost of the composite factor and, respectively, water in i. Water resources comprise both rainfall (green water) and groundwater and stream flow (blue water), the two being substitutes in agricultural production (unlike other production factors):

$$W_{ik} = BlueW_{ik} + GreenW_{ik} \ . \qquad (2)$$

At country level:

[1] We can even consider that production technologies vary across countries, *i.e.* country-specific parameters α_{ik}.

$$\overline{W_i} = Rainfall_i + GroundWater_i \geq \sum_k BlueW_{ik} + \sum_k GreenW_{ik} \quad (3)$$

Farmers decide only how much to irrigate each crop, and take the amount of rainfall as exogenous and at no cost.

Under perfect competition, factor costs reflect the market-induced remuneration of production factors. Still, they may not correspond to their actual economic value. Indeed, most countries don't' have an explicit market for water resources, and we observe a great diversity in the way countries manage water access and establish water bills. Consequently, we treat factor costs as given (exogenous).

We consider farmers as price-takers and each product k to be internationally traded at a unique world price p_k. Farmers maximize their profits by taken as given the technological and endowment constraints, the country-specific costs of production factors, and the world prices of cultivated crops:

$$\pi_{ik} = p_k \cdot y_{ik} - c_i \cdot X_{ik} - r_i \cdot BlueW_{ik} \ , \quad (5)$$

Using (1) and (2) in (5), and considering that rainfall water comes at no cost, we obtain:

$$\pi_{ik} = p_k \cdot X_{ik}^{1-\alpha_k} \cdot (BlueW_{ik} + GreenW_{ik})^{\alpha_k} - c_i \cdot X_{ik} - r_i \cdot BlueW_{ik} \quad (6)$$

The first order conditions $\left(\frac{\partial \pi_{ik}}{\partial X_{ik}} = 0; \frac{\partial \pi_{ik}}{\partial BlueW_{ik}} = 0\right)$ imply:

$$X_{ik} = \frac{1-\alpha_k}{\alpha_k} \cdot \frac{r_i}{c_i} \cdot (BlueW_{ik} + GreenW_{ik}) \quad (7)$$

$$p_k^* = \left(\frac{c_i}{1-\alpha_k}\right)^{1-\alpha_k} \cdot \left(\frac{r_i}{\alpha_k}\right)^{\alpha_k} \quad (8)$$

$$y_{ik}^* = \left(\frac{1-\alpha_k}{\alpha_k}\right)^{1-\alpha_k} \cdot \left(\frac{r_i}{c_i}\right)^{1-\alpha_k} \cdot (BlueW_{ik} + GreenW_{ik}) \quad (9)$$

where p_k^* and y_{ik}^* are the price and production values that maximize producers' profits.

By definition, blue water footprint of product k in country i is the amount of cubic meters of irrigation water used to produce one tone of this product. It represents producers' unitary demand for irrigation water. We use expression (9) to express the blue water footprint of product k in country i as:

$$BlueWFP_{ik} = \frac{W_{ik}}{y_{ik}^*} - \frac{GreenW_{ik}}{y_{ik}^*} = \left(\frac{1-\alpha_k}{\alpha_k}\right)^{\alpha_k - 1} \cdot \left(\frac{r_i}{c_i}\right)^{\alpha_k - 1} - \frac{GreenW_{ik}}{y_{ik}^*}. \quad (10)$$

$GreenW_{ik}$ is the amount of rainfall on areas dedicated to cultivating this product.[2] Relying on expression (3), we can consider the last term of equation (10) as a positive function of the overall rainfall in country *i*: $\frac{GreenW_{ik}}{y_{ik}^{*}} = f(Rainfall_i)$.

Expressing c_i from (8) and plugging it into equation (10), we obtain the following expression for the use of irrigation (blue water footprint) that reflects farmers' profit maximization decision:

$$BlueWFP_{ik} = \alpha_k \left(\frac{1}{r_i}\right) p_k - f(Rainfall_i)\,. \tag{11}$$

Equation (11) shows that farmers' demand for irrigation decreases with the cost of irrigation and with the amount of rainfall. On the opposite, farmers tend to irrigate more intensively water-intensive products (with large α_k) and products trade at a higher price.

3. Data for the empirical analysis

The present section presents the empirical data we employ to test the relationship between the producers' demand for irrigation water and the international price of irrigated goods resulting from our model (equation (11) from section 2).

