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Catherine Laroche-Dupraz, Angela Cheptea

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Article

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Angela Cheptea [1,*] and Catherine Laroche Dupraz [2]

[1]UMR 1302 SMART-LERECO, INRAE, Rennes, France
[2]UMR 1302 SMART-LERECO, L'Institut Agro – AGROCAMPUS OUEST, Rennes, France

*Corresponding author: UMR 1302 SMART-LERECO, French National Research Institute for Agriculture, Food and Environment (INRAE) 4, Allèe Adolphe Bobièrre, CS 61103, 35011 Rennes Cedex, France. Tel: ; E-mail: angela.cheptea@inrae.fr

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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. We develop a simple model establishing a positive link between the demand for irrigation water of agricultural producers and the international price of irrigated crops. Unlike previous works that focus on the cost and scarcity of water resources, we emphasize the role of international trade in the allocation of water resources in agriculture. We test our model empirically using data on 243 irrigated crops exported by 183 countries, and find that countries' irrigation behavior is strongly linked to the global price of crops. The export price effect is stronger when countries are net exporters of irrigated crops and weaker for cereals that constitute a pillar of most countries' domestic food security.

Keywords: Irrigation, Water resources, Virtual water, International trade, Agri-food products

JEL codes: Q15, Q17, Q25, Q27, F18

1 Introduction

The amount of water used to produce a good or service is referred in the recent literature as *virtual water* or *water footprint*.[1] The concept of virtual water, introduced in the early 1990s, 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 term *virtual water trade*, which was rapidly identified as a potential indicator for guiding policy makers on issues related to water use, water scarcity, and water management (Antonelli and Sartori, 2015). International trade indirectly brings about a 'virtual' redistribution of global water resources. 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. 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. These works separate the *green water*, which corresponds to rainfall water, from the *blue water*, which corresponds to irrigation water brought in surplus on farming plots.

Most of the existing literature aims to quantify virtual water flows between countries, and to assess the role of international trade in mitigating or increasing water scarcity. Based on the observation that as much as 20–24 per cent of water resources embedded in food production are internationally traded, Rosa *et al.* (2019) highlight that domestic and international demand for agricultural products generate unsustainable irrigation practices worldwide. Our work complements this assertion of the globalized dimension of unsustainable irrigation. In this paper, we analyze the market incentives of observed irrigation practices. More specifically, we show how world food prices affect the demand for irrigation water, which is reflected by the blue water footprint. We use data on 243 irrigated crops exported by 183 countries, and find that countries' irrigation behavior is strongly linked to the global price of crops.

Both concepts of water footprint and virtual water trade are employed almost exclusively with respect to agricultural products, for which water is an essential production input. Pioneer works on these issues led to the emergence of a 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. Debaere, 2014; Antonelli and Sartori, 2015; 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. Targeting an efficient use of water resources at country level, rather than globally, may lead to opposite conclusions. After examining changes in food trade patterns of eleven Southern and Eastern Mediterranean countries in relation to their water resources availability, Yang *et al.* (2007) argue that for water-scarce countries it is more efficient to domestically produce and export crops with a high water use value, such as vegetables and fruits, and to import water-intensive food commodities with a low water use value, such as cereals, vegetable oil, and sugar. These studies use virtual water 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. Wichelns (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, Wichelns' 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. Although irrigation greatly contributed to the development of agricultural production throughout the 20th century, the expansion of irrigation through extensive subsiding led to an overuse of the water resources, causing environmental damage and generating international conflicts over the allocation of resources (Schoengold and Zilberman, 2007). To reach a more reasonable use of water resources, Schoengold and Zilberman (2007) recommend that the price of water paid by the user should be linked to its marginal cost. 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. There is still a lack of policy-oriented approaches assessing whether countries should tailor their exports and imports to ensure water and food security, expend irrigated areas to reduce food import dependence, or develop other strategies for managing water resources (Yang *et al*., 2007; Novo *et al*., 2009). For instance, Novo *et al.* (2009) emphasize that the economic value of blue water is also important and that the opportunity cost of water should be reflected in trade patterns. We attempt to bridge this gap in the literature. The economic theory predicts that an increase in the price of a good induces a rise in the demand for its production factors. What we show in the present paper is that the demand for irrigation is induced to a great extent by the price of irrigated products on the global market. This shows that an efficient management of water resources should not ignore the country's involvement in international trade and its trade strategy.

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.* (2020) 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 abovementioned works. Tuninetti *et al.* (2017) use the average country-level agricultural production costs to value virtual water of internationally traded 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 Spain. In line with Schoengold and Zilberman (2007), authors recommend the use of alternative socioeconomic indicators to improve the assessment of the real opportunity cost of water. Fracasso (2014) and Fracasso *et al.* (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 potential value of irrigation water as a production input. Precisely, we consider the price of agricultural and food products on the international market.

