Environment and Development Economics (2022), **27**, 470–490
doi:10.1017/S1355770X21000401

RESEARCH ARTICLE

Virtual water and the inequality in water content of consumption

Mohamad Afkhami,[1] Thomas Bassetti,[2] Hamed Ghoddusi,[3] and Filippo Pavesi[4,5]*

[1]Blend 360, Columbia, MD, USA; [2]Department of Economics and Management "Marco Fanno", University of Padova, Padova, Italy; [3]Orfalea College of Business, California Polytechnic State University, San Luis Obispo, CA, USA; [4]Carlo Cattaneo University (LIUC), Castellanza, VA, Italy and [5]Stevens Institute of Technology, Hoboken, NJ, USA
*Corresponding author. E-mail: fpavesi@liuc.it

(Submitted 9 November 2020; revised 16 September 2021, 12 November 2021; accepted 1 December 2021; first published online 21 March 2022)

Abstract
We present evidence that international trade may exacerbate the initial unequal distribution of hydric resources. This result is driven by the fact that countries exporting agricultural goods are relatively abundant (with respect to capital) in the combined availability of water and arable land but, in absolute terms, scarce in capital and not richer in water in comparison to more developed ones. Due to both the scarcity of capital and the lower relative price of natural resources with respect to capital, the total value of production in these developing countries is modest, implying that international trade can lead to a less even distribution of the water content of consumption. Policies sustaining water prices and, more generally, those of natural resources (or lower capital costs) may contribute to offsetting this effect and allow for trade to play a positive role in reducing the uneven distribution of water endowments.

Keywords: global water trade; Heckscher-Ohlin; international trade; virtual water; water crisis; water inequality

JEL classification: F14; F18; O13; Q25; Q27; Q56

1. Introduction

The availability of water is an essential element to human development (Mehta, 2014). Indeed, the numerous problems caused by the limited availability of hydric resources are well documented by the vast literature that explores the impact of water scarcity on crucial issues such as development, conflict, and food security (see, e.g., Famiglietti, 2014; Gleick, 2014; Schleussner *et al.*, 2016). Therefore, a major challenge ahead of the global development agenda necessarily involves avoiding or reducing water shortages at both the local and global levels (Jury and Vaux, 2007; Hanjra and Qureshi, 2010).

The importance of this issue is confirmed by stylized facts that clearly indicate a negative trend for both the level and the distribution of freshwater resources over time. This evidence is presented in figure 1, which displays four different measures of global trends in the availability of freshwater resources based on World Bank data. The top left panel

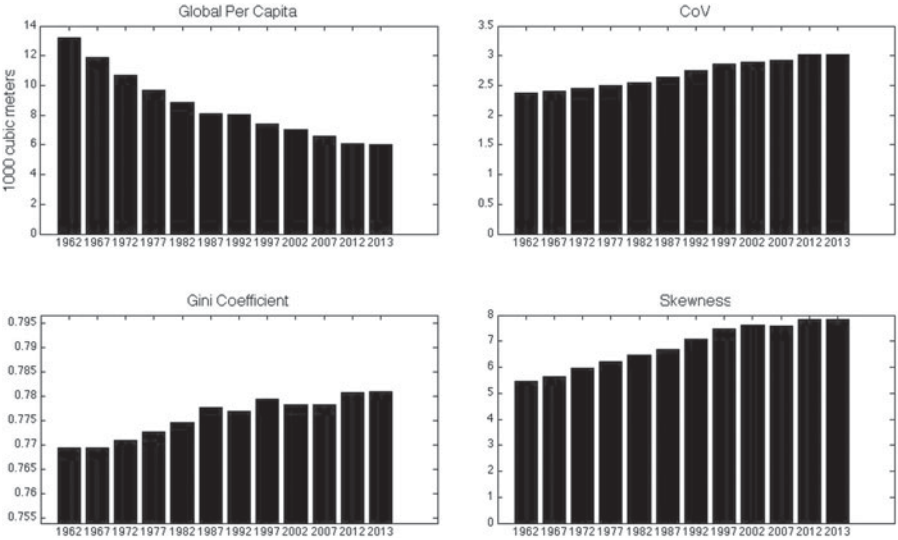

Figure 1. Dynamics of freshwater distribution over time.
Notes: The upper left panel shows the trend of global per capita endowment of freshwater. The upper right shows the coefficient of variation (CoV) for the per capita distribution of freshwater among more than 200 countries. The lower left panel is the Gini coefficient, and the lower right panel is the skewness of the per capita distribution of water.
Source of data: World Bank.

shows the evolution of per capita water endowments at the worldwide level and suggests that freshwater is becoming a scarcer resource. The other three panels of figure 1 illustrate the trends in the distribution of per capita water endowments. The top right panel shows the coefficient of variation (CoV) of the per capita distribution of water, the bottom left panel is the Gini coefficient, and the bottom right panel is the skewness of the distribution. All three reported statistics suggest that water distribution has become more unequal and also skewed over time.[1]

Based on these stylized facts, this paper investigates whether trade may alleviate the increased inequality in water endowments by allowing water-scarce regions to import water-intensive goods from water-abundant areas (Yang and Zehnder, 2002; Porkka *et al.*, 2017). We show that international trade may actually increase the ex-post inequality in the water content of consumption. In particular, we find that countries that export water-intensive goods are relatively abundant in natural resources (land and water) with respect to capital (both human and physical) but poorer in capital without being richer in water, in absolute terms, with respect to countries exporting capital-intensive goods. Therefore, since the total value of the production factors of countries that are relatively abundant in natural resources is modest, international trade can lead to a less even distribution of the water content of consumption. The likelihood of this happening depends on the relative price of natural resources with respect to capital factors. Indeed, for a given cost of capital, countries characterized by a relative abundance of natural resources with

[1]It should be noted that climate change and population growth have been identified as two main causes of water and food insecurity (Barnett *et al.*, 2005; Misra, 2014).

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

respect to capital will be more likely to reduce their water content of consumption, the lower are the prices of natural resources. Intuitively, this result is driven by the fact that, for relatively lower prices of natural resources compared to those of capital, the country that exports resource-intensive goods will receive a lower share of global income from international trade and will therefore be able to purchase and consume a smaller quantity of goods as a consequence of trade. Thus, policies devoted to sustaining water prices or increasing the costs of water depletion are particularly relevant, as are those that promote lower capital costs.

Our analysis relies on the notion of *Virtual Water* (VW), which refers to the total amount of water involved in the production of a given good. This concept was first introduced in the early 1990s in response to the popular belief that water shortage will be a major cause of future wars (Allan, 1997, 1998) and is particularly useful when investigating the role that trade may play in leveling the unevenness in the initial distribution of water resources. Indeed, unlike other natural resources, such as crude oil, timber and copper, water cannot be produced in one location and economically transported to others for direct usage. Thus, the only viable way to transfer water from one region to the other is to import water embedded in traded goods.

Our main contribution is to show that once we take into account that water-intensive goods are typically also land-intensive, whereas they are less intensive in terms of physical and human capital (see, e.g., Ansink, 2010; Wichelns, 2010), trade may not necessarily lead to a more even water content of consumption. Indeed, we find that VW trade may actually result in a more unequal ex-post distribution of per capita water consumption across countries.

In terms of methodology, we begin by introducing a modified Heckscher-Ohlin (HO) model of international trade that incorporates composite production factors. In line with the traditional HO model, we reduce the input space going from four separate factors of production to two composite factors – one including water and arable land, and the other including physical and human capital. Throughout the paper, we use the term *natural resources* to refer to the composite factor including land and water, and the term *capital* to refer to the factor containing physical and human capital.[2] This allows us to take into consideration that agricultural production is typically more intensive in water and land, while industrial production typically requires larger amounts of physical and human capital. Thus, we account for the existence of strong complementarities among factors of production. The existing literature has already emphasized that 'water availability should be considered neither the main nor the unique determinant of VW flows' (Fracasso *et al.*, 2016: 1056), and water endowments should be expressed in relative terms with respect to the stock of arable land (Kumar and Singh, 2005).