In this paper, we focus on irrigation water, *i.e.* the use of water resources resulting from a prior decision taken by farmers to build and maintain an irrigation infrastructure; farmers choose which products to irrigate and how intensively. On the opposite, farmers have no say on the amount of rainfall used by their crops. Since most countries in the world irrigate some crops, our focus on irrigation water does not hamper the generalization of the results we obtain.

We use the data on water footprint computed by Mekonnen and Hoekstra (2011a, 2016).[3] This database provides information on the average annual blue and green water footprints for 353 agricultural products in 207 countries and territories, over the 1996-2005 period. Blue water footprints provide information on how intensively each agricultural product is irrigated in each country (in terms of m^3 of irrigation water per ton of product). Although farmers might also decide how extensively to irrigate each product (the size of irrigated farming plots),[4] irrigation requires an adapted infrastructure that cannot be rapidly extended or relocated. We consider countries' irrigation infrastructures, and accordingly the size of irrigated farming plots, as

[2] Water endowment in our case corresponds to the water that can be used in agriculture. It comprises only the share of the rainfall in land areas dedicated to agriculture (some of the country's rainfall may be in forests, mountains, inhabited areas, *etc.*). Note that $GreenW_{ik}$ is proportional to the share of country *i*'s arable land dedicated to the cultivation of crop *k*.
[3] This data is available at http://waterfootprint.org/en/resources/waterstat/ .
[4] To our knowledge, there is no database collecting statistical data on the size of irrigated farming plots by product and country.

constant. This is a reasonable assumption for a data panel spanning across only ten years. Under these conditions, farmers decide only which products to farm on irrigated plots.

We use the export price (unit value) as a proxy for the market value of that product. We prefer this value to the domestic price for two reasons. First, unlike domestic prices that can be strongly distorted by agricultural policies (*e.g.* subsidies, quotas) or the size of demand, export prices reflect more accurately the market value of a product. Second, export prices can be computed at same level of product disaggregation as our water footprint data (6-digit of the HS classification). Domestic prices are usually collected at a different (broader) level of product definition.

We use the BACI trade database and compute the export unit value as the ratio between the monetary value of exports and the amount of traded products expressed in physical units (tons). Since BACI trade data are in FOB terms, export unit values are not inflated by trade costs (*e.g.* when products are shipped to more remote markets, require special transportation and storage facilities due to high perishability, or face high import tariffs). We observe a high variation of unit values across destinations, for a given exporting country and good.

We consider two types of product-specific export prices: world average exports prices (p_k) and country-specific export prices (p_{ik}). The former reflect the expected price on the global market; the latter corresponds to the actual (observed) price at which countries sell the products to their trade partners. To obtain country-specific unit values for each product, we take the median unit value across the country's export destinations. The world price is the average of country-specific export prices. According to equation (11), it should have a positive effect on irrigation. The country-specific price embeds the irrigation cost and, therefore, we use it as a proxy for variable r_i in equation (11). Hence, we expect it to have a negative impact on irrigation intensity.

We acknowledge that processed agricultural goods exported by a country can be obtained from domestic or imported unprocessed goods (*e.g.* pasta from wheat). This information is generally unavailable in trade data. Water footprints are computed assuming that solely domestic inputs where used in the production process. To reconcile this difference between the two databases, we restrict our sample to unprocessed goods. We end up with a data panel covering 183 countries and 159 products (6-digit HS codes).

We need to control for the fact that water-intensive products require more intensive irrigation. This characteristic is well reflected in the green water footprint, provided by Mekonnen and Hoekstra (2011a, 2016). These authors compute green water footprints by taking into account country and product-specific agronomic production systems. Moreover, in the absence of irrigation, farmers place (grow) water-intensive products in water abundant areas. This confirms our choice to use green water footprints to proxy the water-use intensity of irrigated products (parameter α_k in our model). Since data on green water footprints varies across countries, the use of this variable permits to consider that country adopt different production functions.

The rainfall ($Rainfall_i$) is the average value of annual precipitations (in mm) from the World Development Indicators database of the World Bank. It reflects the country's level of water abundancy. Water-scarce countries are identified by a lower level of precipitations.