More specifically, we question whether a country's irrigation choices depend 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. We illustrate the presence of a direct link between the volume of traded virtual water and the price of agricultural products, based on a data panel covering a large number of unprocessed products and trading countries. Unlike previous works, which focus on the cost of water resources, we adopt a perspective based on the demand for water resources in agriculture. Our analysis sheds light on how the established international trade patterns lead to a more or less intensive use of irrigation water for 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 cereals and of products for which countries are net exporters. Our main conclusions 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 (Debaere, 2014; Antonelli and Sartori, 2015; 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 export revenues of arid Central Asian countries. All these specializations arise due to an intensive use of irrigation.

Schoengold and Zilberman (2007) show the primordial role played by irrigation in minimizing the risk of production and in limiting the variance of farmers' profits using a model where farmers decide how much of their land to allocate to irrigation. Contrary to this work, we consider the farm-level irrigation infrastructure and land allocation to irrigation as given, farmers choosing only which products to irrigate, i.e. to cultivate on the effectively irrigable surfaces.

Since irrigation is costly, we expect that countries irrigate more intensively 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 irrigation behavior 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

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

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 $0 < \alpha_k < 1$. Parameter α_k reflects how water intensive is product k.

As in a standard Heckscher–Ohlin trade model, we assume fixed factor endowments for all countries and perfect factor mobility across sectors (within each country), but none at the international level (across countries). These assumptions lead to factor price equalization across sectors (cultivated crops) in each country. Let c_i and r_i represent the marginal cost of the composite factor and, respectively, water in country 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):

$$W_{ik} = BlueW_{ik} + GreenW_{ik}. \tag{2}$$

Similarly to other factors of production, water resources are assumed limited at country level.[2] Farmers decide only how much to irrigate each crop, and take the amount of rainfall as exogenous and costless.

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 taking as given the technological and endowment constraints, the country-specific costs of production factors, and the world prices of cultivated crops:

$$\pi_{ik} = p_k \cdot y_{ik} - c_i \cdot X_{ik} - r_i \cdot BlueW_{ik}. \tag{3}$$

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 do not have an explicit market for water resources, and we observe a great diversity in the way countries manage water access and establish water bills. We assume that the cost of irrigation water for agricultural producers r_i is fixed by domestic policy makers in accordance with the level of domestic support to the agricultural sector, not by an open intersectoral water market.[3] Also, we let the composite factor X_i to be used in a non-traded sector (e.g. housing) together with a sector-specific factor F_i. The domestic market equilibrium in this sector determines the marginal cost of the composite factor, c_i. Therefore, in our case, trade does lead to factor price equalization across countries, contrary to the traditional Heckscher–Ohlin model.[4]

Using equations (1) and (2) in (3), and considering that rainfall water comes at no cost, we obtain

$$\pi_{ik} = p_k \cdot X_{ik}^{1-\alpha_k} \cdot \left(BlueW_{ik} + GreenW_{ik}\right)^{\alpha_k} - c_i \cdot X_{ik} - r_i \cdot BlueW_{ik}. \tag{4}$$

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

$$X_{ik} = \frac{1-\alpha_k}{\alpha_k} \cdot \frac{r_i}{c_i} \cdot \left(BlueW_{ik} + GreenW_{ik}\right). \tag{5}$$

Farmers in each country i chose only the amount of production factors X_{ik} and $BlueW_{ik}$ to allocate to each product k, yielding the optimal production level y^*_{ik} that maximizes producer profits:

$$y^*_{ik} = \left(\frac{1-\alpha_k}{\alpha_k}\right)^{1-\alpha_k} \cdot \left(\frac{r_i}{c_i}\right)^{1-\alpha_k} \cdot \left(BlueW_{ik} + GreenW_{ik}\right). \tag{6}$$

As price takers, farmers consider world prices p_k as exogenous.[5] Still, first-order conditions imply that the following identity holds at equilibrium:

$$(c_i)^{1-\alpha_k} \cdot \ (r_i)^{\alpha_k} = p_k \ \cdot (1-\alpha_k)^{1-\alpha_k} \cdot (\alpha_k)^{\alpha_k}. \tag{7}$$

Combing equations (6) and (7), we can express the irrigation water used in each country i for each product k:

$$BlueW_{ik} = y^*_{ik} \ p_k \alpha_k r_i^{-1} - GreenW_{ik}. \tag{8}$$

We do not have data on the amount of green and blue water used for each crop in each country. However, we have information on the use of water resources per unit of cultivated crop, i.e. water footprints: $BlueWFP_{ik} = \frac{BlueW_{ik}}{y^*_{ik}}$ and $GreenWFP_{ik} = \frac{GreenW_{ik}}{y^*_{ik}}$. Without loss of generality, we can divide the left- and right-hand terms of equation (8) by the produced quantity:

$$BlueWFP_{ik} = p_k \ \alpha_k r_i^{-1} - GreenWFP_{ik}. \tag{9}$$

This not only solves the missing data problem but also permits to account for the fact that producers can sell the cultivated crops or the processed agricultural products obtained from these crops.[6]

Note that $BlueWFP_{ik}$ represents producers' *use of irrigation water per unit of produced good*.[7] Equation (9) shows that farmers' use of irrigation decreases with the cost of irrigation (r_i) and with the green water footprint ($GreenWFP_{ik}$). On the opposite, farmers tend to irrigate more intensively water-intensive products (with large α_k) and products traded at a higher price (p_k). This equation is consistent with a classical result in economic theory that the demand for a production factor—here irrigation water—increases with the price of the product. It is precisely the strength of this effect that we aim to measure, all things equal.