This modified HO model, which properly accounts for composite production factors, illustrates that trade will lead to less even per capita consumption of water resources across countries if the following two conditions are satisfied: (1) countries that have a relative abundance of natural resources (i.e., resources that are more intensively used in agriculture versus manufacturing/services) tend to specialize in water-intensive agricultural goods; and (2) on average, those countries that are 'exporters' of these natural resources are, in absolute terms, scarce in capital in comparison to their trade partners,

[2]Notice that our definition of natural resources does not include other types of natural resources such as oil, fisheries and minerals.

without being abundant in absolute terms in either water or land.[3] Our empirical analysis confirms that these conditions are indeed satisfied, thus allowing us to state that according to a standard workhorse model of international trade, virtual trade will have a negative impact on water equality. Our claim is, therefore, that VW trade does not lead to more even distribution of the water content of consumption across countries.

To confirm that the two conditions stated above are satisfied, our empirical analysis proceeds in steps. As a preliminary step, by adopting a recent data reduction technique that combines ideas from principal component analysis (PCA) and hierarchical clustering in an elegant and simple manner, we confirm that the use of composite production factors is indeed a valid assumption. More specifically, with respect to other data reduction techniques that create synthetic components retaining also weakly correlated variables, the methodology we adopt is particularly relevant in our setting because it generates pairs of strongly correlated variables, greatly simplifying the interpretation of components. This approach allows us to test the factor proportion theory properly and empirically verify that the relevant composite production factors are indeed those suggested by the theoretical framework, namely natural resources (water and land) and capital (physical and human).[4] As a second step, we confirm condition 1 using the so-called 'interactional approach' pioneered by Deardorff (1982) and Forstner (1985) and test the validity of the composite factor HO theory by regressing net exports on a set of country-level factor endowments and industry-level factor intensities. To validate condition 2, we first define countries that are net exporters of natural resources, and then we show that they are not more abundant in water than net importers of natural resources.[5]

The country-level analysis is justified by the fact that, although it is well-established that within-country trade plays a major role in determining the ultimate distribution of water resources, international trade provides a cleaner setup to assess the role of trade on water distribution.[6] Indeed, while intranational VW movements may be affected by domestic policies aimed at, for example, subsidizing the production of water-intensive goods in regions where hydric resources are more abundant, these policies are less likely to be enacted at the international level. More specifically, with the exception of certain cross-border trade agreements (i.e., EU, NAFTA, etc.), there is an absence of a transnational political body that has the authority to engage in any form of water redistribution policy, beyond attempting to regulate trade between countries. Therefore, the cross-country analysis provides a valid test of the impact of trade on VW distribution.

The rest of the article is organized as follows. Section 2 briefly presents the related literature. Section 3 introduces the theoretical framework. Section 4 discusses the methodology and data, while the results of the empirical analysis are presented in section 5. Finally, section 6 concludes and proposes topics for future research.

[3]Here, although our variables are always expressed in per capita terms, we use the typical HO terminology, where factors of production may be scarce or abundant in relative and/or absolute terms.

[4]Indeed, as argued by Leamer and Bowen (1981), Aw (1983) and Forstner (1985), when there are more than two factors of production, usual regression procedures might provide inappropriate tests of the factor proportions theory. This happens in case of severe factor complementarities (see, e.g., Harkness, 1983).

[5]In the online appendix, we confirm the robustness of our findings by estimating alternative models and addressing potential endogeneity issues related to capital endowments. In particular, we carry out an instrumental variable (IV) analysis that allows us to exclude the possibility that our conclusions may be biased due to endogeneity issues.

[6]As a rough estimate of the relevance of cross-country trade in water-intensive goods, it is useful to consider that in 2009 the share of the total food produced that was internationally traded for human consumption was equal to 23 per cent (D'Odorico *et al.*, 2014).

2. Related literature

Our paper belongs to a growing literature that considers the intersection between international trade and VW. In particular, we contribute to the stream that critically examines the impact of VW trade.[7] Kumar and Singh (2005), for example, use cross-country data from 151 countries showing that pure water endowments do not fare well in explaining much of the VW trade. Fracasso (2014) estimates a trade gravity model and finds that bilateral flows are affected by water endowments and pressure on water resources, in addition to the classic determinants of the gravity model. Utilizing the same model and examining VW flows across the Mediterranean basin, Fracasso *et al.* (2016) verify that larger water endowments do not necessarily result in more VW exports. Seekell *et al.* (2011) use trade data to argue that VW flows are directed by global economic structures and trade relations rather than by the relative scarcity of water within nations. They also argue that VW trade is unlikely to mitigate water inequality as the water used in agriculture (the dominant water need of countries) cannot be completely compensated by VW transfers. In a study with a similar approach and conclusion, Suweis *et al.* (2011) find that 4 per cent of international trade connections account for 80 per cent of VW transfers. However, this conclusion does not take into account the per capita distribution of natural resources, the presence of VW in non-agricultural products, and the effects of multilateral trade. Putting weight on abundance, Lenzen *et al.* (2013) include the scarcity of water resources at the country level to analyze global water trade and draw a new structure of global VW networks under this assumption.

A novel aspect of our paper, with respect to this literature, is to offer country-level empirical evidence affirming the role of capital (physical and human) endowments in determining the pattern of VW trade. We empirically show that once natural resources and capital are properly accounted for, trade will not give way to a more even distribution of water resources.

Two papers closely related to our work are Ansink (2010) and Reimer (2012). Ansink (2010) refutes the major claim of the VW paradigm by illustrating cases in which the HO model does not necessarily imply a more equal distribution of water resources. Reimer (2012), however, defends the validity of the HO model by showing that it is actually consistent with a more even relative redistribution of water resources across countries. We elaborate on this discussion by illustrating how Ansink's claim remains true. This is done by stressing that the relevant dimension when assessing the validity of the VW promise is the impact of trade on the per capita consumption of water resources across countries.

Our paper is also closely related to Debaere (2014), which provides a systematic analysis of the role of water endowments in determining countries' exports of water-intensive goods. However, while Debaere aims at testing a quasi-HO model (see Romalis, 2004), we investigate how factor composition, measured as relative endowments of natural resources and capital, influences VW trade. Therefore, although we use the same dataset employed in Debaere (2014), we adopt a partially different approach, which delivers results that are consistent with the stylized facts presented in figure 1. First of all, because our focus is on the distributional effects of VW trade, we use a measure of net exports as

[7] Antonelli and Sartori (2015) provide the most recent review of the academic and policy debate surrounding the notion of VW, while other papers that critically address VW trade include Sayan (2003), Yang and Zehnder (2007), Wichelns (2010), Perry (2014), Carr *et al.* (2015) and Rosa *et al.* (2018). Other examples of studies aiming to measure the global and regional VW trade flows include Dietzenbacher and Velázquez (2007), Guan and Hubacek (2007), Feng *et al.* (2012), and Bae and Dall'Erba (2018).

the dependent variable instead of total exports (see, e.g., Deardorff, 1982; Forstner, 1985; Romalis, 2004; Levchenko, 2007; Nunn, 2007; Debaere, 2014). In this way, we account for the presence of intra-industry trade.[8] Second, we use a hierarchical decomposition technique to reduce the input space going from four separate factors to two composite factors. This allows us to address a well-known issue in the VW literature: the fact that typically water-abundant products are also land-abundant products, and therefore the availability of arable land becomes an important determinant of VW flows (see, e.g., Kumar and Singh, 2005; Fracasso *et al*., 2016). In a quasi-HO perspective, the use of a water-land composite factor might also be useful in explaining why Debaere (2014) finds that water has little impact on trade patterns compared to the classic production factors (labor and capital). In the last part of the analysis, we also show that both our choices of using net exports as the dependent variable and reducing the number of factors improve the analysis without affecting our results.

