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agricultural products?**

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

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.

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

JEL codes: Q17, Q25, F18, N50

L'irrigation est-elle motivée par la valeur économique des produits agricoles échangés sur le marché mondial ?

Résumé

Des travaux récents dans la littérature analysent comment le commerce international atténue ou renforce les différences de dotation en eau entre les pays et si la réglementation du commerce pourrait être utilisée pour améliorer l'utilisation des ressources en eau au niveau mondial. Dans ce papier nous développons un modèle simple identifiant un lien positif entre la demande en eau d'irrigation des producteurs agricoles et le prix international des produits irrigués. Contrairement aux travaux précédents qui s'intéressent au coût des ressources en eau, nous mettons en avant le prix des biens échangés comme un élément central du prix virtuel de l'eau d'irrigation. Nous testons en suite notre modèle à l'aide des données sur 243 produits irrigués exportés par 185 pays et trouvons un lien fort entre le comportement des pays en matière d'irrigation et le prix mondial des produits irrigués. Ce résultat indique que les producteurs agricoles internalisent dans leur décisions le prix de l'eau d'irrigation. L'effet du prix à l'exportation est plus fort lorsque les pays sont des exportateurs nets de cultures irriguées et plus faible pour produits essentiels pour assurer la sécurité alimentaire, tels que les céréales. Nos résultats enrichissent la discussion sur la question plus large de l'utilisation rationnelle d'un point de vue économique des ressources en eau dans l'agriculture.

Mots-clés : ressources en eau, eau virtuelle, commerce international, produits agro-alimentaires, irrigation

Classification JEL : Q17, Q25, F18, N50

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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:

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

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

$$W_{ik} = \text{Blue}W_{ik} + \text{Green}W_{ik} \quad (2)$$

At country level:

$$\bar{W}_i = \text{Rainfall}_i + \text{GroundWater}_i \geq \sum_k \text{Blue}W_{ik} + \sum_k \text{Green}W_{ik} \quad (3)$$

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:

$$\pi_{ik} = p_k \cdot y_{ik} - c_i \cdot X_{ik} - r_i \cdot \text{Blue}W_{ik} \quad (5)$$

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

$$\pi_{ik} = p_k \cdot X_{ik}^{1-\alpha_k} \cdot (\text{Blue}W_{ik} + \text{Green}W_{ik})^{\alpha_k} - c_i \cdot X_{ik} - r_i \cdot \text{Blue}W_{ik} \quad (6)$$

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

$$X_{ik} = \frac{1-\alpha_k}{\alpha_k} \cdot \frac{r_i}{c_i} \cdot (\text{Blue}W_{ik} + \text{Green}W_{ik}) \quad (7)$$

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

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

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

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:

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

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.

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.

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. 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).

We use the data on water footprint computed by Mekonnen and Hoekstra (2011a, 2016).³ This database provides information on blue and green water footprints for 353 agricultural products in 207 countries and territories, computed as an annual average over the 1996-2005 period.

Blue water footprints provide information on how intensively each agricultural product is irrigated in each country (in terms of m³ 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 constant. This is a reasonable assumption for a data panel spanning across only ten years. Under these conditions, we assume that farmers decide only which products to farm on irrigated plots.

Green water footprints permit to control for the fact that water-intensive products require more intensive irrigation. Mekonnen and Hoekstra (2011a, 2016) 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 supports our choice to use green water footprints as a proxy for 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 countries adopt different production functions.

We use the export price (unit value) as a proxy for the market value of each 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 the 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

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.

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 prices p_{ik} for each product, we take the average unit value across the country's export destinations, weighted by the share of each destination market in global agri-food imports. We compute world prices p_k as the average of country-specific export prices, using the same weights as above. We approximate prices by unit values (*i.e.* as the value divided by the volume of trade). However, small or exceptional trade flows do not report consistently both types of data (value and volume), generating a few abnormal unit values. To exclude these outliers, for each product k we drop the bottom 5% and the top 5% of unit values in the data.

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

Unlike export prices and other explanatory variables in equation (11), water footprint data do not vary across years. To reconcile these differences, for each time-varying explanatory variable we take the annual average, computed over the same period as water footprints.