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.

3 Data for the empirical analysis

The current 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 8 in Section 2). For variables $BlueWFP_{ik}$ and $GreenWFP_{ik}$, we use the data computed by Mekonnen and Hoekstra (2011a, 2011b, 2016).[8] This database provides information on blue and green water footprints for 353 agricultural products of the HS classification[9] in 207 countries and territories, computed as an annual average over the 1996–2005 period. Therefore, we cannot exploit the temporal variation of the data, including of explanatory variables.

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),[10] 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 10 years. Accordingly, we assume that farmers decide only which products to farm on irrigated plots.

Green water footprints reflect the rainfall water captured by each crop in each country, measured in m^3 of rainfall water per ton of product. Mekonnen and Hoekstra (2011a, 2011b, 2016) compute green water footprints by taking into account country- and product-specific agronomic production systems.

Testing the model described in Section 2 requires information on the water intensity of each product, regardless of the place of growth, captured by parameter α_k. We proxy this parameter by the product-specific variation in the use of water resources across products and countries. More specifically, we regress the overall water footprint (blue plus green) for all products and countries in our panel on product-specific fixed effects. We associate the estimated coefficient of the fixed effect corresponding to product k with the water intensity of this product (α_k). We recalibrate the magnitude of parameters α_k such that they take values in the interval $]0; 1[$. By construction, parameters α_k capture only a share of the variation in blue water footprints across products. We adopt this solution rather than including product fixed effects for two reasons. First, using product fixed effects does not permit to estimate the effect of product prices (p_k), which also vary only across products. Second, a proxy for α_k permits to estimate its effect on the use of irrigation water per product (our dependent variable).[11]

We use the export price as a proxy for the market value of each irrigated 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 (six digits of the HS classification).[12]

World average export prices (p_k) reflect the expected price on the global market. We obtain these prices from unit values from the BACI trade database,[13] computed as the ratio between the monetary value of exports (in USD) and the amount of traded products expressed in physical units (tons). Since BACI trade data are in FOB terms,[14] export unit values are not inflated by trade costs (e.g. higher prices for products shipped to more remote markets, products that require special transportation and storage facilities, or products that face high import tariffs). We observe a high variation of unit values across destinations, for a given exporting country and good. Small or exceptional trade flows do not report consistently both types of data (value and volume), generating a few aberrant unit values. To exclude these outliers, for each product k we drop the bottom 5 per cent and the top 5 per cent of unit values in the data. Similarly to water-intensity parameters α_k, we compute global prices by isolating the variation of unit values across the product dimension. We achieve this by regressing annual bilateral unit values on product fixed effects and associate the price of product k to the parameter estimate of the corresponding fixed effect. This approach is in line with empirical works on international trade that use origin and destination fixed effects to control for prices (e.g. Hillberry and Hummels, 2003) and similar to Baldwin and Harrigan's (2011) analysis of the variation of unit values across space.[15]

In the absence of data on the true cost of irrigation in each country (r_i), in equation (9) we use country-specific fixed effects to control for this variable. This approach does not permit to estimate the effect of irrigation cost, but yields unbiased estimates of the effect of our main variables of interest (price and water intensity) on countries' irrigation behavior. To check the robustness of our results, we also use two alternative country-specific control variables that may or may not be linked to the irrigation cost:

— The level of country's average annual rainfall in mm. It reflects the country's level of water abundancy. Water-abundant countries should have a lower irrigation cost. At the same time, the presence of costless alternative water resources implies lower irrigation needs. Therefore, the effect of this variable on countries' irrigation practices is ambiguous.

Table 1. Descriptive statistics.

Variable		Unit	Nb obs	Mean	Std. Dev.	Min	Max
Blue water footprint	$BlueWF_{ik}$	m^3/ton	9,447	816	3,696	0	150,204
Green water footprint	$GreenWF_{ik}$	m^3/ton	9,447	2,526	6,452	4.00	279,397
Product-specific water intensity	α_k	$\in]0; 1[$	9,447	0.039	0.066	0.000	0.999
Product-specific world price	p_k	USD/ton	9,447	3.106	3.234	0.156	68.683
Rainfall	$Rainfall_i$	mm	9,446	952	672	51	3,240
Per capita GDP		USD	9,404	8,108	10,865	130	44,334

— The country's per capita GDP. Irrigation infrastructure is costly and requires a minimum amount of initial investment and maintenance. This suggests that low-revenue countries have less access to irrigation. At the same time, more efficient irrigation systems are also more expensive, both because of the technological advance and the higher energy use. Therefore, it is interesting to test whether rich countries actually use less irrigation water.

Data on both these variables are obtained from the World Development Indicators database of the World Bank.