3. Theoretical framework

We adopt a simple theoretical framework to illustrate how capital scarcity may affect the impact of trade on the redistribution of per capita VW resources across countries. More specifically, we show that while the relative abundance of natural resources versus capital is what determines the specialization in resource-intensive goods, this does not necessarily lead to a more even distribution of the water content of consumption. Indeed, if countries that are relatively rich in natural resources are typically not endowed with more water and poor in capital, the water content of consumption may become more unequal with trade. This is driven by the scarcity of capital in these countries as well as by the lower relative prices of natural resources with respect to capital. Both of these forces contribute to reducing the share of global income that accrues to countries exporting natural-resource-intensive goods, therefore ultimately reducing the water content of their consumption.

Our framework follows the core logic of the HO model of international trade based on two goods, two countries, and two production factors. Y_1 denotes a water-land-intensive agricultural crop, and Y_2 denotes a capital-intensive industrial product. The production of each of the two commodities requires a combination of two composite factors: natural resources and capital. This assumption is consistent with previous contributions and suggests that the endowment of water should be replaced with that of water and land combined. Indeed, water is traded by moving water-land-intensive commodities, such as grain, from one country to another (see, e.g., Merett, 2003; Kumar and Singh, 2005; Ansink, 2010; Fracasso *et al*., 2016).[9] Likewise, any measure of the capital required to produce a given good includes both physical and human capital. Using the standard notation of international trade models, the two countries, home and foreign (where we denote the latter with an asterisk (*)), are characterized by different endowments of natural resources and capital. The natural resource endowment, R, encompasses both

[8]Debaere (2014) uses total exports as the dependent variable because the quasi-HO prediction states that: despite the existence of intra-industry trade, countries capture larger shares of world production and exports in commodities that more intensively use their abundant factors. This means that Debaere's focus is on the determinants of total exports instead of net exports.

[9]For instance, countries such as Afghanistan and Malawi have a comparative advantage in the production of water-intensive goods 'not only because they have lower capital endowments (e.g., human capital, infrastructure, and technology), but also because they have larger endowments of arable land to use their water endowment effectively' (Ansink, 2010: 2029).

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

water (W) and arable land (L) and is a compact form to represent the effective water endowment; similarly, capital, C, includes both physical capital (K) and human capital (H).[10]

One of the main findings of the HO model is that, under the standard assumptions that markets clear, national budget constraints are satisfied, and preferences and technologies are homogeneous across countries, allowing for final goods to be traded between two countries will result in the equalization of production input prices across countries (i.e., factor price equalization), even absent any trade or mobility of production factors. If the two countries have a sufficiently similar ratio of factor endowments, they will produce in the so-called cone of production, in which both countries will use the same combination of inputs; though, they may produce different quantities of each good. In other words, the HO model predicts that a country that is relatively abundant in capital will produce more of the capital-intensive good, whereas a country that is relatively abundant in employable water will focus on the water-land-intensive good.

For example, if we assume that home is relatively abundant in natural resources (i.e., $R/C > R^*/C^*$), it will produce more water-land-intensive goods (Y_1) and will become a net exporter of water-land. The relatively capital-abundant country (foreign), on the other hand, will focus on producing a larger quantity of capital-intensive goods (Y_2) and will become a net importer of water-land-intensive goods. However, in what follows, we show that these conditions are not sufficient to allow for trade to lead to a more equal per capita consumption of water resources across countries. In particular, this may occur if countries that are relatively abundant in natural resources (land and water) with respect to others are also typically not rich in water and poor in capital. This effect is magnified when the price of natural resources is comparatively low with respect to that of capital.

As a starting example of how this may occur, consider the trade patterns of the following two countries:

(a) A land-abundant country that is not particularly rich in water (e.g., Morocco, Nigeria) as well as poor in other production factors (i.e., human and physical capital). This country may have a sufficiently large amount of arable land that guarantees a comparative advantage in the production of agricultural goods. Therefore, it may become a net exporter of VW even if it is not rich in water. The income accruing from its exports, which positively influences the water content of consumption, may be limited when the relative price of natural resources with respect to capital is low.

(b) A country that is not lacking in water but also has large endowments of other production factors (e.g., capital or skilled labor) may be considered capital-abundant (e.g., Canada, New Zealand). The country's endowments will be prevalently channeled toward producing those goods that require a higher intensity of factors in which it is more abundant. In practice, a developed country with high productivity in the service and industrial sectors may devote fewer resources

[10] In this setup water and land are considered factors that are imperfect substitutes (in the numerical example we consider the case of perfect complements to simplify exposition) that jointly determine the amount of employable water. For instance, a country with plenty of water and a small amount of arable land (e.g., the Netherlands) or a large area of arable land but low per capita water (e.g., Tunisia) will have a similar effective water endowment. The same logic applies to physical and human capital that jointly contribute to determining the total quantity of available capital.

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

to the production of agricultural products, despite having a significant endowment of water.[11] In this case, a higher price of capital with respect to natural resources boosts the country's share of income, which translates into a greater water content of consumption as a consequence of trade.

To make this point clearer, we resort to our HO model with composite production factors in order to illustrate that a standard model of international trade is indeed consistent with the fact that trade may lead to a less even distribution of the water content of consumption in per capita terms.[12] Thus, the question we are posing is whether, on average, countries specializing in agricultural production and which are, therefore, comparatively richer in natural resources with respect to capital, are particularly scarce in capital without being rich in water, with respect to those specializing in manufacturing and services.

More formally, and following on the example above, we assume that home (foreign) is the country that has a relative abundance of natural resources (capital) (i.e., $R/C > R^*/C^*$), and, to allow for meaningful comparisons across countries, we consider all values in per capita terms. We represent the vector of factor endowments with V (V^*), global income with Y^g and the share of global income with s (s^*). Applying the standard assumptions of the HO model of identical homothetic preferences and identical goods prices via trade, each country's consumption of goods is just the share of its global output, namely sY^g for home and s^*Y^g for foreign. Considering factor price equalization implied by HO, and assuming that r is the return on R and c is the return on C, it follows that $Y = rR + cC$ and $Y^* = rR^* + cC^*$, where $Y^g = Y + Y^*$. In order to obtain the factor content of consumption, which is the relevant variable to determine the net export of factors, we define A as the matrix of factor demands, where each row of the matrix represents the quantity of each factor needed to produce a given good. Factor market clearing implies that $AY^g = V^g$, where $V^g = V + V^*$ is the global endowment vector. Therefore, the factor content of consumption for home (foreign) is simply equal to sV^g (s^*V^g). We can now state the following proposition.

Proposition 1. (See proof in the online appendix) If home (foreign) has a relative abundance of natural resources (capital) (i.e., for $R/C > R^*/C^*$), it will be a net exporter of natural resources (capital), but trade will lead to a less even distribution of water content of consumption if: (i) $W \leq W^*$; and (ii) $C < C^*\frac{W}{W^*} - \frac{r}{c}\left(\frac{W^*R - WR^*}{W^*}\right) \equiv \underline{C}$.

Notice that both resource endowments and factor prices play a crucial role in determining whether international trade will increase water inequality. Indeed, if countries that have a relative abundance of natural resources with respect to capital are also richer in arable land than in water, such that $R > R^*W/W^*$, condition (*ii*) implies that,

[11] Although in this simple HO model we do not consider heterogeneity in factor productivity across countries, we do control for this in the empirical analysis. Indeed, countries that are more abundant in capital may also be characterized by higher agricultural productivity and therefore potentially produce and export more water-land-intensive goods with respect to less developed countries, even if a larger share of the human and physical capital is devoted to manufacturing and services.