For each country, data on water footprints covers only unprocessed agricultural commodities and their domestic first-stage transformation. Hence, we are certain that the water footprint associated with, say, Italian pasta corresponds to the water footprint of embedded Italian (not imported) wheat. This permits to disregard agri-food products obtained from imported inputs, such as English tea produced from imported tealeaves. Overall, there are 243 products (HS 6-digit codes) and 185 countries in our final dataset. 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	9 447	816	3 696	-	150 204
Green water footprint	m ³ /ton	9 447	2 526	6 452	4.00	279 397
Country specific export price	USD/ton	9 447	3.36	7.25	0.04	207.77
World average export price	USD/ton	9 447	3.22	3.20	0.20	61.70
Rainfall	mm	9 446	952	672	51	3 240
Average annual logarithmic growth rate of						
- the country specific export price		9 447	-0.06	1.16	-8.54	8.18
- the world average export price		9 447	-0.25	0.47	-2.14	1.87

4. Main estimation results

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

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

where ε_{ikt} is as zero mean noise term. According to equation (11), we expect the global price p_k and the green water footprint $GreenWF_{ik}$ to have a positive effect on irrigation, and rainfall $Rainfall_i$ to have a negative effect. We have no direct measure for countries' marginal cost of irrigation r_i , which reduces the use of irrigation. This cost may be reflected in the country-specific export price p_{ik} , or absorbed by country-specific fixed effects.

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 statistically non-significant coefficient for the country-specific export price. These findings indicate that countries base their decision to irrigate on the price at which products can be sold on the global market, and are consistent with general assumptions 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 rainfall) irrigate less. This confirms our expectation that irrigation is less necessary in areas with natural water abundance. The positive and strongly significant coefficient for the green water footprint confirms that water-intensive crops require more irrigation.

In column (2) of Table 2, we add product fixed effects. The latter are collinear with the global export price p_k , which is dropped from the estimation. Note that the effect of the country-specific export price remains non-significant. This points out that countries' irrigation response to the export price is driven by variation across products.⁵

The estimation in column (3) includes country fixed effects, and drops the collinear rainfall variable. Exporter fixed effects control for the average level of countries' export price, as well as for irrigation costs. In this case, the effect of both global and country-specific export prices are positive and significant. We interpret this result as follows. Not only do countries irrigate more intensively products with higher global prices, but also they irrigate more intensively the products they are able to sell at a higher price.

To explore the variation of the export price across time, in columns (4), (5), and (6) of Table 2 we add the average annual growth rates of these variables. This permits to include additional information on the yearly variation of prices, even though our estimated equation has no time dimension.⁶ Results are similar to our baseline estimation in column (1), and, in addition, show that products with an increasing global price benefit from a more generous irrigation. This confirms that countries intensify their irrigation efforts for products for which they expect a better remuneration on the global market in the years to come.

In the last two columns, we split the sample according to countries' trade balance on the irrigated (and exported) products. Unsurprisingly, the global export price has a significant effect only for net exporters. Indeed, 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 finding 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.

⁵ Indeed, variable p_{ik} brings little additional information with respect to p_k and other explanatory variables. The coefficient of p_{ik} is barely significant even when we drop p_k from the estimation. We also explored the variation of country-specific export price p_{ik} across countries for the same globally traded product and across products exported by the same country (results can be provided upon request). We found that the positive effect of p_{ik} comes mainly from differences across products exported by the same country, and to a lower extend by cross-country differences in the price of a given product. The effect of the price on the top 5% most expensive products exported by a country is 1.6 times stronger than the effect for the top 50% most expensive products.

⁶ Alternative measures capturing the time distribution of these variables (*e.g.* standard deviation and inter-quartile distance) are highly correlated with the mean values (already included in the estimation) and do not bring any additional information. Data on annual precipitations and other explanatory variables present small fluctuations across time. Adding the average growth rates of these variables into the estimation yields no statistically significant effects.

5. Product-level effects

As an illustration of the results found in section 4, in Figure 1 we picture the correlation between the blue (irrigation) water footprint and the export unit value in the United States, for unprocessed crops for which the country is a net exporter. It seems that 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 this product (accounting for 88% of world exports in 2017 according to USDA, 2018). 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.