For each country, data on water footprints cover only unprocessed agricultural commodities (e.g. wheat) and their domestic first-stage transformation (e.g. wheat flour, pasta). For processed products, water footprints correspond to a situation where only domestic inputs are used in the production process. Thus, the water footprint of Italian pasta corresponds to the water footprint of embedded Italian (not imported) wheat. However, exported processed products may have been obtained from the transformation of imported commodities (e.g. Italy exports pasta produced from imported wheat or wheat flour). Trade data do not permit to separate products according to the origin of commodities, and the share of imported inputs in a country's exports increases with the level of processing. To ensure that the data on water footprints and on exports correspond to the same domestically produced goods, we exclude highly processed products from our database. This eliminates agri-food products obtained from imported commodities, such as English tea produced from imported tealeaves. Our final database after these adjustments covers 243 products (HS six-digit codes) and 183 countries. Table 1 summarizes the descriptive statistics for variables in our data panel.

4. Main estimation results

Equation (9) predicts that the export price and water intensity have a positive effect on the use of irrigation water per product, while the cost of irrigation and the green water footprint have a negative impact. We start by estimating this prediction assuming a log-linear relationship between the explained and explanatory variables:

$$\ln BlueWF_{ik} = \beta_0 + \beta_1 \cdot \ln p_k + \beta_2 \cdot \ln \alpha_k + FE_i + \beta_3 \cdot \ln GreenWF_{ik} + \varepsilon_{ik}, \tag{10}$$

where country fixed effects FE_i control for the marginal cost of irrigation and ε_{ik} is a zero-mean noise term.[16] This log-linear transformation of equation (9) permits to differentiate between the technical and economic determinants of irrigation demand. Technical factors of irrigation are captured here by the water intensity parameter and the green (rainfall) water footprint, while the export price reflects the main economic factor. To our knowledge, the economic determinants of irrigation were not previously addressed in the literature.

Results from estimating equation (10) are displayed in column (1) of Table 2.[17] We find confirmation of our main predictions: crops with a high global export price and

Table 2. Determinants of the demand for irrigation water: linear relationship.

	Explained variable: ln $BlueWF_{ik}$				
	(1)	(2)	(3)	(4)	(5)
ln Export price (p_k)	0.24***	0.13**	0.13**	0.20***	0.18***
	(0.04)	(0.06)	(0.05)	(0.05)	(0.05)
ln Water intensity (α_k)	0.29***	0.67***	0.46***	0.72***	0.51***
	(0.04)	(0.06)	(0.05)	(0.05)	(0.05)
ln Green water footprint ($GreenWF_{ik}$)	0.23***	−0.29***	0.04	−0.41***	−0.07
	(0.05)	(0.08)	(0.07)	(0.08)	(0.07)
ln Rainfall			−1.05***		−1.00***
			(0.11)		(0.11)
ln Per capita GDP				−0.28***	−0.21***
				(0.09)	(0.08)
Fixed effects	Country	No	No	No	No
Number of observations	8,777	8,777	8,776	8,736	8,735
R^2	0.617	0.140	0.278	0.174	0.297

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

water-intensive crops are irrigated more intensively ($\beta_1 > 0$; $\beta_2 > 0$). Contrary to our expectations, the green water footprint seems to enter the equation with a significant positive effect. This result is due to the high correlation of the green water footprint with our measure of water intensity: Corr ($\ln \alpha_k$; $\ln GreenWF_{ik}$) = 0.758, indicating that abundance of green water implies specialization in crops with high water intensity. Hence, the effect of the green water footprint estimated in Table 2 comes essentially from the variation of this variable across countries. When country fixed effects are included in the estimation (column 1), the effect of the green water footprint corresponds only to the residual variation of this variable, after purging its variation across the country and product dimensions. The estimate of parameter β_3 becomes negative when we drop country fixed effects (column 2), or replace the latter by per capita GDP (column 4). This parameter becomes statistically non-significant when we include rainfall as an additional country-specific control variable (columns 3 and 5) because green water footprint and rainfall refer to the same source of water.[18]

Both per capita GDP and rainfall affect negatively the demand for irrigation water. These findings indicate that farmers irrigate less when cultivated crops receive alternative water resources from rainfall (measured by green water footprint or rainfall), and suggest that the irrigation systems of rich countries incur smaller water losses. Different irrigation patterns for rich and poor countries may arise from differences in the efficiency of their irrigation systems, as well as 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, rich countries generally 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. Moreover, Berbel *et al.* (2015) and Sears *et al.* (2018) highlight that water-saving investments may lead to increased water use and/or consumption (a rebound effect) due to an increase of irrigated areas and/or energy use.[19]

Next, we estimate equation (9) respecting the non-linear functional form. This permits to include observations with no irrigation ($BlueWF_{ik} = 0$) that were dropped in Table 2. We fix the way in which variable $GreenWF_{ik}$ enters into equation (9) and estimates the coefficients corresponding to the rest of the explanatory variables:[20]

$$BlueWF_{ik} = \gamma_0 \cdot (p_k)^{\gamma_1} \cdot (\alpha_k)^{\gamma_2} \cdot (FE_i) \cdot \upsilon_{ik} - GreenWF_{ik}, \tag{11}$$

Table 3. Determinants of the demand for irrigation water: non-linear structural form.