[12] Note that in order to allow for comparisons across countries, we consider all variables in per capita terms, which implies that countries that are richer in per capita terms are not necessarily richer in absolute terms.

when these countries are also scarce in capital, trade will lead to a less even distribution of the water content of consumption. Moreover, *ceteris paribus,* trade is more likely to increase inequality in water content of consumption when the prices of natural resources (capital) are lower (higher). Therefore, there is room for policy interventions devoted to sustaining natural resource prices and/or lowering capital costs.

The economic intuition behind proposition 1 is the following. Countries that are relatively abundant in natural resources with respect to capital will have a comparative advantage in producing and exporting products requiring a greater intensity of natural resources. If these countries also have limited capital endowments and are not rich in water, they obtain a modest share of world income from trade, which leads to a reduction in their water content of consumption. In addition, the lower is the price of natural resources (r) compared to that of capital (c), the smaller is the share of world income that the relatively less capital-abundant country receives from trade. Therefore, the threshold level of capital (C) required to offset the perverse negative effect of trade on water distribution increases, and this makes it more likely that trade may increase water consumption inequality for a given initial distribution of capital.[13]

In terms of empirically testable implications, given the unavailability of panel data on water consumption, we rely on an indirect strategy to identify whether on average the pattern of endowments of countries that export agricultural versus industrial products are at odds with trade leading to a more even distribution of water content of consumption across countries. Indeed, proposition 1 implies that, based on our modified HO model, if the following two conditions are jointly satisfied, trade will lead to a less even distribution of per capita water content of consumption across countries:

1) *HO Model and Composite Factors* – The standard comparative advantage results of the HO model are satisfied for the composite factors R and S, implying that countries that are relatively abundant in natural resources (capital) will be net exporters of natural resources (capital).
2) *Capital Scarcity* – Countries that are net exporters of natural resources are, in absolute terms, also (weakly) scarcer in water ($W \leq W^*$), and strictly scarcer in capital so that the following condition is satisfied: $C < C^* \frac{W}{W^*} - \frac{r}{c}\left(\frac{W^*R - WR^*}{W^*}\right)$.

In the next section, we aim to verify whether these two conditions are jointly satisfied.

4. Methodology and data

4.1 Methodology

4.1.1 Composite factors

As mentioned in section 3, agricultural production is usually more intensive in water and land, while industrial production usually requires larger amounts of physical and human capital. In order to properly account for this feature, we use a data reduction algorithm that combines PCA with a hierarchical clustering technique. As for PCA, this algorithm is designed to reduce a multidimensional dataset to a small number of components that account for the largest part of original data variation. However, with respect to other data

[13]In the online appendix, we provide a numerical example illustrating how trade may lead to a less even distribution of water content of consumption.

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

reduction techniques that create synthetic components also retaining weakly correlated variables, this methodology creates pairs of strongly correlated variables, greatly simplifying the interpretation of components. This permits us to empirically verify whether the relevant composite production factors are indeed those suggested by the theoretical framework, namely natural resources (water and land) and capital (physical and human).

More specifically, starting from a set of m initial variables, the algorithm proceeds as follows: it first identifies the two variables with the highest correlation coefficient and then performs a PCA on these to create a new composite dimension. Subsequently, it keeps the principal component with the largest variance (i.e., the new variable) and discards the other elements and the original variables. The new dataset will consist of $m - 1$ variables (the new component and the remaining $m - 2$ initial variables). Then the algorithm repeats the previous steps for a total of $m - 1$ times until only one element remains. This procedure is a hierarchical clustering technique, and the output can be conveniently represented as a cluster dendrogram with m levels. Components that are close in the dendrogram and that are merged early constitute sets of highly correlated variables.[14] As a final step, the algorithm uses a cross-validation score criterion to select the minimum set of components explaining the largest part of data variability, ranking them in order of importance and keeping the interpretation of components as simple as possible.

Our methodology addresses an important limitation of the empirical literature testing the factor proportion theory. Indeed, when there are more than two inputs, traditional regression procedures based on many factors of production provide inappropriate tests of the factor proportion theory (see, e.g., Leamer and Bowen, 1981; Aw, 1983; Forstner, 1985). That is, the estimates of the HO model suffer from the limitations of the traditional setting: two factors, two goods, and two countries. This happens because the HO model requires a positive-definite matrix of factors intensities. However, this condition is sufficient only in the two-factor case, while in the case of multiple factors, the cone of diversification becomes a hyper-space, and further econometric restrictions are necessary. In other words, if there are complementarities among factors intensities, the estimates of the HO model might become rather inaccurate (see Harkness, 1983).[15]

4.1.2 Testing the factor proportion theory

In the second part of the analysis, starting from the results of the treelet algorithm, we design a proper test for the factor proportion theory. In particular, by adopting the so-called 'interactional approach' pioneered by Deardorff (1982) and Forstner (1985), we can test our first theoretical claim. This approach consists of regressing net exports on a set of country-level factor endowments and industry-level factor intensities.[16] Formally,

[14]Unlike PCA, this algorithm exploits the local structure of the covariance matrix and is robust to multiscale measures. Nonetheless, we have also checked the robustness of our conclusions using a PCA, and results are available upon request from the authors.

[15]In the robustness check section, we prove that our approach leads to more accurate results than a full four-factor model in which all factors of production enter the model separately.

[16]Other studies used this method to test a quasi-HO model as well as a quasi-Rybczynski effect (see, e.g., Romalis, 2004; Levchenko, 2007; Nunn, 2007; Debaere, 2014). Our article differs from these studies mainly because they use exports instead of net exports as the dependent variable. Nonetheless, when we test the VW hypothesis, we must take into account the intra-industry trade. In this way, we control for the fact that, in a specific sector, a country might be simultaneously an exporter and an importer.

we estimate the following *interactional* equation:

$$NX_{ij} = \alpha_j + \beta_1 R_i + \beta_2 C_i + \gamma_1 R_i * \rho_j + \gamma_2 C_i * \rho_j + \varepsilon_{ij}, \qquad (1)$$

where α_j is a vector of sector fixed effects; NX_{ij} is the natural logarithm of the exports-to-imports ratio for country i in sector j; R_i and C_i are the endowments of natural resources (water and land) and capital (physical and human) for country i as indicated by the treelet analysis; ρ_j is the natural resource intensity (or water-land intensity) of sector j resulting from the treelet analysis; estimated coefficients are in small Greek letters and ε_{ij} is the disturbance term.[17] Since production technologies are certainly heterogeneous across industries, but they might be common across countries, we use a standard Hausman test to compare a model with both country and industry dummies with a model with only industry dummies. We found that these two specifications do not differ significantly, and therefore we opted for the most parsimonious specification. Indeed, this specification has at least two important advantages: it is more efficient than a specification with two large sets of dummies and allows us to estimate the direct effects of factor endowments on trade flows. As argued by Forstner (1985), on average, the OLS estimates of an interactional regression test of the HO hypothesis must be positive, and this must be true for both total and partial effects.

4.1.3 Capital scarcity and trade

In the third part of the analysis, we test our second condition on capital scarcity. More precisely, we investigate whether net exporters of natural resources are more abundant in water and/or scarcer in capital factors.