We consider two additional control variables that may affect the economic productivity of irrigation water. First, the share of agriculture in a country's total water use (in %) indicates the level of water pressure faced by the country's agricultural sector. Secondly, we use the per capita GDP (in current USD) as a proxy for the cost of irrigation equipment (initial investment and maintenance). Data on both variables are obtained from the World Development Indicators database of the World Bank.

Data on the share of water resources used in agriculture and annual precipitations are missing for a large number of years (different years for different countries), but depict insignificant variations across time. We fill in the missing data with country-level averages computed on observed data.

Table 1 summarizes the descriptive statistics for variables in our data panel.

Table 1 Descriptive Statistics

Variable	Unit	Nb obs	Mean	Std. Dev.	Min	Max
Blue Water Footprint	m^3/ton	14,366	819.71	3,721.85	0	150,204
Green Water Footprint	m^3/ton	14,366	2,675.08	6,662.30	4	257,913
Country specific export price (unit value)	USD/ton	14,323	203.18	9,983.86	.0027	1,121,092
World average export price	USD/ton	14,366	144.65	686.97	.2279	1,4295.34
Water use in agriculture	%	12,324	59.81	29.64	.2081	99.59
Rainfall	mm	14,363	972.72	683.44	51	3240
Per capita GDP	USD	14,270	8,619.53	11,693.51	117.41	66,775.38

4. Main estimation results

We test the model derived in section 2 with empirical data by estimating the following equation:

$$BlueWF_{ik} = \beta_0 + \beta_1 \cdot p_{ikt} + \beta_2 \cdot p_{kt} + \beta_3 \cdot GreenWF_{ik} + \beta_4 \cdot Rainfall_i + \varepsilon_{ikt} \qquad (12)$$

Subscript t denotes annual dimension of the data and ε_{ikt} is as zero mean noise term.

Results from estimating equation (12) are reported in column (1) of Table 2. All explanatory variables enter the model with the expected sign. We find a positive and significant coefficient for the global price of the irrigated product and a small negative coefficient for the country-specific export price. These results indicate that countries base their decision to irrigate on the price at which products can be sold on the global market, but they fail to channel products to the markets paying the highest price. These findings are consistent with general assumption of international trade models. Producers base their decisions on anticipated prices, reflected by global prices in our model, without knowing the actual price at which they will be able to sell their products on international markets, *i.e.* the country-specific export price in our model. We also find that water-abundant countries (with higher levels of annual precipitations) irrigate less. This confirms our expectation that irrigation is less necessary in areas with natural water abundancy. The positive and strongly significant coefficient for the green water footprint confirms that water-intensive crops require more irrigation.

To understand how irrigation depends on different country-specific characteristics, in columns (2) to (4) of Table 2 we estimate a version of equation (12) augmented by the share of agriculture in country's water use and by per capita GDP. The fair correlation of these variables with each other and with the other explanatory variables in equation (12) permits to include them separately or simultaneously. The magnitude of coefficients is directly linked to the measurement unit of each variable and, therefore, is not comparable across variables. We focus only on the sign of the effect. Countries that channel a larger share of their water resources to agriculture irrigate more intensively. These countries rely more heavily on agricultural resources and try to increase the productivity of their crops through irrigation. We also find that richer countries (with a higher per capita GDP) irrigate more. This result suggests that irrigation is a costly activity and not all countries can afford to build and maintain an extensive irrigation system. Note that adding these two control variables leaves unaffected the significance and magnitude of other effects.

The decision on how intensively to irrigate each crop may be driven by country- or product-specific controls that were omitted by our model in Table 2. To check whether these factors may bias our results, we estimate equation (12) with product and country fixed effects, used separately and jointly. We report obtained results in columns (2) to (4) of Table 3. Recall that our rainfall variable is a country-specific average over the period (due to missing data). Hence, it is perfectly collinear with country fixed effects and is omitted from estimations in Table 3. For comparability, in column (1) of Table 3 we estimate our model without the rainfall variable with no fixed effects. All estimated effects remain statistically significant and change only slightly in magnitude with respect to effects found in Table 2.

Data on water footprint data does not vary across years. To reduce the autocorrelation of time-varying explanatory variables, we consider data only for years 1997, 2001, and 2005. Ideally, we would use time varying data on water footprints. We are currently working on this limit of our data. We re-estimate the model on average data for the entire period, adding to the estimation variables reflecting the variation of our time-varying variables across years and groups of products *(e.g.* standard deviation, upper 5-10 percentiles).[5]

[5] This is on-going work. The corresponding results will be included in a updated version of the paper.