	Explained variable: $BlueWF_{ik}$			
	(1)	(2)	(3)	(4)
Export price (p_k)	0.17***	0.11***	0.14***	0.15***
	(0.01)	(0.02)	(0.01)	(0.01)
Water intensity (α_k)	0.63***	0.66***	0.64***	0.64***
	(0.01)	(0.01)	(0.01)	(0.01)
Rainfall		−0.04		−0.04
		(0.03)		(0.03)
Per capita GDP			−0.21***	−0.21***
			(0.02)	(0.02)
Fixed effects	Country	No	No	No
Number of observations	9,447	9,446	9,404	9,403
R^2	0.748	0.648	0.700	0.701

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

where γ_0, γ_1, and γ_2 are the estimated parameters and υ_{ikt} is a zero-mean error term. Results are reported in Table 3. All explanatory variables enter the model with the expected sign: $\gamma_1 > 0$; $\gamma_2 > 0$. We also obtain a much higher fitted power of the model compared with Table 2. Even in the absence of fixed effects, right-hand-side variables explain two-thirds of the differentiated use of irrigation water across products and countries. This emphasizes the importance of the correct functional form when estimating the model. In columns (2)–(4), we add the same country-specific variables as in the last three columns of Table 2. Unsurprisingly, since all estimations in Table 3 include the green water footprint, the impact of rainfall on irrigation is no longer significant.

Overall, we find a positive and significant coefficient for the global price of the irrigated product. This result indicates that countries' demand for irrigation water depends on the price at which products can be sold on the global market, which is consistent with the general assumptions of international trade models. Our data on product- and country-specific irrigation (blue water footprints) lack time variability. Therefore, the estimated price effect reflects how differences in prices across products affect countries' choice of which products to irrigate and how intensively. Our results highlight the strong role of economic incentive reflected by the international price of crops on irrigation practices of farmers in different countries. To our knowledge, this mechanism was never revealed in the literature on water resources. This economic mechanism comes on top of technical drivers of irrigation usually considered in the literature. In accordance with our expectations, we find that water-intensive products are irrigated more intensively. We also find confirmation for the fact that water-abundant countries (with higher levels of rainfall) and high-revenue countries use irrigation water more efficiently.

5. Price effects differentiated by products and countries

In this section, we investigate how the effect of product prices in the global market on irrigation practices, established and discussed in Section 4, varies across our sample. The heterogeneity of priorities and constraints faced by producers of various crops in different countries may yield a differentiated response in their irrigation practices to changes in product prices.

First, we test whether there is a difference in the effect of the export price on the blue water footprint for cereals and the rest of crops. Unlike the rest of products, cereals are staple food crops, essential for feeding the world population and for reaching food security. Cereals are farmed by a large number of countries with very different climate and water endowments,

Table 4. The effect of the export price on irrigation: cereals vs other products.

	Explained variable: $BlueWF_{ik}$ (non-linear structural form)				
	Full sample (1)	Cereals (*stricto sensu*) (2)	Rest of crops (3)	Cereals (*lato sensu*) (4)	Rest of crops (5)
Export price (p_k)	0.17***	0.02	0.19***	0.00	0.20***
	(0.01)	(0.02)	(0.02)	(0.01)	(0.02)
Water intensity (α_k)	0.63***	0.90***	0.63***	0.85***	0.63***
	(0.01)	(0.11)	(0.01)	(0.03)	(0.01)
Fixed effects	Country	Country	Country	Country	Country
Number of observations	9,447	776	8,671	1,918	7,529
R^2	0.748	0.736	0.751	0.738	0.759

Notes: Standard errors in parentheses. ***, ** and * indicate statistical significance at 1, 5, and 10 per cent. The *stricto sensu* definition of the cereals group covers 14 crops; the *lato sensu* definition includes 21 additional primary transformation products of these crops.

and are largely traded internationally. In the case of cereals, these aspects (not captured by the model) may prevail over economic determinants, leading to a weaker sensitivity of irrigation behaviors to differences in the export price. 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 with 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 too low.[21]

There are fourteen non-transformed cereal crops and twenty-one primary transformation products of these crops in our data sample. In Table 4, we estimate equation (11) separately for cereals and the rest of crops. The first column recalls results for the entire sample, the same as in column (1) of Table 3. The export price effect on the blue water footprint is statistically non-significant from zero for cereals, but positive and significant for the rest of products in our sample. This result is confirmed when we confine the cereals subsample to non-transformed cereal crops in our data (a *stricto sensu* definition), as well as when we include first-transformation products of these crops (a *lato sensu* definition).[22]

Second, we question whether the price effect varies across net importing and net exporting countries. We expect the effect to be stronger for countries that are net exporters of the irrigated product, because in this case a large share of production is oriented to international markets. This assumption 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 this hypothesis, we split the sample according to countries' trade balance for each irrigated product. We estimate equation (11) on each subsample and display results in Table 5.