To address this relevant question, we must distinguish between exporters and importers of natural resources. This distinction is more difficult in a multisector context than in a two-sector model. A possible solution would be to compute the water contents of trade for each sector and aggregate the results to obtain the countries' net export of VW. However, this exercise would require knowing the outputs' prices. Because we cannot construct an aggregate measure of net exports of natural resources, we use equation (1) to identify countries that are exporters of natural resources. We define as importers of natural resources those countries for which the trade balance does not decrease with the natural resource intensity (ρ_j) and exporters of natural resources those countries that pass from being net importers to being net exporters when ρ_j rises. Notice that this definition implies that exporters of natural resources must necessarily be exporters in the sectors characterized by the highest natural resource intensity.

Formally, using equation (1), we first determine the threshold level of the ratio (R_i/C_i) that distinguishes net importers from net exporters in the sector with the highest intensity of natural resources, and then we test whether they differ from the others for their scarcity of capital but not for their abundance of water. More precisely, we use a t-test to verify whether exporters of natural resources are more abundant (scarcer) in water and land (physical and human capital) than importers of natural resources.

Finally, we conduct several robustness checks to exclude the possibility that our results may be driven by strong aprioristic assumptions. In particular, we check

[17] Notice that the direct effects of factor intensities are completely absorbed by the vector of industry fixed effects. In the rest of the analysis, although we do not have a longitudinal dataset, we often refer to a full set of industry-specific dummies as 'fixed effects.'

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

whether our results depend on model specification, measurement choices or endogeneity issues.[18]

4.2 Data

This study takes advantage of the cross–country dataset described in Debaere (2014). The primary sources of the initial dataset, together with a brief description of the variables entering the analysis, are provided in online appendix table A1. We use data from Feenstra *et al.* (1997) to supplement the dataset with a measure of multilateral imports. This additional variable is necessary to compute the net exports from each country in each industry. The final sample consists of 68 countries (developed and developing) and 194 industries. Due to missing values, we have a total number of observations equal to 11,187, although our regression analyses drop out 13 singleton observations. Table A2 in the online appendix reports the sample composition by country.

In line with the existing literature on the HO theory, our dependent variable is a measure of net exports (NX).[19] Because we consider a multilateral trade context instead of bilateral trade, we cannot ignore the existence of intra-industry trade, and therefore net exports undoubtedly represent the most appropriate dependent variable. In this way, we control for the fact that, in a specific sector, a country might simultaneously be an exporter and an importer. Nonetheless, in the robustness checks, we also consider the effects of factor endowments on exports and imports, separately. This allows us to identify the main channel through which capital accumulation affects net exports.

The set of independent variables can be divided into two groups. The first group consists of four different variables measuring the country's endowments of water, land, physical and human capital, whereas, the second group refers to four variables capturing the sectors' factor intensities. As a measure of water endowment, W, following Gleick *et al.* (2009) and Debaere (2014), we take the natural logarithm of a country's available renewable freshwater per capita (cubic kilometers per capital). This variable measures the quantity of renewable water that can be used for human activities without threatening environmental sustainability and is the sum of the average annual surface runoff and the groundwater recharge (see Johnson *et al.*, 2001; Gleick *et al.*, 2009; Debaere, 2014). As argued by Debaere (2014), this measure of water endowment is particularly appropriate if one is concerned about endogeneity issues, because it is not related to the current use of water. Moreover, the endowment of renewable freshwater per capita captures the opportunity cost of water much better than other measures based on water prices. Indeed, the markets for the production factors of the agricultural sector (in particular water) are either missing or are highly regulated or subsidized by governments. These institutional frictions and distorted price signals do not reflect water scarcity or firm-level production choices, which might significantly differ from those that would result in the presence of a competitive market-clearing price. In contrast, the per capita endowment of water implicitly proxies the cost of water scarcity, since rationing and shortages are more likely when water is scarce.

[18]These results can be found in the online appendix.

[19]Since the log-transformation of the difference between exports and imports would not necessarily be a linear function, we use the exports-imports ratio to estimate a linear regression model in which countries' endowments interact with sectors' factors intensities. This specification can easily be log-linearized and becomes $NX = ln(X)\ ln(IM)$, where X is country's total exports, and IM is its total imports. In this way, we can assume a standard Cobb-Douglas function for both exports and imports.

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

Data on the endowment of land, L, comes from the World Bank's World Development Indicators and is the natural logarithm of arable land in hectares per capita in 1997. The definition of arable land is provided by the Food and Agriculture Organization (FAO) and includes land under temporary crops (double-cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. In contrast, land abandoned as a result of shifting cultivation is excluded. Worldwide, arable land represents less than one-third of agricultural land, which also includes permanent crops and permanent pastures.[20]

The stock of physical capital, K, corresponds to the natural logarithm of the average capital stock per worker in 1992, whereas the stock of human capital, H, is the natural logarithm of the ratio of workers completing high school to those not completing high school in 1992. The primary source for both stocks of capital is Antweiler and Trefler (2002).

The second group of independent variables includes four different measures of sectors' factor intensities. The measure of water intensity (w_b^d) is the relative ranking of US direct blue water intensities. Blue water is particularly important for households' consumption and refers to water from rivers, lakes and groundwater that can be used in production activities. However, the water used for the production of agricultural and industrial products can come from both blue and green water resources and may or may not have a grey water footprint, where green water represents the part of rainwater absorbed by soil and vegetation. This implies that countries may significantly differ in terms of the nature of their VW imports and exports. Indeed, some water-stressed countries (e.g., Iran) may paradoxically become net exporters of blue water even if, overall, they are net importers of water. This happens because water-abundant countries are usually large exporters of green water, and therefore, we may have that some net importers of water actually export blue water and import green water, experiencing additional pressure on their blue water resources. Therefore, in the robustness checks, we test whether our conclusions hold even when we augment the model with indirect blue water intensities (w_b^{di}) and green water intensities (w_{gb}^d and w_{gb}^{di}). Sector's land intensity (l) is the ratio of land use to total factor use as recorded by the Global Trade Analysis Project (GTAP). Finally, physical and human capital intensities (k and h, respectively) come from Bartlesman and Gray (1996). As a robustness check, we allow agricultural technology to vary across countries. In particular, following Debaere (2014), we adjust the US water intensity with Mekonnen and Hoekstra's (2011) data on the countries' intensity of green and blue water employed in agriculture. Table 1 provides the main descriptive statistics for the collected data.

5. Results

5.1 Data structure and input complementarities

The biplots reported in panels A and B of figure 2 provide a graphical representation of the correlation structure presented in online appendix table A3. For the sake of readability, we omitted data points. Notice that physical and human capital stocks exhibit

[20]The FAO occasionally adjusts its definitions of land use categories and revises earlier data; however, complete consistency in reporting methods across countries is practically impossible. For instance, data on agricultural land in different climates may not be comparable. Moreover, in some countries, land use data are based on reporting systems designed for collecting tax revenue, and this is the reason why they give better information.

Table 1. Descriptive statistics (obs = 11,187)

Variable	Mean	SD	Min	p25	p50	p75	Max
Dependent variable							
NX	−2.605	3.757	−14.442	−5.066	−1.896	−0.403	13.816
Endowments							
W	2.016	1.705	−1.846	0.830	1.918	3.299	6.441
L	11.957	1.207	5.572	11.351	12.133	12.658	14.588
K	−4.711	1.312	−8.580	−5.576	−4.522	−3.724	−2.957
H	−1.667	1.120	−4.525	−2.140	−1.423	−1.006	0.925
Intensities							
w_b^d	0.038	0.144	0.000	0.000	0.000	0.000	0.854
w_b^{di}	0.052	0.152	0.001	0.002	0.004	0.013	0.863
$\mathrm{w}_{\mathrm{gb}}^{\mathrm{d}}$	0.045	0.171	0.000	0.000	0.000	0.000	0.956
w_{gb}^{di}	0.065	0.192	0.001	0.002	0.004	0.014	0.960
L	0.026	0.067	0.000	0.000	0.000	0.000	0.28
K	0.784	0.510	0.212	0.453	0.651	0.946	3.568
h	0.376	0.141	0.092	0.295	0.365	0.447	0.853

Notes: This table reports the means, standard deviations, minimum values, three percentiles (25th, 50th, and 75th) and maximum values of observed variables. All variables are in natural logs.

a rather high correlation as well as water and arable land endowments; in contrast, the correlation between natural resources and capital factors is not so high. Regarding factors intensities, sectors characterized by a high intensity of water and land tend to be less intensive in capital, especially human capital. This implies that water and land are usually complements in the production of goods, whereas they are substitutes of human capital and orthogonal to physical capital. Results remain practically unchanged when we replace direct blue water intensities with other measures of water intensity. Overall, the existence of complementarities among inputs clearly emerges from the data.

