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The role of scarcity in global virtual water flows

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Abstract

Recent analyses of the evolution and structure of trade in virtual water revealed that the number of trade connections and volume of virtual water trade have more than doubled over the past two decades, and that developed countries increasingly draw on the rest of the world to alleviate the pressure on their domestic water resources. Our work builds on these studies, but fills three important gaps in the research on global virtual water trade. First, we note that in previous studies virtual water volumes are lumped together from countries experiencing vastly different degrees of water scarcity. We therefore incorporate water scarcity into assessments of virtual water flows. Second, we note that some previous studies assess virtual water networks only in terms of immediate water used for food production, but omit indirect virtual water used throughout the supply chains underlying all traded goods. In our analysis we therefore use input-output analysis to also include indirect virtual water. We note existing conflicting views about whether trade in virtual water can lead to overall savings in global water resources. We re-visit the Heckscher-Ohlin Theorem in the context of direct as well as indirect virtual water in order to determine whether international trade can be seen as a feasible demand management instrument in alleviating water scarcity. We find that the structure of global virtual water networks changes significantly after adjusting for water scarcity. In addition, when indirect virtual water is appraised the Heckscher-Ohlin Theorem can be validated.

Keywords: Virtual water, multi-region input-output analysis, regional aggregation, scarcity, international trade

1 Introduction

Today, the problem of water shortage affects 40% of the global population (Hinrichsen *et al.* 1997). In the past, water policy schemes aimed at alleviating water shortage focused more on the development of irrigation infrastructures for expansion of irrigated area. However, these expansionary policies are not sufficient as demand for water continues to increase (Postel 1999). Moreover, the development of further irrigation projects is debatable, given growing concerns over the adverse environmental effects of large dam projects (McCartney *et al.* 2000). In the coming decades, population growth and economic development, coupled with rising scarcity of water, may lead to further increase in costs of water supply development. This is threatening the economy of many river basins, and thus drawing countries that share these basins into possible water conflicts (Spulber and Sabbaghi 1994; Just and Netanyahu 1998; Beach *et al.* 2000; Dinar and Dinar 2000). Global climate change may put further pressure on the existing hydrological systems with increasing water demand as the variability of water supply are expected to change (Kenneth and Major 2002). Coping with the effects of climate change on water will require stronger demand management measures to enhance the efficient usage of water.

The work described in this article is aimed at shedding further light on questions surrounding the trends outlined above, by investigating two research questions. First, we re-visit the Heckscher-Ohlin (H-O) Theorem in the context of virtual water in order to determine whether international trade can be seen as a feasible demand management instrument in alleviating water scarcity. Since we utilize input-output methods to gain new insights about H-O-type trade-endowment relationships, we secondly examine how water scarcity can be incorporated into input-output assessments of virtual water requirements.

1.1 Revisiting the Heckscher-Ohlin Theorem in the context of virtual water

Allan 1997 claims that international virtual trade can help to distribute uneven endowments of water in the world and achieve global water use efficiency. There exists both evidence and counter-evidence with regard to Allan’s claim that water scarcity and water trade are positively related. Studies supporting Allan’s claim found that direct relationship between water scarcity and import of grains. However these studies are based on trade patterns for certain water intensive crops. Counter evidence found lack of relationship between virtual water trade and water scarcity. Kumar and Singh 2005 found that important determinants for virtual water trade include other factors like the amount of arable land. Other studies that came up with similar conclusions include those by Ramirez-Vallejo and Rogers 2004 and Verma *et al.* 2009.

Ansink 2010 claims that water scarcity is not related to virtual water trade in the way as proposed by Allen. Instead, comparative advantage in terms of water availability is only one of potentially many factors that determine the amount of virtual water trade. Suppose there are two countries A and B. Consider, Country A is water abundant, while Country B is capital abundant. The Heckscher–Ohlin (H-O) Theorem states that the water-abundant country A exports the water-intensive good, while the capital-abundant country B exports the capital-intensive good. But there could be a situation where export of virtual water embedded in the water-intensive good of country A is less than the import of virtual water in a sufficient amount of the capital-intensive good from country B. Such a situation may arise as water is an input to the production of both goods. In such a case, even though the country A exports the water-intensive good, it would still be a net importer of virtual water, and the theorem would fail.

Does the problem lie with the theorem itself, or with the way we have used the theorem to claim that virtual water trade can alleviate water scarcity? The H-O model has survived for more than half a century and still serves as a workhorse trade model that is particularly relevant to analyze trade driven by differences in endowments. On the other hand, the basic approach in quantifying the virtual water trade flows so far may have been too simple to indicate whether a water scarce country is a net importer or exporter of water. Bottom-up techniques calculate the virtual water trade flows by simply multiplying international trade flows (tons/yr) by their associated virtual water content (m^3/ton), and thus fail to take into account indirect, or virtual water requirements. Hence, such a simplistic methodology may not be robust enough to test the H-O theorem. Approaches using input-output tables linked to water accounts are able to make a clear distinction between direct and indirect water consumption (Zhao *et al.* 2009), and can hence be used to derive the complete factor (water) input requirements of each country, on the basis of which the H-O model can be re-tested. Improving input-output analyses of water requirements are therefore the aim of our second research question.

1.2 Incorporating scarcity into input-output analyses of water requirements

It is conceivable that in the future, the assessment of international trade in virtual water will gain importance, similar to the assessment of internationally traded embodied carbon, which is high on the agenda in the debate about countries' responsibility for climate change (Peters and Hertwich 2008a).