For each product, we identify countries as net exporters or net importers based on the sign of their trade balance over the decade. In columns (2) and (3), we use the average trade balance over the analyzed decade. In columns (4) to (6), a country is considered a net exporter (importer) of a specific product if it had a positive (negative) trade balance in that product all years within the decade; this classification generates an intermediate group (column 5) of countries that are net exporters in some years and net importer in other years.

We find that the positive global price effect is twice as large for net exporters relative to net importers, and an intermediate effect for countries switching from net exporters to net importers or vice versa. Our results confirm the above hypothesis that countries where domestic production does not meet domestic demand (which appear as net importers) base their production decisions mainly on domestic market evolutions and are less attracted

Table 5. The effect of the export price on irrigation: net exporters vs net importers.

	Explained variable: $BlueWF_{ik}$ (non-linear structural form)					
	Full sample (1)	Net importers[a] (2)	Net exporters[a] (3)	Net importers[b] (4)	Intermediate[b] (5)	Net exporters[b] (6)
Export price (p_k)	0.17***	0.11***	0.22***	0.11***	0.15***	0.23***
	(0.01)	(0.02)	(0.02)	(0.03)	(0.02)	(0.02)
Water intensity (α_k)	0.63***	0.68***	0.60***	0.68***	0.63***	0.59***
	(0.01)	(0.03)	(0.01)	(0.03)	(0.02)	(0.02)
Fixed effects	Country	Country	Country	Country	Country	Country
Number of observations	9,447	4,515	4,932	2,795	3,533	3,119
R^2	0.748	0.755	0.757	0.748	0.765	0.766

Notes: Standard errors in parentheses. ***, ** and * indicate statistical significance at 1, 5, and 10 per cent.
[a]For each product, countries are identified as net exporters or net importers based on the sign of their average trade balance over the decade.
[b]A country is considered a net exporter (importer) of a specific product if it had a positive (negative) trade balance in that product over the entire decade (all years). This classification leads to an intermediate category of countries that switched from net exporters to net importers or vice versa.

by export opportunities. On the contrary, countries whose domestic production exceeds domestic demand (net exporters) are more sensitive to the evolution of foreign demand and more prepared to engage into complex international transactions.

Recall that our model assumes that producers (farmers) are price takers. Relaxing this assumption, i.e. allowing producers to be price makers, only amplifies our main findings. Indeed, if producers in a given country or region are the main global suppliers of a specific good (e.g. Californian almond producers), they may impose a higher global price for that product.[23] This reinforces the inefficient use of water resources induced by a high global price.

As an illustration, in Fig. 1 we picture the correlation between the blue (irrigation) water footprint and the export unit value in the USA, for unprocessed crops for which the country is a net exporter. It seems that the strong positive correlation between these variables is driven to a 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 m^3 per kg), the USA being the main exporter of this product (accounting for 88 per cent 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 droughts over the last decade. Differently, for cereals, the correlation between irrigation and export price is very small, reflected in Fig. 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).

6 Conclusion and policy implications

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

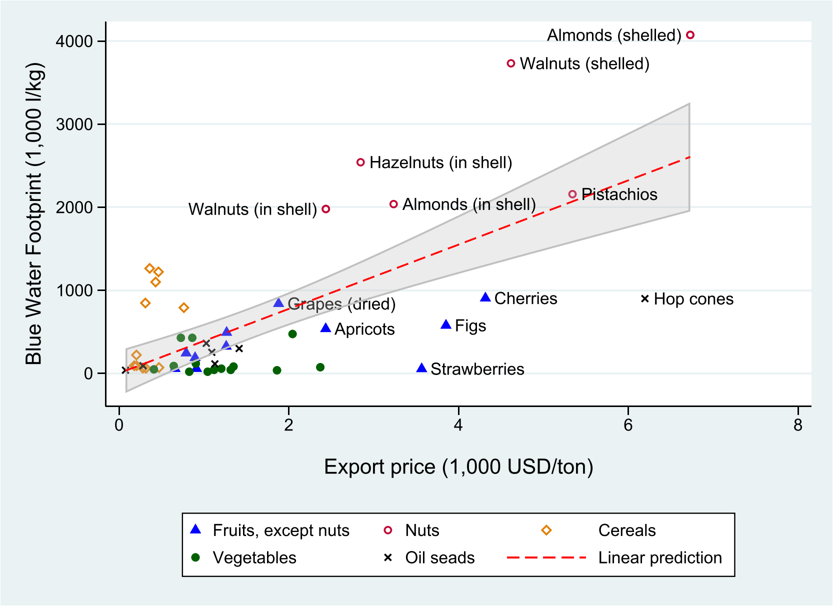

Figure 1. Blue (irrigation) water footprints vs export prices in the USA.

Notes: Median export price in 2005, blue water footprint annual averages over 1996–2005, all products within HS chapters 7–12 for which the USA was a net exporter.