To deal with input complementarities, statisticians often carry out a PCA to tease apart highly correlated data. However, our correlation matrix is rather sparse to use a standard PCA in which a component is usually expected to load more than just two variables. Therefore, to deal with the sparsity of the correlation matrix, we group our variables using the 'treelet' algorithm proposed by Lee *et al.* (2008). The final components are orthogonal and nested in a hierarchical tree combining pairs of variables.

To extract the main components, the treelet algorithm requires the specification of a cut-level for the associated clusters. Panel C of figure 2 provides a graph of cross-validation (CV) scores against different cut-levels; the optimal cut-level (which is 3) is represented as a 'knee' in the CV score. Panel D of figure 2 displays the hierarchical tree behind our data and sorts the corresponding clusters according to the variances of the associated components. Therefore, our data can be summarized with three main components. The first component is a measure of capital resources and, as in section 3, it will be denoted by *C*. This variable captures the strong correlation between physical and human capital stocks. Indeed, the accumulation of physical capital also facilitates the

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

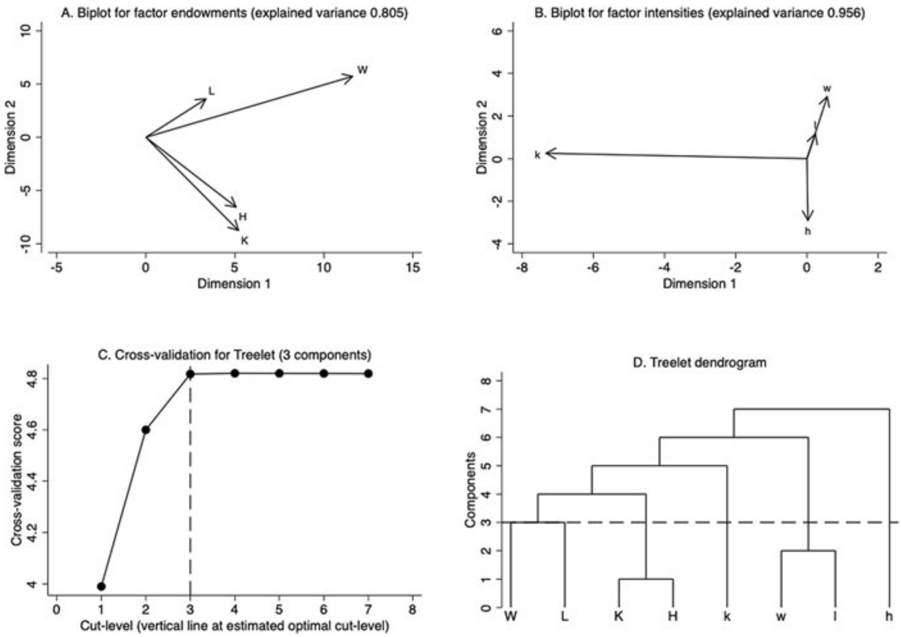

Figure 2. Biplot and treelet results for factor endowments and intensities.
Notes: In panels A and B, the biplots report the first two singular vectors of the data matrix, while the cosine of the angle between arrows approximates the correlation between the variables. Panel C provides the cross-validation scores for the treelet algorithm when three components are retained; this graph strongly indicates a 'knee' located at cut-level 3. This means that the first three components explain almost the entire variance of the data. Finally, panel D displays the treelet dendrogram and shows that capital endowments, water-land intensities, and water-land endowments generate the main three components explaining data variability.

accumulation of human capital (see, e.g., Acemoglu, 1996; Galor and Moav, 2004). The second component is a measure of natural resource intensities and confirms the fact that water-intensive goods, such as agricultural products, are also land-intensive goods (see, e.g., Allan, 2003; Merett, 2003). This component will be denoted by ρ and is strongly associated with the distinction between agricultural and manufacturing sectors. Finally, the last component is a measure of natural resource endowment and is denoted by R. This covariate captures the positive association between the availability of water and the endowment of arable land. After these three components, the fourth component would be a combination of the first and third components, whereas the fifth component would put together the endowments of resources and physical capital intensity. A brief description of these variables, together with some basic descriptive statistics, is available in online appendix table A4.

5.2 HO and composite factors

In this section, we formally test our first theoretical condition. That is, we want to verify if countries that are relatively abundant in natural resources (capital) are also net exporters of natural resources (capital). Table 2 shows the OLS estimates of equation (1) using different definitions of water intensity to construct the natural resource intensity component (ρ_j).

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

Table 2. Net exports ($n = 11{,}174$)

	(1)	(2)	(3)	(4)
R	−0.061* (0.036)	−0.061* (0.036)	−0.061* (0.036)	−0.061* (0.036)
$R \cdot \rho$	0.167*** (0.035)	0.177*** (0.035)	0.163*** (0.035)	0.170*** (0.034)
C	0.748*** (0.056)	0.747*** (0.055)	0.748*** (0.056)	0.747*** (0.055)
$C \cdot \rho$	−0.354*** (0.086)	−0.364*** (0.082)	−0.353*** (0.083)	−0.371*** (0.074)
Sector dummies	Yes	Yes	Yes	Yes
Hausman (p-value)	0.945	0.986	0.923	0.895
F-statistic	82.896	85.154	83.586	89.110
RMSE	3.340	3.334	3.339	3.331
R^2	0.229	0.231	0.229	0.233

Notes: This table contains the OLS estimates of equation (1). In column 1, we interact the natural resource endowment with a natural resource intensity based on direct blue water intensity. Column 2 uses a natural resource intensity component based on both direct and indirect blue water. In columns 3 and 4, we re-estimate the models of columns 1 and 2 also considering green water intensities. All estimates include a full set of sector dummies. We dropped 13 singleton observations. Clustered standard errors are in parentheses.
Significance: $^{*}p < 0.1$, $^{***}p < 0.01$.

In column 1, this intensity is based on arable land and direct blue water intensity. Column 2 considers a measure of natural resource intensity, taking into account both direct and indirect blue water intensity. In columns 3 and 4, the natural resource intensity is obtained by also considering green water intensities. All regressions include a full set of industry dummies, whereas, according to the Hausman tests reported at the end of the table, the cross-country heterogeneity is well captured by factor endowments. Consistently with the inclusion of a full set of industry dummies, we clustered the standard errors at the industry level.

All columns of table 2 deliver the same results. In line with the HO theorem, the coefficient of the interaction term between natural resource endowment (R) and natural resource intensity (ρ) is positive and statistically significant at 1 per cent. This means that countries characterized by water-land abundance export more in sectors characterized by a higher water-land intensity. In contrast, the interaction term between C and ρ shows that when the endowment of capital factors increases, countries tend to be net importers of water-land-intensive goods and net exporters in sectors characterized by a low water-land intensity (i.e., manufacturing industries not related to food processing). The direct effect of R on net exports is negative and slightly significant, whereas the coefficient of C is positive and highly significant. Hence, in sectors characterized by a natural resource intensity close to zero, the endowment of capital factors is a key feature of net exporters.[21]

[21] We also estimated equation (1) using a traditional PCA to reduce the space of factors. Results remain unchanged and are available upon request from the authors.