A tool that is increasingly applied to the assessment of carbon embodied in international trade is multi-region input-output (MRIO) analysis (Hertwich and Peters 2009; Wiedmann 2009b; Sato 2012). MRIO analysis is a variant of input-output (IO) analysis, operating on large databases combining the input-output tables of many regions (Leontief and Strout 1963). It was already one of the items on Leontief's original toolbox (Leontief and Strout 1963, with a first empirical case study by Polenske 1970), but its computational and labour intensity[1] meant that only very few globally comprehensive and sectorally detailed models have been developed so far (Wiedmann *et al.* 2011). Today, there exist only a handful of truly global MRIO tables with environmental satellite accounts (EXIOPOL 2008; WIOD 2010; Peters 2011; Lenzen *et al.* 2012), that are capable of being applied to questions pertaining to international trade of emissions, energy and embodiments of natural resources in general (Peters and Hertwich 2006; Wiedmann *et al.* 2007). Of particular appeal appears to be capability of these MRIO models to elucidate the consumer responsibility of countries for global greenhouse gas emissions (Munksgaard and Pedersen 2001; Peters 2008; Peters and Hertwich 2008a; Peters and Hertwich 2008b; Wiedmann 2009b), also termed their carbon footprint (Hertwich and Peters 2009; Wiedmann 2009a). For example, Wiedmann *et al.* 2008 dispelled belief upheld and expressed by the UK government that British CO_2 emissions had been declining over the years, by

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[1] See Bouwmeester and Oosterhaven 2008; Oosterhaven *et al.* 2008; Tukker *et al.* 2009; Lenzen *et al.* 2010; Peters 2011 for an account of the challenges involved in compiling global MRIO tables.

showing that in reality emissions had only been outsourced abroad to countries such as China, and were growing instead. Whilst greenhouse gas emissions have certainly been the main focus of environmentally-extended (MR)IO analysis, the inter-regional trade of virtual water is attracting more and more interest (Lenzen and Foran 2001; Duarte *et al.* 2002; Okadera *et al.* 2006; Velázquez 2006; Dietzenbacher and Velázquez 2007; Guan and Hubacek 2007; Lenzen 2009).

The advantage of IO analysis over bottom-up techniques is its ability to cover the complete environmental repercussions facilitated through complex supply chains underpinning the production of commodities worldwide. Thus, IO analysis is able to quantify carbon or water footprints without systematic truncation errors that affect bottom-up methods such as process analysis (Lenzen 2000). This has already been shown by Feng *et al.* 2011 in a comparison of global water footprints calculated using IO analysis and a bottom-up method. However, one drawback of IO analysis is that industry sectors and commodities are usually represented in more or less aggregated groups, thus preventing assessments for specific products or activities. Hybrid techniques combining IO and process analysis have been developed in order to benefit from the strengths of both approaches (Suh *et al.* 2004).

The problem of a lack of detail is especially true for world IO tables. Existing MRIO tables distinguish in the order of 129 regions, each broken down into typically 57 sectors.[2] Some of the regions in these tables are single countries, some are groups of countries.[3] There are two specific problems arising from the lack of regional detail in world input-output tables, when these are applied to the environmental indicator of water. First, many areas of critical water problems exist in developing countries that are not distinguished in existing MRIO databases. Second, existing MRIO databases group together countries characterised by widely varying degrees of water scarcity.[4] However, calculating global water footprints by adding the use of scarce water in one region to the use of abundant water in another region makes little sense, because such footprints would not be able to indicate regions and/or commodities in need of policy measures to mitigate water-related problems. This problem is evident for example in the global virtual water study by Feng *et al.* 2011, and it is this regional aggregation and water scarcity aspect that is the second focus of our work.

In this work, we therefore offer a method for incorporating water scarcity into MRIO analyses of global water requirements. For the first time, we characterise national footprints and trade balances in terms of scarce water. In addition, we apply the input-output technique of structural path analysis (SPA) in order to identify major global routes conveying pressure on water resources from centres of consumption to regions of water scarcity.

The remainder of this paper will unfold as following: In Section 2 we will explain our methodology and data sources. In particular, we will explain how we separate water-scarce from water-abundant

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[2] GTAP (Global Trade Analysis Project 2008) Version 8: 57 sectors and 129 regions; EXIOPOL (EXIOPOL 2008): EU27 and 16 non-EU countries, and about 130 sectors; WIOD (WIOD 2010): 27 EU countries and 13 other major countries in the world, 35 industries and 59 products.

[3] See for example GTAP's region breakdown at https://www.gtap.agecon.purdue.edu/databases/regions.asp?Version=8.211.

[4] For instance, the GTAP database includes in its composite region "Rest of former Soviet Union" the countries Tajikistan, Turkmenistan, and Uzbekistan. These countries vary widely in per-capita water withdrawals (1997, 5484, and 2444 m^3/cap/yr respectively). Similar disparities hold for the GTAP regions "Rest of Central Africa", "Western Africa" and "Eastern Africa".

regions, and how we weight quantities of water used according to their scarcity. In Section 3 we will then present our results, and compare unweighted with weighted footprints. Section 4 concludes.

2 Methodology and data sources

2.1 Multi-region input-output and structural path analysis

The theory of (MR)IO analysis has been explained in detail in many journals and books[5], so that here only its essential elements shall be recapitulated. The basic ingredient of MRIO analysis is a multi-region input-output table containing intermediate demand **T**, final demand **y**, and value added **v** (Fig. 1). Such a table is basically a balanced financial account of actors in the world economy: Industry sectors (for example agriculture) act as intermediate suppliers and demanders of commodities, and their transactions are recorded in the **T** matrix. Households, the government, and the capital sector are final demanders of commodities that these industries produce (recorded in **y**)[6], but they are also the recipients of the components of value added, that is wages, salaries, taxes, and operating surplus.

	Country A	Country B	Country C	
Country A	Domestic transactions in A	Trade from A to B	Trade from A to C	Final demand in A
Country B	Trade from B to A	Domestic transactions in B	Trade from B to C	Final demand in B
Country C	Trade from C to A	Trade from C to B	Domestic transactions in C	Final demand in C
	Value added in A	Value added in B	Value added in C	

Fig. 1: Schematic of a multi-region input-output table.

Each of the input-output components **T**, **y** and **v** contains sub-blocks pertaining to the information of the various countries (Fig. 1). In turn, each of these sub-blocks is broken down into industry sectors (Fig. 2). For example, $y^{\mathrm{A}}_{\mathrm{Mf,Hh}}$represents the final demand of manufactured products by households in A. $T^{\mathrm{A,C}}_{\mathrm{Ag,Mf}}$ represents the international trade of agricultural commodities produced in country A received by manufacturing sectors in country C. $v^{\mathrm{C}}_{\mathrm{Govt,Sv}}$ represents the taxes collected by the government on the production of service providers operating in country C.

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[5] For non-expert introductions into IO analysis and its applications to environmental issues consult Duchin 1992; Goodstein 1995; Dixon 1996; Forssell and Polenske 1998. For reference works on the technique see Leontief 1986 and Miller and Blair 2010.