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. Also, as suggested by Afkhami *et al.* (2020), land-abundant developing countries not particularly rich in water resources may have a comparative advantage in the production of agricultural goods and even become net exporters of virtual water if they lack other production factors (e.g. human and physical capital), which prevents them from specializing in industrial and service sectors.

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 183 countries, and find that countries' irrigation behavior is strongly linked to the global price of crops. In addition to the technical relationship according to which water-intensive crops require more irrigation, our model depicts the importance of an economic mechanism. Countries irrigate more intensively higher priced products for which they expect a better remuneration on the global market. The effect is stronger when countries are net exporters of the irrigated crops and statistically non-significant for cereals. Our findings indicate that agricultural producers internalize the price of irrigation water when choosing which crops to irrigate.

Our analysis relies on average annual water footprints computed over a decade. The absence of the time dimension in our data does not permit to explore interannual changes in irrigation and its drivers. Hence, we do not know whether annual variations in product prices have a stronger or weaker impact on irrigation practices than the annual variation in rainfall.

Our results are in line with the work of Diao and Roe (2003), who showed in the case of Morocco that the efficient allocation of water resources is dependent on not only the water pricing and distribution policies within agriculture but also the policies outside the water sector, and in particular on output support and trade policies. These authors illustrate that a highly protectionist trade policy explains the intensive use of irrigation in this country, a net importer of irrigated crops. Using an intertemporal applied general equilibrium model, they find that the elimination of import tariffs leads to an increase in the country's income due to a more efficient allocation of production factors including irrigation water across sectors, to the detriment of irrigated crops. Differently from these authors, we focus on countries' profit maximization strategies as potential exporters of irrigated crops. We show that global prices of irrigated crops drive the allocation of water resources in agriculture for a large panel of countries and products. Our results suggest that a change in the expected price perceived by the producers of exported goods could significantly modify private trade-offs concerning the development of irrigation systems across agricultural products.

These aspects should to be taken into account by policy makers at the regional level, especially in drought-prone areas where irrigation is massively used for the production of highly valued goods in export markets. Trade policies that affect the price of goods appear as a relevant channel to incite or reduce the use of irrigation water across products, and easier to implement than a differentiated water pricing policy, notably in developing countries. These policies can take the form of product-specific export taxes or binding export quotas linked to the embedded irrigation water. The unsustainable use of water resources can be limited also by adopting policy measures targeting importers, inspired by policy solutions designed (but not yet fully implemented) for limiting green gas emissions (e.g. a generalized carbon tax, emission quotas, and a world market for the latter). Still, one should account for the fact that, unlike green gas emissions that have global impacts, the effects of unsustainable water use arise mainly at the regional level. This raises an important challenge for future research on identifying the adequate and efficient policy tools. More generally, our results encourage countries to consider the impact that their specialization in more or less water-intensive crops may have on the use of domestic water resources when designing their agricultural and trade policies.

Supplementary material

Supplementary data are available at *QOPEN* online.

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Appendix A. A proxy for product-specific water intensity

Estimating the impact of prices in international markets on the irrigation practices of exporting countries, formalized in equations (10) and (11), requires information on how water intensive each product is. Note that water intensity, denoted by α_k in the paper, varies only across products. It captures information on how much water is necessary to cultivate a physical unit of crop, independently of where (in which country) this is done, and whether it relies on rainfall or irrigation water. Differences in geography and climate across countries may lead to important variations in the overall amount of water resources necessary to produce a given crop, as well as in the share of rainfall and irrigation water used in each country. Still, a water-intensive product requires a large amount of water resources regardless of the place where it is cultivated. In the absence of a direct measure of the water intensities, we construct a proxy for α_k based on the water footprint data from (Mekonnen and Hoekstra, 2011a, 2011b, 2016). We use the cross-product variation in the overall use of water resources to identify how water intensive each product is. We compute the overall water footprint of a product k cultivated in country i as the sum of its green (rainfall) and blue (irrigation) water footprints,[24] and regress the results on product-specific fixed effects θ_k and a zero-mean error term u_{ik}:

$$GreenWFP_{ik} + BlueWFP_{ik} = \theta_k + u_{ik}.$$

We normalize our estimates of product fixed effects $\hat{\theta}_k$ to take values between 0 and 1:

$$\tilde{\theta}_k = \frac{\hat{\theta}_k - \min_k \hat{\theta}_k}{\min_k \hat{\theta}_k - \max_k \hat{\theta}_k}.$$

The resulting parameters $\tilde{\theta}_k$ represent our proxy for product-specific water intensities α_k. Accordingly, the recalibrated estimate of the fixed effect corresponding to product k, $\tilde{\theta}_k$, represents the water intensity of this product.