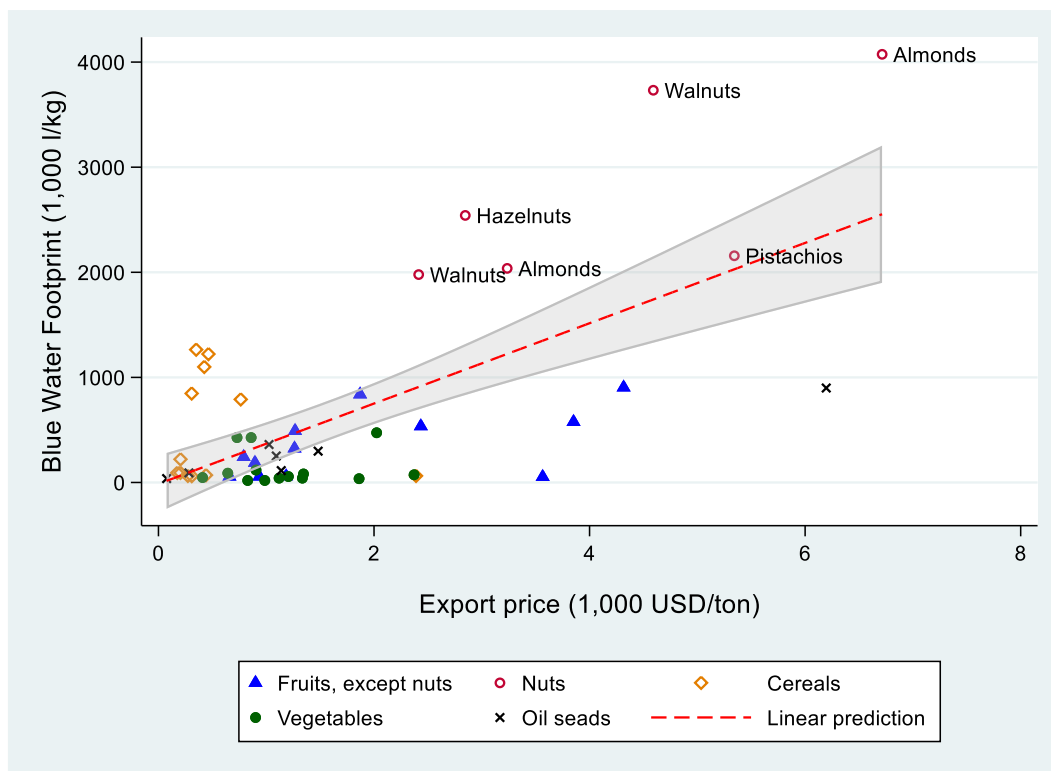
Differently, for cereals the correlation between irrigation and export price is very small, and reflected in Figure 1 by an almost vertical line. Cereals are irrigated despite their relatively low export price per ton with respect to other crops. This observation is consistent with the assumption that 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 meeting food security targets (Mendez-Parra *et al.*, 2016).

These observations suggest that the link between export price and countries irrigation behavior tends to be stronger for heavily exported products, such as nuts, but weaker for commodities essential for meeting domestic food security objectives, such as cereals and other field crops. In the same line of thought, estimation results discussed in section 4 (column (2) of Table 2) indicate that most of the price effect on countries' irrigation behavior is related to the choice of irrigated products. This calls for an analysis of our model at the level of specific groups of products.

Table 2: Baseline estimations

	Full sample				Net exporters Net importers			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Country-specific export price (p_{ik})	9.17 (9.52)	-2.06 (5.53)	10.25 * (5.40)	9.28 (9.49)	9.79 (9.54)	9.87 (9.51)	25.39 (21.68)	-3.25 (6.73)
World average export price (p_k)	79.79 ** (36.99)		88.20 *** (12.86)	79.55 ** (36.96)	79.64 ** (36.88)	79.47 ** (36.88)	112.44 * (63.25)	44.16 (27.53)
Green water footprint	0.20 *** (0.08)	0.20 *** (0.01)	0.22 *** (0.01)	0.20 *** (0.08)	0.20 *** (0.08)	0.20 *** (0.08)	0.19 * (0.10)	0.22 *** (0.06)
Rainfall	-0.84 *** (0.07)	-0.77 *** (0.05)		-0.84 *** (0.07)	-0.84 *** (0.07)	-0.84 *** (0.07)	-0.82 *** (0.11)	-0.86 *** (0.09)
Growth p_{ik}				10.64 (22.31)		7.51 (22.08)		
Growth p_k					158.61 * (84.66)	157.70 * (84.41)		
Fixed effects	no	product	country	no	no	no	no	no
Number obs	9446	9446	9446	9446	9446	9446	4931	4515
R ²	0.16	0.242	0.256	0.16	0.16	0.16	0.179	0.137
Fisher test	64.547	317.995	657.218	53.26	51.99	44.88	36.143	35.202

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

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.