[6] In a multi-region input-output table, exports and imports are endogenous, and as such part of **T**, and not part of **y** as in single-region input-output tables.

	Ag C	Mf C	Sv C	Hh	Govt	Cap
Agriculture A	$T^{\mathrm{A,C}}_{\mathrm{Ag,Ag}}$	$T^{\mathrm{A,C}}_{\mathrm{Ag,Mf}}$	$T^{\mathrm{A,C}}_{\mathrm{Ag,Sv}}$	$y^{\mathrm{A}}_{\mathrm{Ag,Hh}}$	$y^{\mathrm{A}}_{\mathrm{Ag,Govt}}$	$y^{\mathrm{A}}_{\mathrm{Ag,Cap}} \cdots$
Manufacturing A	$T^{\mathrm{A,C}}_{\mathrm{Mf,Ag}}$	$T^{\mathrm{A,C}}_{\mathrm{Mf,Mf}}$	$T^{\mathrm{A,C}}_{\mathrm{Mf,Sv}}$	$y^{\mathrm{A}}_{\mathrm{Mf,Hh}}$	$y^{\mathrm{A,}}_{\mathrm{Mf,Govt}}$	$y^{\mathrm{A}}_{\mathrm{Mf,Cap}} \cdots$
Services A	$T^{\mathrm{A,C}}_{\mathrm{Sv,Ag}}$	$T^{\mathrm{A,C}}_{\mathrm{Sv,Mf}}$	$T^{\mathrm{A,C}}_{\mathrm{Sv,Sv}}$	$y^{\mathrm{A}}_{\mathrm{Sv,Hh}}$	$y^{\mathrm{A}}_{\mathrm{Sv,Govt}}$	$y^{\mathrm{A}}_{\mathrm{Sv,Cap}} \cdots$
Households	$v^{\mathrm{C}}_{\mathrm{Hh,Ag}}$	$v^{\mathrm{C}}_{\mathrm{Hh,Mf}}$	$v^{\mathrm{C}}_{\mathrm{Hh,Mf}}$			
Government	$v^{\mathrm{C}}_{\mathrm{Govt,Ag}}$	$v^{\mathrm{C}}_{\mathrm{Govt,Mf}}$	$v^{\mathrm{C}}_{\mathrm{Govt,Sv}}$			
Capital	$v^{\mathrm{C}}_{\mathrm{Cap,Ag}}$	$v^{\mathrm{C}}_{\mathrm{Cap,Mf}}$	$v^{\mathrm{C}}_{\mathrm{Cap,Sv}}$			

Fig. 2: Schematic of the shaded area in Fig. 1. Note that the **y** and **v** blocks are also broken up by pairs of countries, ie $y^{\mathrm{A,B}}_{\mathrm{Mf,Hh}}$, $y^{\mathrm{C,A}}_{\mathrm{Mf,Hh}}$, $v^{\mathrm{B,C}}_{\mathrm{Cap,Hh}}$, or $v^{\mathrm{A,A}}_{\mathrm{Hh,Sv}}$. For the sake of brevity this detail is omitted here.

Assuming that all monetary transactions and movements of commodities are accounted for, the input-output account satisfies a sector-wise row-column balance, in that (subject to more intricate matters of valuation) gross input is the transpose (prime symbol ‘) of gross output, and

$$\mathbf{T1}^{\mathbf{T}} + \mathbf{y1}^{\mathbf{y}} = \mathbf{x} \text{ and } \mathbf{1}^{\mathbf{T}\prime}\mathbf{T} + \mathbf{1}^{\mathbf{v}\prime}\mathbf{v} = \mathbf{x}' \,, \tag{1}$$

where $\mathbf{1}^{\mathbf{T}}$, $\mathbf{1}^{\mathbf{y}}$ and $\mathbf{1}^{\mathbf{v}}$ are suitable summation operators $\mathbf{1} = \{1,1,\dots,1\}$. Eq. 1 is a matrix identity. Eq. 1 leads to Leontief’s famous demand-pull model of the above circular process in a demand-driven economy. Using the intermediate inputs matrix **T** to define an input coefficients matrix as $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$, where the hat symbol denotes diagonalisation of a vector, and considering that $\mathbf{T} = \mathbf{Ax}$, we find that

$$\mathbf{T1}^{\mathbf{T}} + \mathbf{y1}^{\mathbf{y}} = \mathbf{x} \Leftrightarrow \mathbf{y1}^{\mathbf{y}} = \mathbf{x} - \mathbf{A} \Leftrightarrow \mathbf{y1}^{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\mathbf{x} \Leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y1}^{\mathbf{y}} \,, \tag{2}$$

where **I** is an identity matrix. Eq. 2 is Leontief’s fundamental input-output equation. Usually, analysts assume exogenous final demand **y**, which then drives intermediate demand, directly as well as indirectly along complex supply chains, and ultimately requires the generation of output **x** in order to be met.

The extension of Eq. 2 to environmental effects is straightforward. For example, let **Q** be a row vector holding the water use of all industry sectors in the economy (which would give it a shape equal to the vector **m** in Fig. 1). Using **Q** to define water input coefficients $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$, we find that total water use $Q = \mathbf{qx}$ can be written as

$$Q = \mathbf{qx} = \mathbf{q}\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y1}^{\mathbf{y}} = \boldsymbol{\mu}\,\mathbf{y1}^{\mathbf{y}} \,. \tag{3}$$

Here, $\boldsymbol{\mu} = \mathbf{q}\,(\mathbf{I} - \mathbf{A})^{-1}$ is called a vector of water multipliers, because it multiplies the final demand elements $\mathbf{y1}^{\mathbf{y}}$ in a way that their total effects cascading throughout the supply-chain network (described by **A**) add up to water use **qx** of gross output. For example, assume the purchase of a loaf of bread contained in domestic final demand $\mathbf{y1}^{\mathbf{y}}$. Producing bread does not entail substantial water use. However, irrigating grain, which is two supply-chain stages upstream from bread manufacturing is associated with significant water use, and this water use is contained in the value of $\boldsymbol{\mu} = \mathbf{q}\,(\mathbf{I} - \mathbf{A})^{-1}$ for the bread manufacturing sector, by virtue of **q** containing the water use of grain growing, and **A** distributing $\mathbf{q}_{\mathrm{grain}}$ down the supply chains into $\boldsymbol{\mu}_{\mathrm{bread}}$. In other words, **qx** is a producer representation (a *producer inventory*), and $\boldsymbol{\mu}\,\mathbf{y1}^{\mathbf{y}}$ is a consumer representation (a *water footprint*), of national water use Q (for further interpretations see Lenzen 2009).