According to these computations, vanilla beans are the most water-intensive product in the database, followed by cocoa butter, other cocoa products (paste, beans, etc.), coffee products, and only afterward by nuts. In Madagascar, the largest exporter of vanilla beans, over 400,000 m^3 of rainfall and irrigation water is used to produce a ton of this product. This high water footprint takes into account the fact that vanilla beans grow in tropical rain forests and it takes 6–9 months for vanilla pods to mature. On the opposite end, spinach, sugar beets, and lettuce appear as the least water-intensive products in the database. Indeed, due to their rapid growth (45–60 days to maturity), spinach and lettuce have one of the lowest overall water footprint. For example, in the USA, only 97 m^3 of rainfall and irrigation water is used to cultivate a ton of spinach and only 72 m^3 of water to cultivate a ton of lettuce. These crops rapidly transform water (and other) inputs into the harvested product.

Notes

1 This definition is used for example by Yang *et al.* (2007) and the Water Footprint Network (https://waterfootprint.org/en/water-footprint/what-is-water-footprint/). The amount of virtual water—the

water footprint—is usually measured in terms of cubic meters of water used per kg of produced good (m^3/kg).

2 A country's water resources (rainfall and groundwater) may be larger than the ones used in agriculture. Some of the country's rainfall may fall in forests, mountains, inhabited areas, etc. Moreover, some water resources are used as well in other sectors (e.g. energy, human consumption, etc.).

3 Schoengold and Zilberman (2007) point out that in many countries the price of water is kept well below the marginal value product of the water as an input. Therefore, the allocation of access rights to water resources is often done through non-market mechanisms, such as queuing or a system of rights based on historical references, which do not encourage a judicious use of resources.

4 This yields a more realistic trade model, since observed data confirm the absence of factor price equalization at the global level. In Section 4, we explore differences in water endowments and factor costs across countries in the observed data. A model with factor price equalization across countries would imply that the use of irrigation by product and country does not depend on country-specific variables other than the green water footprint.

5 As usual, global prices p_k are the result of global market clearing (global demand equals global production).

6 Alternatively, one could compute the total irrigation and rainfall water use from production and water footprint data: $BlueW_{ik} = BlueWFP_{ik} \cdot y^*_{ik}$ and $GreenW_{ik} = GreenWFP_{ik} \cdot y^*_{ik}$. However, this may lead to a selection bias because production data, e.g. from FAOSTAT, are not very well documented for poor countries, characterized by a high rate of subsistence farming. Moreover, including in the analysis both primary and processed products is also problematic because of double counting (absence of data on how much of each crop cultivated in each country is sold directly on the market and how much is transformed in processed products).

7 Blue water footprints measure the quantities that farmers actually use on each crop. These quantities include not only the amount of water absorbed by crops but also the waste due to inefficient irrigation.

8 These data are available at http://waterfootprint.org/en/resources/waterstat/.

9 The United Nation's HS (Harmonized System) classification of products is widely used for collecting trade data (https://unstats.un.org/unsd/tradekb/Knowledgebase/50018/Harmonized-Commodity-Description-and-Coding-Systems-HS).

10 To our knowledge, no database collects statistical data on the size of irrigated farming plots by product and country.

11 The computation of water intensities is explained in detail in Appendix A.

12 In addition, domestic prices are usually collected at a different (broader) level of product definition and mainly for primary, rather than processed, agricultural products. See for example FAOSTAT price data.

13 http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=37.

14 FOB (free-on-board) data are the values of the goods at the exporter's customs frontier, excluding costs associated with international transport, insurance, and import tariffs.

15 The main findings of the paper (in Sections 4 and 5) remain unchanged if we use an alternative method for obtaining product-specific export prices. For each pair of country and product, we computed the average of bilateral unit value across the country's export destinations, weighted by the share of each destination market in global agri-food imports. Then, we used the so-obtained country-specific prices (p_{ik}) to compute product-specific averages, weighted by the share of each country in global agri-food trade. We prefer the previous method because it is statistically more robust and unaffected by the choice of weights (which are not completely exogenous).

16 We cluster standard errors at country level to control for the correlation of error terms ε_{ik} for the same country.

17 In 670 observations of our data panel, there is no irrigation (the blue water footprint is equal to zero). We lose these observations when we use logs.

18 Unsurprisingly, estimations without country fixed effects yield a lower R^2 value.

19 Testing these hypotheses requires information on the irrigation technology, pricing, and distribution at country and product level, available for a limited number of countries and not easily comparable.

20 This also permits to control for the multicollinearity bias between green water footprint and water intensity, which is less important in levels than in logs: $\mathrm{Corr}(\alpha_k;\ GreenWF_{ik}) = 0.616$.

21 It would be interesting to conduct a similar analysis on all staple foods, including not only cereals but also roots, tubers, and pulses. Our data sample does not permit to explore this dimension due to the

low comparability of data for staple foods other than cereals related to the low number of countries irrigating the same product.

22 Results are confirmed when we use a dummy for cereals.

23 The oligopolistic/monopolistic price—corresponding to a situation when producers are price makers—is always above the price under free competition—corresponding to the situation when producers are price takers.

24 For most country-product pairs in the database, data on green and blue water footprints are both available or both missing. In a very few cases, only the green water footprint is available. In these cases, we replace the missing data on blue (irrigation) water footprint by zero, but this does not affect anyhow our constructed measure of water intensity.