Table 2: The decision to irrigate and the export price, additional controls

	Explained variable : Blue water footprint			
	(1)	(2)	(3)	(4)
Country-specific export price	-0.0047*	-0.0052**	-0.0047*	-0.0052**
	(0.0025)	(0.0026)	(0.0025)	(0.0026)
World average export price	0.3165***	0.3346***	0.3153***	0.3310***
	(0.0441)	(0.0481)	(0.0442)	(0.0482)
Green water footprint	0.3291***	0.3520***	0.3333***	0.3598***
	(0.0053)	(0.0058)	(0.0053)	(0.0058)
Precipitation (rainfall)	-0.8287***	-0.9102***	-0.8114***	-0.8891***
	(0.0386)	(0.0466)	(0.0386)	(0.0466)
Share of agriculture in country's water use		11.5856***		15.3794***
		(1.0219)		(1.1397)
Per capita GDP			0.0023	0.0203***
			(0.0022)	(0.0027)
Number of observations	14,320	12,289	14,224	12,193
R^2	0.386	0.411	0.389	0.417
F-test	698.975	834.418	850.706	718.184

Notes: All estimations include country- and product-specific fixed effects. Standard errors in parentheses. ***, ** and * indicate statistical significance at 1%, 5%, and 10%.

Table 3: The decision to irrigate and the export price

	Explained variable : Blue water footprint			
	(1)	(2)	(3)	(4)
Country specific export price	-0.0062**	-0.0060**	-0.0062**	-0.0059**
	(0.0027)	(0.0025)	(0.0025)	(0.0024)
World average export price	0.2937***	0.3077***	0.3288***	0.3095***
	(0.0399)	(0.0433)	(0.0366)	(0.0408)
Green water footprint	0.2790***	0.3219***	0.3308***	0.3633***
	(0.0040)	(0.0053)	(0.0041)	(0.0052)
Number of observations	14,323	14,323	14,323	14,321
Fixed efects	-	product	country	product country
R^2	0.252	0.365	0.383	0.471
F-test	1608.849	1252.956	2229.541	1622.614

Notes: Standard errors in parentheses. ***, **, * indicate statistical significance at 1%, 5%, 10%.

5. Strong and weak price effects

In this section we investigate the link between irrigation and export price for specific groups of products. Figure 1 illustrates the correlation between blue (irrigation) water footprints and export unit values in the United States, for unprocessed crops for which the country is a net exporter. The strong positive correlation between these variables is driven to large degree by nuts, products that are highly irrigated and heavily exported. The decision of American nut producers to intensively irrigate appears to be directly linked to the high export price of nuts on international markets. The case of almonds is particularly interesting. Almonds stand out with the highest irrigation rate (4,000 m3 per kg), the United States being the main exporter of almonds (accounting for 88% of world exports in 2017 according to USDA, 2017). However, the irrigation of almonds and other nuts induces a high constraint for the irrigation of other cultivated crops and generates major water-scarcities at the regional level. Tensions on the use of irrigation were particularly high in California, a state affected by successive severe drought over the last decade. Our estimation results from section 4 confirm the intuition that the choice to invest massively in almond irrigation is driven by the expected high price of the product on the international markets, even if this must result in endangering the market sustainability of the California water resource.