The supply-chain information contained in the Leontief inverse $(\mathbf{I} - \mathbf{A})^{-1}$ can be illustrated using the its series expansion (Waugh 1950)

$$(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots , \tag{4}$$

which can be used to “unravel” total national water use Q into

$$Q = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\, \mathbf{y1}^{\mathbf{y}} = \mathbf{q}\, \mathbf{y1}^{\mathbf{y}} + \mathbf{qA}\, \mathbf{y1}^{\mathbf{y}} + \mathbf{qA}^2\, \mathbf{y1}^{\mathbf{y}} + \ldots . \tag{5}$$

The terms in Eq. 5 are called structural paths (Crama *et al.* 1984; Defourny and Thorbecke 1984; Treloar 1997; Sonis and Hewings 1998). The three-stage supply chain described in words above, for example, is contained in an $\mathbf{A}^3$ term

$$Q_{\text{grain,meal}} = q_{\text{grain}}\, A_{\text{grain,flour}}\, A_{\text{flour,bread}}\, A_{\text{bread,restaurant}}\, y_{\text{restaurant}} \,. \tag{6}$$

Note that for an economy represented by a 100-sector $\mathbf{T}$ matrix, there are 100 1st-order ($\mathbf{A}$) paths, 100^2 = 10,000 2nd-order ($\mathbf{A}^2$) paths, 100^3 = 1 million 3rd-order ($\mathbf{A}^3$) paths, and so on. Hence, the series expansion in Eq. 5 contains an infinite number of structural paths such as the one in Eq. 6. Since the elements of $\mathbf{A}$ are smaller than 1, the values of longer paths are usually smaller than those of shorter paths. This feature ensures that the infinite sum in Eq. 5 converges towards a finite value, which is total water use Q in the economy. Thus, structural path analysis is able to provide a collectively exhaustive and mutually exclusive atomic representation of virtual water flow in a complex economic system.

2.2 Measures of water scarcity

Differences in resource endowment and demand conditions are some of the basic reasons for trade to take place between countries. It is clear that regions can gain from trade if they specialize in goods and services for which they have a comparative advantage. A region is therefore considered to have comparative advantage in producing a water-intensive good if the opportunity cost of producing it is lower in that country than in its trading partners (Verma 2009). By reporting on total national water use, existing input-output satellite accounts ignore such comparative advantage in terms of water resource endowments and increasing water demand conditions. We have, therefore, constructed a water scarcity index that can be used as a weight for converting total water use into scarce water use. The water scarcity index we use is based on a measure of water withdrawals as a percentage of the existing local renewable freshwater resources. Global data for this measure are provided by the FAO 2012. According to the FAO, “*this parameter is an indication of the pressure on the renewable water resources*”. A similar measure, the Water Exploitation Index, was developed by Alexander and West 2011; it compares the water stress for various countries, but data are only available for the Asia-Pacific region.

We use the water scarcity index directly as scarcity weights $\mathbf{w}$ specific for each country, and simply element-wise multiply (#) the water use account $\mathbf{Q}$ in order to obtain a scarcity-weighted water use account $\mathbf{Q}^* = \mathbf{Q}\ \#\ \mathbf{w}$. The scarcity-weighted account $\mathbf{Q}^*$ is then subjected to the same Leontief demand-pull calculus (for example Eq. 3 yielding $\boldsymbol{\mu}^*\ \mathbf{y1}^{\mathbf{y}} = \mathbf{q}^*\ (\mathbf{I} - \mathbf{A})^{-1}\ \mathbf{y1}^{\mathbf{y}}$, using $\mathbf{q}^* = \mathbf{Q}^*\hat{\mathbf{x}}^{-1}$) and structural path analysis (Eq. 5) as the unweighted account $\mathbf{Q}$.

2.3 Data sources

This work is concerned with the quantification of global virtual water flows, using MRIO tables at high country and sector detail. For this purpose, we make use of the Eora MRIO database, providing an MRIO system {**T**, **y**, **v**, **x**, **Q**} and derived matrices {**q**, **A**} containing 187 countries, represented at high sector detail (Lenzen *et al.* 2012). Each country is represented at a resolution of 25-500 sectors, depending on raw data availability, for a total of >15,000 sectors. The Eora MRIO presents a completely harmonised and balanced world MRIO table, drawing together data from major sources such as the UN System of National Accounts (SNA), UN COMTRADE, Eurostat, IDE/JETRO, and many national input-output tables.

The Eora MRIO is extended with environmental satellite indicators, one of which measures water requirements, with data taken from the AQUASTAT (FAO 2012) database. The virtual water content (m3/ton) of primary crops is based on yields of the crops and their water requirements. Crop water requirement is the total water required for evapotranspiration, from planting to harvest for a given crop under the condition that water resource availability does not have constraining effects on crop yield (Allen *et al.*, 1998). The crop water requirement of each crop is computed using CROPWAT developed by FAO (FAO 2012).

From the AQUASTAT (FAO 2012) database we also obtained the percentage of total actual renewable freshwater resources withdrawn, also called the Water Extraction Index (*WEI*), for 170 countries for 2000. Of these, 24 did not have *WEI* data for the year 2000 so we used the data for the closest adjacent year (between 1995 and 2005), depending on availability. To bring the *WEI* coverage up to 200 countries, for 30 additional smaller countries with no *WEI* data available we assumed water was essentially perfectly abundant, or *WEI* = 0.01.

We chose the year 2000 for our analysis of global virtual water flows, because the water use information in FAO 2012 is valid for years around 2000, and also because the coverage of countries in the United Nations Official Country Database, on which the Eora MRIO relies, is best for years around 2000.

3 Results

In the following we will use the short-hand “scarce-water” in order to refer to result expressed in terms of scarcity-weighted water consumption.

3.1 Water and scarce-water domestic consumption of nations

We begin with the conventional representation of water use in national water accounts. Tab. 1 shows results obtained from tabulating unweighted water use (panel a) $\mathbf{Q} = \mathbf{qx}$, and scarcity-weighted water use $\mathbf{Q}^* = \mathbf{q}^*\mathbf{x}$ (panel b).