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

5.3 Capital, water and trade

In the previous section, we found that international trade flows are consistent with the HO model in which the factors of production are natural resources and capital (physical and human). Now, we test whether countries that are net exporters of natural resources are also (weakly) scarcer in water and strictly scarcer in capital. This is our second theoretical condition and consists of investigating the distribution of water and capital factors between exporters and importers of natural resources. If this is the case, then VW trade does not lead to a more even distribution of water across countries.

Our second condition can be tested by comparing countries that export natural resources with those that import natural resources. More precisely, we test whether the former differ from the latter for their scarcity of capital but not for their abundance of water. Given the HO theorem, exporters of natural resources must have a comparative advantage in the sector with the highest intensity of natural resources (i.e., the cotton farming sector). Using equation (1) to compute the threshold level of the ratio (R_i/C_i) that distinguishes net importers from net exporters in the sector with the highest intensity of natural resources, we found 19 countries that are exporters of natural resources according to the estimated HO model. These countries are Bangladesh, Bolivia, Brazil, Egypt, El Salvador, Guatemala, Honduras, India, Indonesia, Jamaica, Mauritius, Morocco, Pakistan, South Africa, Suriname, Thailand, Tunisia, Turkey, and Zimbabwe. As shown in figure 3, these countries (those with a triangle mark) have low levels of (physical and human) capital, whereas they are not particularly abundant in water.

In the online appendix, we also report a t-test comparing net exporters of natural resources (i.e., countries with a triangle mark in figure 3) with the rest of the sample. Additional results confirm the graphical perception that the former differ from the latter only for the lower endowment of capital stock (physical and human). In contrast, exporters of natural resources neither differ from the remaining countries in terms of water per capita nor in terms of natural resources per capita. Therefore, since $W = W^*$ and $R = R^*$, our second testable condition collapses to $C < C^*$, and this is a sufficient condition for VW trade to increase the inequality of water content of consumption across countries.

6. Conclusion and future research

A simple application of the basic HO model of international trade implies that, if countries that are non-abundant in water tend to be scarce in capital, then trade may increase the ex-post inequality in the water content of consumption. Our empirical analysis provides evidence that this may be the case, illustrating that a significant determinant of water trade is the level of capital (both physical and human) in a given country. In particular, we find that there is always a threshold level of capital above which a country is a net importer of VW, and on average, countries that are net exporters of water do not have significantly more water than exporters but have significantly less capital. This implies that trade can lead to a divergence in the per capita consumption of VW across countries. Our analysis suggests that policies aimed at imposing higher natural resource costs to enhance the income accruing from trade to countries with a comparative advantage in producing water-land-intensive goods could be beneficial. Indeed, such policies should serve the purpose of offsetting the negative effect of trade on the inequality in the water content of consumption. This argument is similar to the one made in the pollution haven hypothesis literature (Taylor, 2005). According to this literature, governments should impose sufficiently high taxes to influence the role of traditional factor endowments in

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

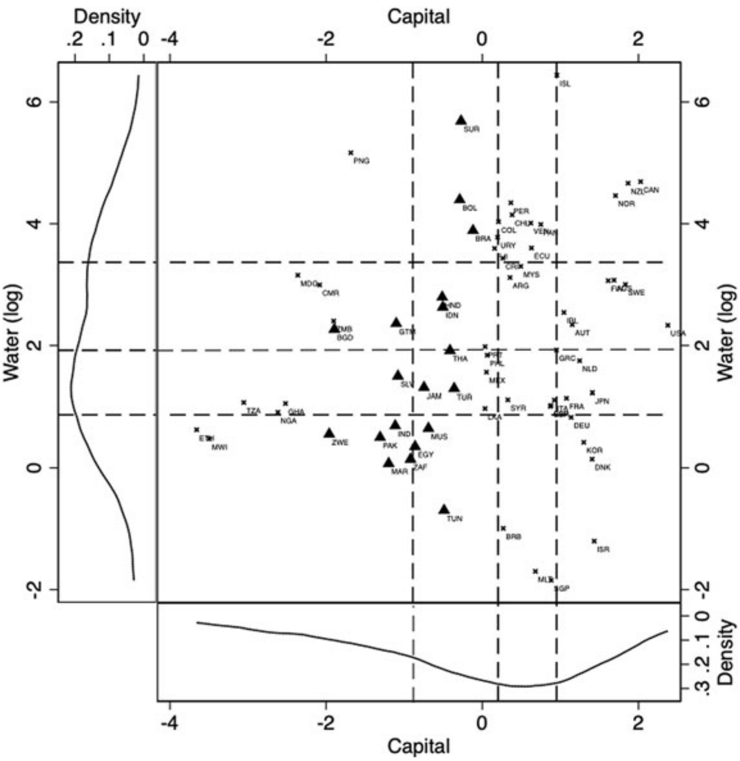

Figure 3. Water and capital endowments by country.
Notes: This graph provides a scatter plot representing our 68 countries in terms of capital-water endowments. On each axis, we reported the distribution of the two endowments estimated using a kernel density function. The dashed lines divide the two distributions into quartiles. Countries represented with a triangle mark are net exporters in the sectors characterized by the highest intensity of natural resources.

determining trade patterns and offset the incentives to over-pollute in countries with lower pollution costs. In our case, policy interventions on factor prices should be strong enough to significantly affect the countries' income from trade and thus their exports.

Our work represents a further step in better understanding the role of water trade in addressing global water issues. However, the VW metaphor requires further empirical exploration, which has so far not been possible due to limitations in data availability. Indeed, future empirical studies relying on panel data are needed in order to analyze the dynamic effects of the role of trade in the global redistribution of water resources.

We also abstracted from important institutional and physical details that determine the allocation of water within each country. Some countries have well-functioning property rights over water resources (such as prior appropriation rules and/or water markets), whereas others lack such institutions and provide water as a common resource.

Based on our results, one possible conjecture is that when less developed countries are also characterized by weak property rights, free trade may even result in over-exploitation of underground water resources. A rigorous examination of the proposed conjecture and a detailed welfare analysis are beyond the scope of the current paper and

https://doi.org/10.1017/S1355770X21000401 Published online by Cambridge University Press

may represent valuable topics for future research. However, our analysis suggests a possible policy in the spirit of Naghavi (2010) that could be adopted to avoid over-exploitation of water resources. Namely, global institutions such as the World Bank could condition the inflow of financial aid to developing countries on the government's application of sanctions (such as export tariffs) for firms that produce goods that involve excessive use of scarce water resources. This could serve the purpose of fostering development policies that also contribute to enhancing environmental sustainability.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1355770X21000401

Acknowledgements. We want to thank Roy Brouwer (The Water Institute / University of Waterloo), Farid Farrokhi (Purdue University), Fulvio Fontini (University of Padua) and Jorge Garcia (University of Waterloo) for comments that greatly improved the manuscript. We also thank all participants at the 24th Annual Conference of the European Association of Environmental and Resource Economists (EAERE, Manchester, 2019) and at the International Institute for Applied Systems Analysis (IIASA), 12th Annual Meeting of the International Water Resource Economics Consortium (IWREC), World Bank, 2016. The usual disclaimer applies.

References

Acemoglu D (1996) A microfoundation for social increasing returns in human capital accumulation. *Quarterly Journal of Economics* **111**, 779–804.

Allan JA (1997) 'Virtual water': a long term solution for water short Middle Eastern economies? Water Issues Group, School of Oriental & African Studies, University of London. Available at https://www.soas.ac.uk/water/publications/papers/file38347.pdf.

Allan JA (1998) Virtual water: a strategic resource. *Ground water* **36**, 545–547.