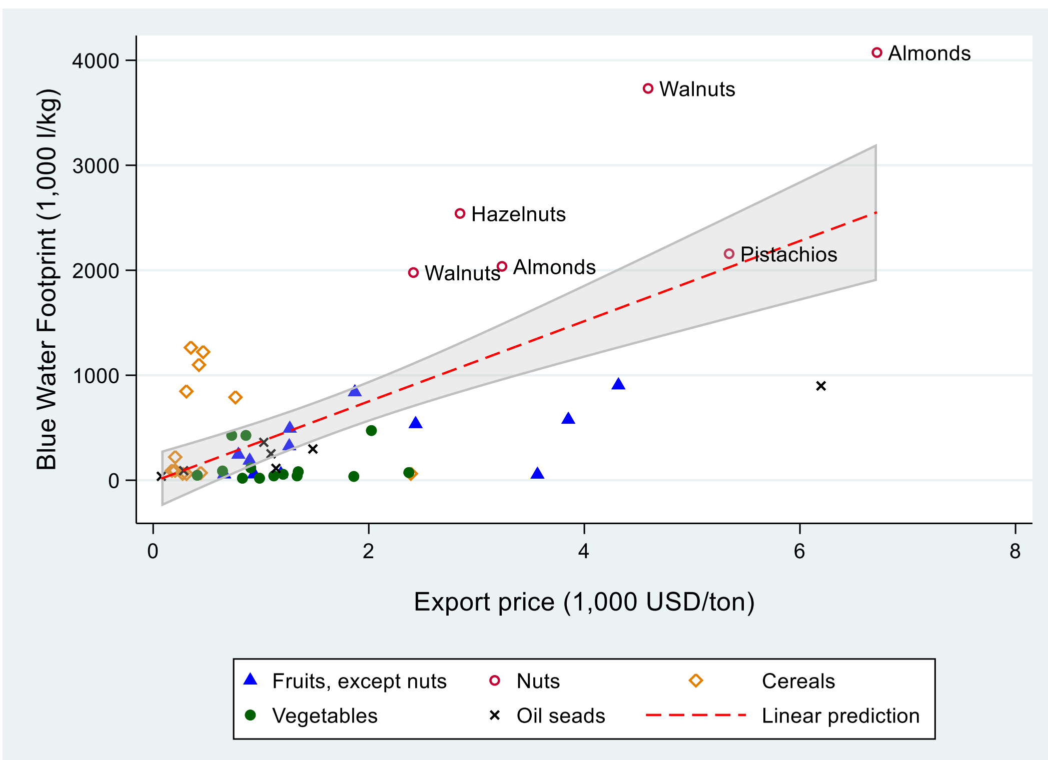

Figure 1: Blue (irrigation) water footprints vs. export prices in the U.S.

Notes: median export price in 2005, blue water footprints annual averages over 1996-2005, all products within HS chapters 7-12 for which the country was a net exporter.

Differently, for cereals the correlation between irrigation and export price is very small, and reflected in Figure 1 by an almost vertical line. Cereals are irrigated despite their relatively low export price per ton with respect to other crops. This observation is consistent with the assumption that the production of cereals is induced primarily by domestic demand, and only excess production is sold on international markets and is subject to export speculations. Indeed, cereals are the main product group subject to export restrictions worldwide, mainly for securing domestic supply and food security reasons (Mendez-Parra *et al.*, 2016). The link between the irrigation intensity and the export price level is less obvious in the case of other crops.

Based on these observations, we test two additional hypotheses regarding the link between export price and countries irrigation behavior:

(i) The link should be stronger for products for which countries are net exporters.
(ii) The link should be weaker for commodities essential for meeting domestic food security objectives, such as cereals.

Hypothesis (i) relies on the following reasoning. Producers of crops for which domestic production does not meet domestic demand (for which the country appears as a net importer) base their production decisions mainly on domestic market evolutions and are less attracted by export opportunities, which involve complex international transactions. On the contrary, producers of crops for which domestic production exceeds domestic demand are more sensitive to the evolution of global demand and more prepared to engage into export operations. This hypothesis is consistent with Antonelli *et al.* (2017), who show that intra-EU virtual water trade is dominated by a small number of exporting and importing countries. To test hypothesis (i), we check how price effects identified in Tables 2 and 3 change when we limit the sample to observations where countries are net exporters (Table 4). We find that the positive global price effect doubles, while the negative country-specific price effect become less significant.[6] We interpret this as a confirmation of our hypothesis (i).

To test hypothesis (ii), we estimate our model for the cereals (Table 5). Cereals are farmed by a large number of countries with very different climate and water endowments, and are largely traded internationally. Moreover, cereals constitute staple food worldwide. Most countries cultivate cereals to ensure their domestic food security. In the case of cereals, food security challenges the objective related to their economic valuation via international trade. In addition, the global markets for cereals are highly integrated, with the bulk of international transactions relying on reference prices published daily for the main cereal products. Compared to other crops, cereals are easily stored and transported. Due to their lower perishability, producers can afford to postpone export if the market price is judged to low. There are fifteen cereals in our data panel. We find non-significant price effects when we estimate the model on these products, which validates our hypothesis (ii).

[6] The variable trade balance has a statistically non-significant effect. These results are not reported in the paper, but can be provided upon request.