Ten countries top-ranked in terms of their water use

Country	Water use in TL
India	1083
China	973
USA	700
Brazil	409
Russia	280
Indonesia	272
Nigeria	255
Thailand	169
Pakistan	161
Mexico	134

(a)

Ten countries top-ranked in terms of their scarce-water use

Country	Water use in TL
India	346
China	190
Pakistan	112
USA	108
Iran	67
Egypt	61
Sudan	48
Uzbekistan	36
Syria	35
Iraq	32

(b)

Tab. 1: Ten countries top-ranked in terms of their water use (a) and scarce-water use (b).

As could be expected, large and/or populous nations such as India, China, the USA, Brazil, Russia and Indonesia occupy top ranks amongst countries in terms of total water use. However, the introduction of scarcity weights sees relatively water-scarce countries such as Nigeria, Pakistan and Turkey gain top positions, whilst relatively water-abundant countries such as Brazil and Russia drop in their ranks.

Country	Unweighted	Scarcity-weighted	Relative diff
Uzbekistan	36.2	36.2	0.0%
Yemen	9.5	9.5	0.0%
Qatar	2.3	2.3	0.0%
UAE	3.2	3.2	0.0%
Saudi Arabia	14.5	14.5	0.0%
Libya	7.4	7.4	0.0%
Egypt	61.4	61.4	0.0%
Turkmenistan	13.7	13.7	0.0%
Syria	36.8	34.7	6.1%
Oman	2.2	2.1	6.1%

Tab. 2a: Ten countries top-ranked in terms of the scarcity-weighting impact. Columns show unweighted and scarcity-weighted national water use in TL, as well as their relative difference $| \mathbf{qx} - \mathbf{q}^*\mathbf{x} | \times 2 / (\mathbf{qx} + \mathbf{q}^*\mathbf{x})$.

Country	Unweighted	Scarcity-weighted	Relative diff
Sierra Leone	5.0	0.0	199%
Fiji	1.5	0.0	199%
Paraguay	12.8	0.0	199%
Gabon	1.3	0.0	200%
Liberia	4.3	0.0	200%
DR Congo	37.6	0.0	200%
Central African Republic	5.4	0.0	200%
Papua New Guinea	8.1	0.0	200%
Ireland	4.1	0.0	200%
Congo	1.3	0.0	200%

Tab. 2b: Ten countries bottom-ranked in terms of the scarcity-weighting impact. Columns show unweighted and scarcity-weighted national water use in TL, as well as their relative difference $| \mathbf{qx} - \mathbf{q}^*\mathbf{x} | \times 2 / (\mathbf{qx} + \mathbf{q}^*\mathbf{x})$.

The impact of the scarcity weighting is least evident in severely water-scarce countries such as in the Middle East and North Africa, where almost all water consumed can be classed ‘scarce’. It is most evident in water-abundant countries often located in equatorial regions such as Central Africa where hardly any water consumed can be regarded as scarce. Those countries record the most drastic decreases of their nominal water footprint.

3.2 Water and scarce-water footprints of nations

We continue with the most aggregate representation of virtual water flow: national water footprints. Tab. 3 shows results $\boldsymbol{\mu}\, \mathbf{y1}^{\mathbf{Y}}$ (panel a) and $\boldsymbol{\mu}^*\, \mathbf{y1}^{\mathbf{Y}}$ (panel b) obtained from evaluating Eq. 3 using unweighted water use coefficients $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$ and scarcity-weighted water use coefficients $\mathbf{q}^* = \mathbf{Q}^*\hat{\mathbf{x}}^{-1}$, respectively. Unweighted water footprints from our study largely agree with those determined by Chapagain and Hoekstra 2004 and Feng *et al.* 2011; this is documented in Lenzen *et al.* 2012.

Ten countries top-ranked in terms of their water footprint

Country	Water footprint in TL
USA	915
China	875
India	858
Brazil	381
Russia	303
Japan	262
Indonesia	243
Germany	234
France	180
Nigeria	175

a)

Ten countries top-ranked in terms of their scarce-water footprint

Country	Water footprint in TL
India	265
China	165
USA	151
Pakistan	81
Iran	58
Egypt	49
Germany	49
Japan	46
Italy	34
France	34

(b)

Tab. 3: Ten countries top-ranked in terms of their water footprint (a) and scarce-water footprint (b).

In contrast to the producer perspective portrayed in Tabs. 1 and 2, the consumer perspective shown in Tab. 3 now sees developed countries such as the USA, Japan, Germany and France assume top ranks, both in terms of water and scarce water. These are joined by three middle-eastern countries (Egypt, Iran, Pakistan), due to both their population size and their location in a water-scarce world region. The relative positions of countries are now determined not only by their domestic water use, but also by the virtual water embodied in their imports.

Country	Unweighted	Scarcity-weighted	Relative diff
Uzbekistan	23.3	22.4	4.2%
Yemen	7.8	7.5	4.2%
Turkmenistan	8.4	7.8	7.0%
Egypt	53.4	49.2	8.3%
Syria	21.8	19.9	8.7%
Iraq	33.9	28.7	16.6%
Qatar	2.8	2.1	25.3%
Tajikistan	4.7	3.5	30.8%
Libya	8.8	6.1	36.8%
Pakistan	117.9	81.0	37.1%

Tab. 4a: Ten countries top-ranked in terms of the scarcity-weighting impact. Columns show unweighted and scarcity-weighted national water footprints in TL, as well as their relative difference $|\mu\,\mathbf{y1}^{\mathbf{y}} - \mu\ast\,\mathbf{y1}^{\mathbf{y}}| \times 2 / (\mu\,\mathbf{y1}^{\mathbf{y}} + \mu\ast\,\mathbf{y1}^{\mathbf{y}})$.

Country	Unweighted	Scarcity-weighted	Relative diff
Chad	9.4	0.1	196%
Guinea	13.0	0.1	196%
Bolivia	23.3	0.2	196%
Benin	8.0	0.1	196%
Panama	33.6	0.3	197%
Mozambique	12.1	0.1	197%
Sierra Leone	2.5	0.0	197%
Uganda	36.1	0.3	197%
Central African Republic	3.0	0.0	198%
DR Congo	33.6	0.1	198%

Tab. 4b: Ten countries bottom-ranked in terms of the scarcity-weighting impact. Columns show unweighted and scarcity-weighted national water footprints in TL, as well as their relative difference $|\mu\, \mathbf{y1}^{\mathbf{y}} - \mu\ast\, \mathbf{y1}^{\mathbf{y}}| \times 2 / (\mu\, \mathbf{y1}^{\mathbf{y}} + \mu\ast\, \mathbf{y1}^{\mathbf{y}})$.

