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Analysis

International trade of scarce water ☆

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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 import water embodied in goods from the rest of the world to alleviate pressure on domestic water resources. At the same time, as demand continues to increase and climate change threatens to alter hydrological cycles, water scarcity is a growing problem. Does research into virtual water trade need to consider water scarcity and differentiate flows out of water-scarce regions from flows out of water-abundant regions? Previous studies sum and compare virtual water volumes originating in countries experiencing vastly different degrees of water scarcity. We therefore incorporate water scarcity into an assessment of global virtual water flows. We use input–output analysis to include indirect virtual water flows. We find that the structure of global virtual water networks changes significantly after adjusting for water scarcity.

1. Introduction

In the past, water policy schemes aimed at alleviating water shortage focused on the development of irrigation infrastructures for expansion of irrigated area. However, such expansionary policies have proven insufficient as demand for water continues to increase (Konar et al., 2012; Postel, 1999). Moreover, the development of further irrigation projects has been criticized given growing concerns over the adverse environmental effects of large dam projects (McCartney et al., 2000). As a result, water shortage affects 40% of the current global population (Hinrichsen et al., 1997). In the coming decades, population growth and economic development, coupled with increasing 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 (Beach et al., 2000; Dinar and Dinar, 2000; Just and Netanyahu, 1998; Spulber and Sabbaghi, 1994). Global climate change may exacerbate scarcity problems as the variability of water supply is 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.

International virtual water trade has been advocated by several researchers (Allan, 1997; Chapagain et al., 2006; Yang et al., 2006) to help to distribute uneven endowments of water in the world and achieve global water use efficiency. Ridoutt and Pfister (2010a) argue that 90% of water extraction is associated with the life cycle of products rather than with direct use by households, thus lending importance to the analysis of water-intensive supply chains. Dalin et al. (2012) showed 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 import water embodied in goods from rest of the world to alleviate pressure on domestic water resources. Some studies based on trade patterns for certain water-intensive crops support this view by showing a direct relationship between water scarcity and grain imports. However, many other authors have found no relationship between virtual water trade and water scarcity (Ansink, 2010; Kumar and Singh, 2005; Ramirez-Vallejo and Rogers, 2004; Verma et al., 2009). Examining global virtual water flows is hence useful for understanding the influence of international trade on water resources, and one question posed by this study is whether the consideration of water scarcity significantly affects the patterns of global trade in virtual water.

The impact of economic activity cannot be measured in terms of quantities of water used alone. The consumption of water entails a range of consequences such as for water quality, resources and availability, and more indirectly for example for biodiversity and human health. Probably the first researchers to propose a scarcity weighting for water use data were Frischknecht et al. (2006b) (see an update in Frischknecht et al., 2006a). Their Ecological Scarcity method was applied to water requirements of biofuels (Frischknecht et al., 2009) and even in an input–output analysis of Swiss

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consumption and production (Jungbluth et al., 2011). Since then, water use, water pollution or degradation, and water scarcity or (un)availability have recently been successfully included in Life-Cycle Assessment (LCA; Boulay et al., 2011; Pfister et al., 2009; Ridoutt and Pfister, 2013), notably by Pfister, Ridoutt and colleagues in Switzerland and Australia (Cooney, 2009). This is often done via scarcity weights or characterization factors (Hanafiah et al., 2011; Ridoutt and Pfister, 2013), and with additional research aims such as characterizing individual products (Gerbens-Leenes et al., 2012; Jefferies et al., 2012; Ridoutt and Pfister, 2010b), impacts on human health (Boulay et al., 2011), land resources stress (Pfister et al., 2011), or even fish species disappearance (Hanafiah et al., 2011). Kounina et al., 2012 provide a comprehensive review of methods applied in LCA for measuring freshwater use.

The approach most often used in LCA for quantifying the virtual water flows is a bottom-up technique called process analysis. A prominent detailed study with a global scope is that by Pfister et al. (2011). In process analysis virtual water flows are calculated by taking into account some but not all indirect virtual water requirements. While bottom-up techniques can offer high product resolution enabling for example to differentiate the water intensity of different crops, they may be affected by the truncation of the assessment's system boundary, resulting in indirect parts of virtual water flows remaining allocated to producers, not consumers (Feng et al., 2011). Approaches using Multi-Region Input–output (MRIO) tables linked to water accounts are able to make a clear distinction between direct and total indirect water consumption[1] (Arto et al., 2012; Feng et al., 2011), and can hence be used to derive the complete virtual water flows (see *Supporting Information* (*SI*) *S1*). The "classical" water footprint approach using process-based analysis addresses a slightly different research question, focusing often on water embodied in bilateral trade rather than on total virtual water in supply chains to final demand.