Allan JA (2003) Virtual water – the water, food, and trade nexus: useful concept or misleading metaphor? *Water International* **28**, 106–113.

Ansink E (2010) Refuting two claims about virtual water trade. *Ecological Economics* **69**, 2027–2032.

Antonelli M and Sartori M (2015) Unfolding the potential of the virtual water concept. What is still under debate? *Environmental Science & Policy* **50**, 240–251.

Antweiler W and Trefler D (2002) Increasing returns and all that: a view from trade. *American Economic Review* **92**, 93–119.

Aw B-Y (1983) The interpretation of cross-section regression tests of the heckscher-ohlin theorem with many goods and factors. *Journal of International Economics* **14**, 163–167.

Bae J and Dall'Erba S (2018) Crop production, export of virtual water and water-saving strategies in arizona. *Ecological Economics* **146**, 148–156.

Barnett T, Adam J and Lettenmaier D (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**, 303–309.

Bartlesman E and Gray WB (1996) The NBER manufacturing productivity database. Technical Working Paper 205, National Bureau of Economic Research, Cambridge, MA.

Carr J, Seekell DA and D'Odorico P (2015) Inequality or injustice in water use for food? *Environmental Research Letters* **10**, 024013.

Deardorff AV (1982) The general validity of the heckscher-ohlin theorem. *The American Economic Review* **72**, 683–694.

Debaere P (2014) The global economics of water: is water a source of comparative advantage? *American Economic Journal: Applied Economics* **6**, 32–48.

Dietzenbacher E and Velázquez E (2007) Analysing andalusian virtual water trade in an input–output framework. *Regional Studies* **41**, 185–196.

D'Odorico P, Carr JA, Laio F, Ridolfi L and Schleussne SV (2014) Feeding humanity through global food trade. *Earth's Future* **2**, 468–469.

Famiglietti JS (2014) The global groundwater crisis. *Nature Climate Change* **4**, 945–948.

Feenstra RC, Lipsey RE and Bowen HP (1997) World trade flows, 1970–1992, with production and tariff data. Technical Report 5910, National Bureau of Economic Research, Cambridge, MA.
Feng K, Siu YL, Guan D and Hubacek K (2012) Assessing regional virtual water flows and water footprints in the Yellow River basin, China: a consumption based approach. *Applied Geography* **32**, 691–701.
Forstner H (1985) A note on the general validity of the Heckscher-Ohlin theorem. *The American Economic Review* **75**, 844–849.
Fracasso A (2014) A gravity model of virtual water trade. *Ecological Economics* **108**, 215–228.
Fracasso A, Sartori M and Schiavo S (2016) Determinants of virtual water flows in the Mediterranean. *Science of the Total Environment* **543**, 1054–1062.
Galor O and Moav O (2004) From physical to human capital accumulation: inequality and the process of development. *The Review of Economic Studies* **71**, 1001–1026.
Gleick PH (2014) Water, drought, climate change, and conflict in Syria. *Weather, Climate, and Society* **6**, 331–340.
Gleick PH, Cooley H, Morikawa M, Morrison J and Cohen MJ (2009) *The World's Water* 2008–2009*: The Biennial Report on Freshwater Resources*, Vol. **6**. Washington, DC: Island Press.
Guan D and Hubacek K (2007) Assessment of regional trade and virtual water flows in China. *Ecological Economics* **61**, 159–170.
Hanjra MA and Qureshi ME (2010) Global water crisis and future food security in an era of climate change. *Food Policy* **35**, 365–377.
Harkness J (1983) The factor-proportions model with many nations, goods and factors: theory and evidence. *The Review of Economics and Statistics* **65**, 298–305.
Johnson N, Revenga C and Echeverria J (2001) Managing water for people and nature. *Science (New York, N.Y.)* **292**, 1071–1072.
Jury WA and Vaux Jr HJ (2007) The emerging global water crisis: managing scarcity and conflict between water users. *Advances in Agronomy* **95**, 1–76.
Kumar MD and Singh OP (2005) Virtual water in global food and water policy making: is there a need for rethinking? *Water Resources Management* **19**, 759–789.
Leamer EE and Bowen HP (1981) Cross-section tests of the Heckscher-Ohlin theorem: comment. *The American Economic Review* **71**, 1040–1043.
Lee AB, Nandler B and Wasserman L (2008) Treelets – an adaptive multi-scale basis for sparse unordered data. Discussions. *The Annals of Applied Statistics* **2**, 435–500.
Lenzen M, Moran D, Bhaduri A, Kanemoto K, Bekchanov M, Geschke A and Foran B (2013) International trade of scarce water. *Ecological Economics* **94**, 78–85.
Levchenko AA (2007) Institutional quality and international trade. *The Review of Economic Studies* **74**, 791–819.
Mehta L (2014) Water and human development. *World Development* **59**, 59–69.
Mekonnen MM and Hoekstra AY (2011) National water footprint accounts: the green, blue and grey water footprint of production and consumption. Value of Water Research Report Series 50, Delft: UNESCO-IHE Institute for Water Education.
Merett S (2003) Virtual water and occam's razor. *Water International* **28**, 103–105.
Misra A (2014) Climate change and challenges of water and food security. *International Journal of Sustainable Built Environment* **3**, 153–165.
Naghavi A (2010) Trade sanctions and green trade liberalization. *Environment and Development Economics* **15**, 379–394.
Nunn N (2007) Relationship-specificity, incomplete contracts, and the pattern of trade. *The Quarterly Journal of Economics* **122**, 569–600.
Perry C (2014) Water footprints: path to enlightenment, or false trail? *Agricultural Water Management* **134**, 119–125.
Porkka M, Guillaume JH, Siebert S, Schaphoff S and Kummu M (2017) The use of food imports to overcome local limits to growth. *Earth's Future* **5**, 393–407.
Reimer JJ (2012) On the economics of virtual water trade. *Ecological Economics* **75**, 135–139.
Romalis J (2004) Factor proportions and the structure of commodity trade. *The American Economic Review* **94**, 67–97.
Rosa L, Rulli MC, Davis KF, Chiarelli DD, Passera C and D'Odorico P (2018) Closing the yield gap while ensuring water sustainability. *Environmental Research Letters* **13**, 104002.

Sayan S (2003) H-O for H_2O: can the Heckscher-Ohlin framework explain the role of free trade in distributing scarce water resources around the Middle East? *Review of Middle East Economics and Finance* **1**, 215–230.

Schleussner C-F, Donges JF, Donner RV and Schellnhuber HJ (2016) Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proceedings of the National Academy of Sciences* **113**, 9216–9221.

Seekell D, D'Odorico P and Pace M (2011) Virtual water transfers unlikely to redress inequality in global water use. *Environmental Research Letters* **6**, 024017.

Suweis S, Konar M, Dalin C, Hanasaki N, Rinaldo A and Rodriguez-Iturbe I (2011) Structure and controls of the global virtual water trade network. *Geophysical Research Letters* **38**, L10403.

Taylor MS (2005) Unbundling the pollution haven hypothesis. *Advances in Economic Analysis & Policy* **4**, 1–28.

Wichelns D (2010) Virtual water: a helpful perspective, but not a sufficient policy criterion. *Water Resources Management* **24**, 2203–2219.

Yang H and Zehnder AJ (2002) Water scarcity and food import: a case study for southern Mediterranean countries. *World Development* **30**, 1413–1430.

Yang H and Zehnder AJ (2007) Virtual water: an unfolding concept in integrated water resources management. *Water Resources Research* **43**, W12301.

Cite this article: Afkhami M, Bassetti T, Ghoddusi H, Pavesi F (2022). Virtual water and the inequality in water content of consumption. *Environment and Development Economics* **27**, 470–490. https://doi.org/10.1017/S1355770X21000401