The impact of the scarcity weighting on national water footprints is least evident in severely water-scarce countries such as in the Middle East, Central Asia and North Africa, where almost all water consumed can be classed ‘scarce’. It is most evident in water-abundant countries often located in equatorial regions such as Central Africa and Central America, where hardly any water consumed can be regarded as scarce. Those countries record the most drastic decreases of their nominal water footprint.

3.3 Water and scarce-water net importers

Scarcity weighting reduces the trade balance in TL, but does not change dramatically the identity of net importers (Tab. 6). The latter are exclusively developed, relatively water-abundant countries that appear to import some of their virtual water as scarce water.

Ten countries top-ranked in terms of their net water imports

Country	Net water imports in TL
Japan	-222
USA	-217
Germany	-168
UK	-108
France	-97
Italy	-71
Hong Kong SAR	-68
South Korea	-47
Netherlands	-46
Spain	-45

(a)

Ten countries top-ranked in terms of their net scarce-water imports

Country	Net water imports in TL
USA	-46
Japan	-39
Germany	-32
France	-21
UK	-20
Italy	-16
Russia	-15
Hong Kong SAR	-12
Mexico	-10
Netherlands	-10

(b)

Tab. 5: Ten countries top-ranked in terms of their net imports of water (panel a: $\mathbf{q}\ \mathbf{ex} - \boldsymbol{\mu}\ \mathbf{im}$) and scarce-water (panel b: $\mathbf{q}^*\ \mathbf{ex} - \boldsymbol{\mu}^*\ \mathbf{im}$), where **ex** and **im** are vectors of exports and imports by product, respectively.

However, scarcity weighting does elevate a number of countries towards a net importer status (Tab. 6). These countries appear more importing (or less exporting) after scarcity weighting. In other words, their imports are more water-scarce than their exports.

Country	Unweighted	Scarcity-weighted
Indonesia	29.1	-0.7
Canada	4.0	-8.6
Panama	10.3	-0.2
Cameroon	9.6	-0.1
Mozambique	9.0	0.0
Papua New Guinea	6.9	0.0
New Zealand	5.2	-0.6
Guinea	4.7	0.0
Guatemala	4.4	-0.1
Liberia	3.5	0.0

Tab. 6: Ten net water importers top-ranked in terms of the scarcity-weighting impact. Columns show unweighted and scarcity-weighted net virtual water imports in TL.

Indonesia, New Zealand, and Papua New Guinea, for example, receive a major part of their imports (40%, 27%, and 9%, respectively) of their embodied scarcity-weighted water from Australia[7], which is considerably water-scarce. Mauritania, another water-scarce exporter, sends embodied water to Portugal (23% of exports), Algeria (18%), Tunisia (13%), Spain (6%), and Nigeria (5%). An impressive 70% of scarcity-weighted water exports from Ethiopia are embodied in coffee sent to Japan. The

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[7] Wheat, cotton and live cattle to Indonesia; sugar, grapes and other prepared foods to New Zealand; meat and other prepared food to Papua New Guinea.

USA, UK, and Germany are among the top recipients of embodied water from Kenya, Congo, Gabon, Senegal, Mali, and Chad.

Tab. 6 hence supports the interesting finding that proximate and therefore important trade partners of water-stressed countries play an important role in exacerbating water scarcity. This effect is especially drastic along geographical divides of water scarcity and abundance, such as the Timor Strait, the Sahel, and the Kalahari.

3.4 Water and scarce-water net exporters

Contrary to net imports, scarcity weighting reduces the trade balance in TL, as well as leads to changes in the identity of top-ranking net exporters (Tab. 7). Net exporters are almost exclusively (with the exception of Australia) developing, relatively water-scarce countries, however more Middle-Eastern and Central Asian countries rank top after scarcity weighting.

Ten countries top-ranked in terms of their net water exports

Country	Net water exports in TL
India	225
China	99
Sudan	82
Nigeria	80
Thailand	68
Myanmar	66
Cote d'Ivoire	46
Pakistan	43
Argentina	40
Australia	40

(a)

Ten countries top-ranked in terms of their net scarce-water exports

Country	Net water exports in TL
India	80
Sudan	47
Pakistan	32
China	24
Syria	15
Uzbekistan	14
Egypt	12
Australia	10
Morocco	10
Thailand	9

(b)

Tab. 7: Ten countries top-ranked in terms of their net exports of water (panel a: $\mathbf{q}\ \mathbf{ex} - \boldsymbol{\mu}\ \mathbf{im}$) and scarce-water (panel b: $\mathbf{q}^*\ \mathbf{ex} - \boldsymbol{\mu}^*\ \mathbf{im}$), where **ex** and **im** are vectors of exports and imports by product, respectively.

Egypt exports its scarce water embodied in cotton and cotton products, but also vegetables, fruit and their products to Saudi Arabia (16% of exports), Japan (12%), USA (9%), Germany (8%) and Italy (7%)

Similar to results listed in Tab. 6, scarcity weighting elevates a number of countries towards a net exporter status (Tab. 8). Water-scarce countries with water-abundant neighbours, such as the USA and Mexico, Mediterranean and Middle-Eastern countries, and South Africa, appear more exporting (or less importing) after scarcity weighting. In other words, their exports are more water-scarce than their imports. This finding confirms the important role of geographical abundance-scarcity divides for regional water scarcity.

Country	Unweighted	Scarcity-weighted
USA	-216.6	-45.6
Spain	-45.3	-5.4
Mexico	-37.2	-10.0
Turkey	-30.0	-9.3
Israel	-13.1	-1.6
Greece	-14.0	-3.6
Iran	-0.2	8.5
South Africa	-8.2	-0.4
UAE	-7.4	-1.2
Kuwait	-5.0	-1.2

Tab. 8: Ten net water exporters top-ranked in terms of the scarcity-weighting impact. Columns show unweighted and scarcity-weighted net virtual water exports in TL.