Steen-Olsen et al. (2012) published an interesting MRIO-based water footprint study using a hybrid approach pioneered by Ewing et al. (2012). The advantage of this hybrid approach is brought about by the detailed physical satellite accounts by country, type and sector that are appended to the conventional MRIO table. However this advantage applies only to the direct, and 1st-order indirect water footprint effects. This is because for indirect supply-chain effects, Steen-Olsen's hybrid analysis relies on the resolution of the MRIO just as any other MRIO water footprint study. In addition, the databases that are used to construct these physical satellites do not hold sufficient information on the identity of the using sectors, necessitating some prorating procedure, and leading to allocation errors.[2]

There exist a number of MRIO-based virtual water accounts and studies for the world (EXIOBASE, 2012; Feng et al., 2011; WIOD, 2012), however there are two specific shortcomings in these accounts which we seek to address here. 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 characterized by widely varying degrees of water scarcity. 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 (Feng et al., 2011; Pfister et al., 2009). In response, for the first time, we characterize national footprints and trade balances in terms of scarcity-weighted water for 187 individual countries. In addition, we apply Structural Path Analysis to identify major global routes conveying pressure on water resources from centers of consumption to regions of water scarcity.

So far, most virtual water concepts reflect water consumption without accounting for water scarcity. Indeed the Virtual Water concept was originally proposed to describe an alternative strategy to address 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 et al., 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. Further, it makes difficult to interpret a situation in which the opportunity cost of lower water consumption in terms lower water footprint could be higher than that of with higher water footprint, which depends upon where the water is sourced (Ridoutt and Pfister, 2010b). Our study addresses this concern by using a water scarcity index as a weight for converting total water use into scarce water use, incorporating water scarcity as a factor into global virtual water flow concept.

2. Methods

We employed the Eora global Multi-Region Input–output (MRIO) database (Lenzen et al., 2012a) containing an intermediate demand matrix **T**, final demand **y**, and value added **v**. The Eora MRIO provides a completely harmonized and balanced world MRIO table, drawn together from major sources such as the UN System of National Accounts (SNA), UN COMTRADE, Eurostat, IDE/JETRO, and many national input–output tables. It is publically available free of charge for research use at www.worldmrio.com. We extended this with a satellite account **Q** holding information on water use taken from the FAO's AQUASTAT database (FAO, 2012), which covers 204 countries (17 more than Eora). We choose the year 2000 for our analysis of global virtual water flows because the coverage of countries in the United Nations Official Country Database, on which the Eora MRIO relies, is best for years around 2000.

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 (Alexander and West, 2011). The crop water requirement of each crop is computed using CROPWAT developed by the FAO (2012). In the MRIO database, 187 countries are represented at a resolution of 25–500 sectors each, and 15,909 sectors in total. The per-crop water usage from the FAO was attributed to the corresponding sectors in each country by using correspondences matrices[3] for each country that allocate crops in detailed HS + classification to the less detailed sectoral classifications used in the MRIO. (This step introduces some loss of fidelity since the original data sources had to be aggregated to fit into the less

[1] The term 'virtual water' refers exclusively to indirect consumption, while the term Water Footprint includes both direct use (e.g. turning on the faucet at home or drinking imported Perrier) and indirect use.

[2] For example assume that for Australia and New Zealand only an aggregated 'Vegetable and fruit growing' sector existed in the MRIO, and New Zealand had manufacturing sectors called 'Vegetable products' and 'Fruit products'. Assume further that Australia exported grown vegetables and fruit to New Zealand, reflected in two data sources: a) in the UN ComTrade database, distinguished by traded product and country origin but not by using industry, and b) New Zealand's import matrix, distinguished by using industry but not by traded product and not by country origin. This means that in an unsupervised prorating procedure, the New Zealand vegetable products sector would end up using Australian fruit and the New Zealand fruit products sector would end up using Australian vegetables. Such issues can only be dealt with by manual correction of mis-allocated entries, thus rendering the hybrid approach perhaps not much less labor-intensive than pursuing a detailed expansion of a regular MRIO database (the strategy pursued in the Eora MRIO database).

[3] For more on correspondence matrices see Lenzen et al. (2012a).