Table 4: The decision to irrigate and the export price: net exports

	Explained variable : Blue water footprint			
	(1)	(2)	(3)	(4)
Export Price	-0.0171***	-0.0041	-0.0196***	-0.0114*
	(0.0078)	(0.0072)	(0.0069)	(0.0064)
World Average Export Price	0.6194***	0.6103***	0.6400***	0.5852***
	(0.0560)	(0.0631)	(0.0492)	(0.0560)
Green Water Footprint	0.2849***	0.3480***	0.3588***	0.4042***
	(0.0045)	(0.0058)	(0.0045)	(0.0057)
Number of observations	8,033	8,033	8,033	8,026
Fixed efects	-	product	country	product country
R^2	0.345	0.482	0.510	0.601
F-test	1411.625	1237.721	2226.459	1694.173

Notes: Standard errors in parentheses. ***, **, * indicate statistical significance at 1%, 5%, 10%.

Table 5: The decision to irrigate and the export price: cereals

	Explained variable : Blue water footprint			
	(1)	(2)	(3)	(4)
Export Price	-0.0079	-0.0109	0.0021	0.0002
	(0.0107)	(0.0102)	(0.0080)	(0.0068)
World Average Export Price	-0.0170	-0.0074	-0.0235	0.0043
	(0.0327)	(0.0366)	(0.0233)	(0.0229)
Green Water Footprint	0.1122***	0.1019***	0.1398***	0.2035***
	(0.0152)	(0.0153)	(0.0162)	(0.0160)
Number of observations	1,923	1,923	1,923	1,913
Fixed efects	-	product	country	product country
R^2	0.028	0.113	0.557	0.686
F-test	18.592	15.224	25.122	54.172

Notes: Standard errors in parentheses. ***, **, * indicate statistical significance at 1%, 5%, 10%.

6. Conclusion

A recent trend of literature investigates how virtual water trade compensates or worsens (accentuates) the differences in countries' endowments in water resources and whether trade regulation should be used to improve the use of water resources at the global level. These works consider water as a production input and its value is proxied by (evaluated at) the cost of irrigation water. However, in most countries there is no explicit market for water resources, and we observe a great diversity concerning the ways in which countries manage access to their water resources and establish water bills. In this paper, we build a simple model emphasizing the link between the use of irrigation water and the expected value of irrigated agricultural products on international markets.

We test this relation empirically using data on 159 irrigated crops exported by 183 countries, and find that countries' irrigation behavior is strongly linked to the global price of crops. This indicates that agricultural producers internalize the price of irrigation water when choosing which crops to irrigate. Results are robust to the use of additional control variables and fixed effects. The export price effect is stronger when countries are net exporters of irrigated crops and weaker for cereals.

Using an intertemporal applied general equilibrium model, Diao and Roe (2003) already showed in the case of Morocco that the efficient allocation of water resources is not only dependent on water pricing and distribution policies within agriculture, but also on the policies outside the water sector, and in particular output support and trade policies. At the scale of our sample, our results confirm this idea, suggesting that a change in the price signal perceived by the producers of exported goods (via, for example, an export tax on the products concerned) could significantly modify the private arbitrations concerning the development of irrigation systems. This information should to be taken into account by policy makers at the regional level, especially in drought-prone areas where irrigation water is massively used for the production of highly valued goods in export markets.

Our analysis relies on average annual water footprints from Mekonnen and Hoekstra (2011a, 2016) computed over a decade. This limits the validity of our results with respect to time variations. Ideally, we would use annual water footprints and explain countries' irrigation decisions by export prices observed in the past (with a one year lag). This calls for an extension of the present analysis using fully time-varying data.

In addition, our model does not account for differences in the efficiency of irrigation systems. We find that rich countries irrigate more intensively. We interpret this finding as their higher capacity to build and maintain irrigation infrastructures. At the same time, it is well-established that rich countries have more efficient irrigation technologies, while the irrigation systems of poor countries suffer from significant water losses. This should produce a negative effect of per capita GDP on irrigation. To dissociate these two effects requires information on the irrigation technology at country and product level. This reinforces the need to focus the analysis on similar substitutable products.

Further research should take into account other factors that influence the choices made by producers, such as the water pricing and distribution policies, and the efficiency of irrigation systems. This would enrich our understanding of the effects of public intervention on water use, given that water management and billing varies greatly across countries and regions.

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