3.5 Global Structural Path Analysis (SPA) of scarce water footprints

We evaluated Eq. 5 using the data sources described in Section 2.4 in order to extract and rank those global structural paths that are most important in terms of the virtual water embodied in them. In the following we use the logic and notation from Eq. 6 when describing our results.

During the execution of our SPA algorithm (documented in Lenzen 2002), we excluded direct effects (such as $Q_{\text{bread}} = q_{\text{bread}}\ y_{\text{bread}}$) without any trading nodes, and also indirect effects with any number of trading nodes, but where no international trade was involved (such as $Q_{\text{grain,meal,Australia}} = q_{\text{grain,Australia}}\ A_{\text{grain,flour,Australia}}\ A_{\text{flour,bread,Australia}}\ A_{\text{bread,restaurant,Australia}}\ y_{\text{restaurant,Australia}}$). This is because such supply chains have already been extensively dealt with in single-region IO studies, whereas we focus on recent advances in global MRIO analysis.

One caveat in our SPA is that the granularity of the path nodes as well as the magnitude of the path value depends on the sector resolution in the MRIO classification. For example, the agricultural sector of many developing countries in the Eora database is not further disaggregated because of a lack in raw data, leading to paths such as ‘Agriculture > Food manufacturing’, with relatively high path values. As a result, many such short structural paths feature top-ranking in terms of internationally traded virtual water. This finding is rather obvious, and hence we will in the following focus our attention on longer and more diverse paths.

The top path is Fig. 9 represents cotton from Pakistan (high-quality long fibre for business shirts) that is woven into cloth for high-quality Italian men’s apparel designs, and made up into shirt and suit linings in Hong Kong. Just this 2-node global supply chain consumes 1 ML of scarce Pakistani water annually. The second path reflects 880,000 L of scarce Iraqi water pumped into medium-age oil fields in order to flood the deposit from below and force-float the crude oil to the top of the stratum. The oil thus extracted is refined in the USA, and then supplied by petrol wholesalers to consumers in Singapore. The path originating from Egypt represents citrus fruits, cane sugar and vegetable saps and extracts that are processed in the Netherlands and sent to soft drink factories in the USA. This chain is likely to include gum arabic, an important ingredient in soft drink syrups. Indian coconuts are processed in Germany and the Netherlands to give coconut oil that in turn provides the acidic taste to American soft drinks. This chain could also contain “coconut water”, a new health drink with an isotonic concentration much like blood. One can also buy “instant coconut powder for soft drinks and desserts”. Even though highly complex and specialised, this supply chain consumed 100,000 L of scarce Egyptian water. Sri Lanka most probably supplies coconut, abaca, ramie and other vegetable textile fibers to China for blending and weaving, and subsequent fabrication of clothes in Hong Kong. Most of Australian cotton is sent to Indonesia for spinning (into raw cotton yarn and staple yarn) and weaving, then to Taiwan for further processing and design, and finally to Hong Kong for apparel fabrication.

Water-using industry	Intermediate suppliers		Industry supplying final demand	Virtual water content of path (ML)	Number of path nodes
Pakistan agriculture	Italy textiles		Hong Kong wearing apparels	1.04	2
Iraq mining and drilling	USA petroleum refineries		Singapore petroleum products	0.88	2
Egypt agriculture	Netherlands food and beverages		USA soft drink and ice	0.12	2
India coconuts	Germany food	Netherlands food and beverages	USA soft drink and ice	0.10	3
Sri Lanka agriculture	China other textiles		Hong Kong wearing apparels	0.07	2
Australia cotton	Indonesia made-up textile	Taiwan other fabrics	Hong Kong wearing apparels	0.05	3

Tab. 9: Selected results from a global Structural Path Analysis of scarce virtual water. Supply-chain causality runs from left to right, starting with the water-using industry, via intermediate suppliers, to the industry supplying final consumers.

3.6 Testing the Heckscher-Ohlin Theorem

We have used ordinary least square (OLS) regression to explore how various factors related to economic, and agricultural development influence per-capita total (unweighted) water embodied in imports. We chose per-capita GDP *y*, per-capita water withdrawals *w*, per-capita agricultural land area *A*, and the percentage of total actual renewable freshwater resource withdrawn (the water scarcity index *s* introduced earlier) as explanatory variables in a multivariate regression of per-capita virtual water embodied in national imports m, of the form

$$m = \alpha + \beta_1 y + \beta_2 yw + \beta_3 A + \beta_4 s \,, \tag{7}$$

where the α and β_i $(i = 1, \ldots, 4)$ are the constant and regression coefficients related to the associated variables.

We considered, but finally excluded the Human Development Index (HDI) developed by UNDP, even though it can in principle influence virtual water trade (Falkenmark 1989) . In our analysis we also find that the HDI significantly influences virtual water import as GDP. However, as HDI and GDP are highly correlated, we have omitted the former to ensure that multi-collinearity does not lead to biased regressor estimates. Similarly, the remaining explanatory variables in the equation are chosen so that the statistical correlations between them are low enough to warrant the assumption of their independence.

Barbier 2004 examined the existence of an inverted-U relationship between economic growth and the rate of water utilization for a broad cross-section of countries, and found strong support for the hypothesized relationship. In that light, we explored whether there also exists a concave relationship between virtual water trade (imports) and GDP, but could not find any significant nonlinear relationship between the two. However, as water withdrawn and GDP are correlated (as also evident in our data), it makes sense to examine the nonlinearity using an interactive term, where we combine GDP y with water withdrawals *w*. Kumar and Singh 2005 examined whether arable land availability influences virtual water trade dynamics, and found that virtual water trade in terms of net water exports increases with increase in gross cropped area. In our multivariate regression, we include a similar variable – per-capita agricultural area as an explanatory variable in the regression to explain variations in net water import across countries.

We also explore how the variation in virtual water trade can be explained by the endowment of factors, as postulated by Heckscher-Ohlin (H-O) theorem. We examine whether any relationship exists between water scarcity and the extent of virtual water trade across countries. We test for both individual and joint influence, by considering all explanatory variables in isolation and in paired products.