To explore this issue into more detail, we estimate equation (12) separately for broad groups of substitutable products, in both agronomical and consumption terms, and display results in Table 3.⁷ To ease comparison, column (1) reports the results on the entire sample (the same as in column (1) of Table 2). We find sizable differences across product groups, both in terms of the magnitude and the significance of effects.

We find no effect of the global price for field crops, as well as for none of its narrower groups (“cereals, flours, and starch” and “oilseeds and vegetable oils”). Indeed, field crops (cereals, oilseeds and vegetable oils) are farmed by a large number of countries with very different climate and water endowments, and are largely traded internationally. Moreover, these products constitute staple food worldwide, and are cultivated primarily for food security reasons. In addition, most field crops are traded on highly integrated global markets, and are

⁷ We do not report results separately for sugar, textiles, and tobacco, although we include them in the full sample. Each of these categories counts a small number of products, and dissimilar from the rest of groups and difficult to merge with other products.

easily stored and transported. Due to their lower perishability, producers can afford to postpone export if the market price is judged too low.

The effect of the global price is positive and statistically significant for the rest of product groups. The effect is particularly strong for leguminous crops in column (3). The positive effect for the orchards group in column (5) is driven mainly from the strong positive effect on coffee, tea, cacao, spices (column (5b)) and to a lower extent by fruit and nuts (column (5a)). The negative effect of the country-specific price found for leguminous and vegetables shows that, on average, countries fail to export these products to markets paying the highest price.

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Table 3: Effects by product groups

	all products	field crops	leguminous	vegetables	orchards	fruit & nuts	coffee & tea & cocoa & spices
	(1)	(2)	(3)	(4)	(5)	(5a)	(5b)
Country-specific export price (p_{ik})	9.17 (9.52)	2.06 (6.07)	-38.53 * (19.68)	-1.56 ** (0.63)	12.09 (19.24)	-3.68 (9.96)	9.29 (53.71)
World average export price (p_k)	79.79 ** (36.99)	-76.26 (95.50)	544.60 ** (247.89)	28.65 *** (5.86)	58.24 ** (29.32)	38.83 * (21.04)	137.49 ** (55.15)
Green water footprint	0.20 *** (0.08)	0.29 ** (0.14)	0.19 *** (0.07)	0.13 *** (0.02)	0.27 *** (0.09)	0.25 *** (0.07)	0.30 ** (0.12)
Rainfall	-0.84 *** (0.07)	-0.82 *** (0.15)	-0.57 *** (0.11)	-0.08 *** (0.01)	-1.58 *** (0.18)	-1.13 *** (0.11)	-2.59 *** (0.55)
Constant	818.53 *** (163.83)	962.36 *** (108.01)	-191.72 (413.47)	93.06 *** (13.71)	1369.18 *** (251.63)	1311.28 *** (146.96)	1098.32 (842.60)
Number obs	9446	2808	557	1806	3056	2470	586
R ²	0.160	0.086	0.113	0.138	0.277	0.142	0.447
Fisher test	64.55	31.10	10.74	39.41	30.28	29.88	9.55

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

6. Conclusion

A recent trend of literature investigates how virtual water 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. These works consider water as a production input and measure its economic value using irrigation costs. 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 the 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 243 irrigated crops exported by 185 countries, and find that countries' irrigation behavior is strongly linked to the global price of crops. Countries irrigate more intensively the higher-priced products. The effect remains significant when we control for the average level of a country's export price. In addition, countries irrigate more the products with the highest increase in global price. Our results also shows that the irrigation behavior is shaped by the global (expected) price rather than the country-specific export price. The export price effect is stronger when countries are net exporters of the irrigated crops and varies greatly across product groups. For instance, we find a non-significant effect for field crops. Hence, our findings indicate that agricultural producers internalize the price of irrigation water when choosing which crops to irrigate.

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 on output support and trade policies. At the scale of our sample, our results confirm this idea, suggesting that a change in the expected price 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. Accordingly, all variables in the estimated model are annual average over the same period. This limits the validity of our results with respect to time variations. Ideally, we would like to

use annual water footprints and explain countries' irrigation decisions by export prices observed in the past (with a one-year lag). A natural extension of the present analysis would be to employ time-varying data.

Another possible extension of our work is account for differences across countries in the efficiency of their irrigation systems, and in their water pricing and distribution policies. Rich countries may irrigate more intensively due to 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. Similarly, underpricing irrigation water may lead to an overuse of water resources and to the perpetuation of inefficient irrigation systems. Testing these hypotheses requires information on the irrigation technology, pricing and distribution at country and product level. This would enrich our understanding of the effects of public intervention on water use.

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