Per-capita imported virtual water	*Coef*	*t*	*P* > *t*
Per-capita GDP	0.19	9.73	0
Per-capita GDP × Per-capita water withdrawals	-0.00012	-4.51	0.000
Per-capita agricultural area	50.04	4.94	0
Water Scarcity Index	1.45	3.06	0.003
Constant	-590.82	-3.89	0.000
$R^2 = 0.5323$	*F*(4,132) = 37.56		
Adjusted $R^2 = 0.5182$	*Prob* > *F* = 0.00		
No. of observations: 137			

Tab. 10: Results from a multivariate regression of per-capita imported virtual water against a number of explanatory variables described in the main text. *Coef* = Regression coefficients; *t* = Student's *t* statistic; *P* > *t* shows the 2-tailed probability used in testing the null hypothesis that *Coef* = 0. The *F*-statistic is based on the Mean Square Model divided by the Mean Square Residual.

The factors listed above explain 65% of the cross-country variation in per-capita imported virtual water (Tab. 10). Our results reveal that economically developed countries import more virtual water than developing countries. The relationship becomes stronger for countries where the domestic water extraction is low. It is reflected in the negative sign of the joint term combining per-capita GDP and per-capita water withdrawals. This result clearly indicates a tendency for developing countries to source water-intensive commodities from abroad whilst protecting their own water resources and allowing sufficient natural outflow.

Our results also suggest that per-capita agricultural land area strongly influences virtual water imports. However, Kumar and Singh 2005 found a positive relationship between net exports and gross cropped area. They interpret the increase in per-capita agricultural land as increased ability to tap the water in the soil profile, and hence explain the relationship between cultivated land and virtual water trade from the supply or water availability side. In contrast, we interpret the increase in agricultural land differently as a cause of higher food demand, based on Boserup's hypothesis (). In this context, our result implies that with increasing food demand, a country may import more virtual water.

In addition, we also find a positive relationship between water imports and water scarcity, through the inclusion of the water scarcity index in our regression study. According to our regression, water scarcity induces countries to import water-intensive commodities from elsewhere, thus validating the H-O Theorem, and contradicting the findings by Ramirez-Vallejo and Rogers 2004 and Verma *et al.* 2009. This contradiction may be due to differences in the calculation approach: Unlike other studies, we take into consideration all indirect water consumption induced by international trade flows.

4 Conclusions

With water becoming scarcer globally, virtual water trade is taking in increasingly important place in water policy discussions, and is often advocated as one in a set of feasible policy option to mitigate the spatial variability in water availability. However, before concrete policy implications can be drawn, it is pertinent to identify whether a country is relatively water scarce in terms of virtual water consumption, and this is where the current literature lacks information. Studies published so far either indicate water scarcity without dealing with indirect effects that ripple through international supply chains, or quantify virtual water trade without considering scarcity. Our study is unique in that it has filled a research gap by using a Multi-Region Input-Output framework to quantify both the direct and indirect consumption of scarce water. The approach adds value to the literature on virtual water by identifying major global routes conveying pressure on water resources from centres of consumption to regions of water scarcity, thus facilitating water policy dialogue and formulation.

Wichelns[i] 2011 critique of the virtual water metric lists eleven issues that hypothetically negate its global use as a stress measure for the water system. By using only the “blue” or managed water component, applying a scarce water correction and following the water-containing good or service to the final consumption country, this study has answered most of those criticisms. Wilchens’ ninth criticism, “that consumers in one region [are not] responsible for water scarcity or water quality degradation in another”, is not supported analytically here. Additionally, it does not concur with evolving policy dialogues in the area of greenhouse emissions ({Peters, 2008 #3914}) and biodiversity decline ({Lenzen, 2012 #4960}) where original producers and final consumers are judged in the first case, to share responsibility equally.

The evolution and structure of trade in virtual water by Dalin[ii] et al. 2012 reveal that the number of trade connections and volume of virtual water trade have more than doubled in the last 22 years. An important difference in that study was that it focused only traded food commodities and its virtual water combined both blue (extracted) and green (soil) water. A key finding focused on soy exports to China and the change from USA to Brazil and Argentina as the main suppliers. Their interpretation suggests global water savings and increasing efficiencies of water use due to these trade flows because of water availability and growing conditions in the producing countries. The whole-economy and scarce-water focus in this study highlights textile chains and possibly cotton growing as drivers of scarce water extraction and thus possible causes of concern. The studies show broad agreement in Dalin *et al* citing China as the largest virtual water importer while this analysis shows China as second behind the USA as both producers and consumers of scarce water.

A difference in resource endowment is often regarded as one of the basic reasons for trade between countries. The value of our approach to scarcity weighting of water requirements is revealed in our validation of the Heckscher-Ohlin Theorem, indicating that water-scarce countries are likely to import more water than water-abundant countries, thus contradicting the results of previous studies in which virtual water flows were not quantified.

Overt emphasis on international trade in scarce water resources may distract from tractable responses within countries. Feng[iii] et al. 2012 for China, Faramari[iv] et al 2010 for Iran and Zeitoun[v] et al. 2010 for Egypt highlight national responses where water-rich regions could provide larger shares of water intensive food production allowing water in scarce regions to be re-allocated to products and services with higher value returns per unit of water. Hoekstra[vi] 2009 however emphasises the high import-dependency in virtual water terms of many water scarce countries on limited numbers of grain producers such as the USA, Brazil and Argentina. Thus the tension grows between calls for international ‘virtual water’ treaties and legal rights, and ensuring that each sovereign state makes its own required regional and industry adjustments to improve food security of its citizens.

While this study entrains the global complexity needed to adjust production chains and trade dynamics there are two areas still beyond its reach. Firstly, the question of why and how to significantly adjust production chains that consume scarce water will be difficult. For countries such as Uzbekistan and Pakistan, nearly 25% of their total exports are raw cotton and yarns, derived from scarce water use and thus difficult to change while maintaining commerce and national stability. Elsewhere[vii] we have argued for a three-tier approach having producers utilise the best production methods, having intermediate agents trade only in certified good, and empowering consumers through product labelling and education. The second area concerns the planetary boundary concept of Rockstrom[viii] et al and how water, and scarce water, interacts with issues of rising nutrient use, biodiversity decline, land clearance, amongst others. Rockstrom and Karlberg[ix] 2010 call for a green revolution focusing on rainfed systems, green rather than blue water, and improved accounting of water at global and regional scales. This study can highlight many of the ‘at risk’ production chains and countries and so might become one of the starting points. It may also underpin a global certification framework that could lead to product labelling.

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