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Water for Food: Evolution and Projections of Water Transfers Through International Agricultural Trade

Carole Dalin[1] and Ignacio Rodríguez-Iturbe[2]

Summary

Water resources are unevenly distributed on the planet. In some regions, while population grows and diets shift toward water-intensive products like meat, water resources are placed under increased pressure, leading to water and food security issues. Besides, many areas of the world are expected to suffer from increasingly frequent and intense droughts under climate change, which will strain water resource use in agriculture even more and potentially lead to crop failures (Field *et al.*, 2012). However, other regions have abundant water resources, prosperous agriculture and might slightly benefit from climate change in terms of crop yields (Parry *et al.*, 2007). Thus, among different strategies to increase agricultural water-use efficiency (i.e. mechanization, water-saving irrigation, fertilizers, etc.), trade of water-intensive products (e.g. agricultural commodities), or virtual water trade (VWT), is a way to improve global water-use efficiency by virtually transferring water resources to water-stressed regions.

In two articles published in peer-reviewed journals, (Dalin *et al.*, 2012a) and (Dalin *et al.*, 2012b), forming part of the Ph.D. dissertation of Carole Dalin (Dalin, 2014), we focus on the virtual water trade network associated with international food trade, built with annual trade data (FAO, 2010) and annual estimates of the virtual water content of food commodities (the amount of water required to produce a unit of product in each country (Hanasaki *et al.*, 2008b)).

In the first study, the evolution of this network from 1986 to 2007 is analyzed and linked to trade policies, socio-economic circumstances and agricultural efficiency. We find that the number of trade connections and the volume of water associated with global food trade more than doubled

[1] Grantham Research Institute, London School of Economics, London WC2A 2AE, UK.
[2] Department of Civil and Environmental Engineering, Princeton University, Princeton NJ 08540, USA.

in 22 years. Despite this growth, constant organizational features were observed in the network. However, both regional and national virtual water trade patterns significantly changed. Indeed, Asia increased its virtual water imports by more than 170%, switching from North to South America as its main partner, while North America oriented to a growing intra-regional trade (Figure 1). A dramatic rise in China's virtual water imports is associated with its increased soy imports, following a domestic policy shift in 2000. Significantly, this shift has led the world's soy market to save water on a global scale, but also relies on expanding soy production in Brazil, which contributes to deforestation in the Amazon. We find that the international food trade has led to enhanced savings in global water resources over time, indicating its growing efficiency in terms of global water use.

In the second study, we determine which variables control the virtual water trade network's structure and temporal evolution from 1986-2008, and estimate changes in the network under future scenarios. Our fitness model reproduces both the topological (connections) and weighted (flows) characteristics of the network for the whole period. Undirected and directed network properties are well reproduced in each year, assuming as sole controls each nation's GDP (Gross Domestic Product), mean annual rainfall, agricultural area, and population. The future structure of the network is estimated using climate and socio-economic projections, showing that volumes of virtual water traded will become increasingly heterogeneous and the importance of dominant importing nations will further strengthen.

Evolution of global virtual water trade flows[3]

On a global average, agricultural water productivity has improved during the 22-year period from 1986-2007 (crop yields increased by 10-47%). In particular, major soy exporters significantly reduced their water use for soybean production, notably by increasing soy yield (72% increase in Argentina from 1997-2007). Interestingly, Brazil and Argentina changed their soy yield and water productivity fast enough to reach a slightly higher level of soy water productivity than the USA by 2007 (around 1,500 *kgwater/kgsoy* vs 1,650 *kgwater/kgsoy* in the USA). Thus, as countries become major exporters of a certain crop, they tend to increase their agricultural water productivity for this crop – notably through higher yield per area – more than other countries do on a global average. This is also reflected by the positive global

[3] Additional findings, as well as detailed material and methods, can be found in the published article (Dalin *et al.*, 2012a) and its appendix.

water savings from food trade, corresponding to trade flows from relative more water-productive areas to less productive ones.

Despite water being only one of the many factors of agricultural production and trade (other factors include the economy, labor, agricultural land, etc.), we find that in 2000, global water savings represented 4% of the water used in agriculture, and this percentage increased to 9% in 2007. This illustrates that food trade actually reduces global water use by transferring commodities to relatively less-productive regions, as irrigation requirement per unit of crop vary widely among world regions (Hanasaki *et al.*, 2008b, a; Foley *et al.*, 2011). Particularly, the soy trade dramatically re-organized and changed from a system that lost water at the global scale to the most efficient food trade system in terms of water. However, deforestation of the Amazon rainforests, partially due to the expansion of Brazil's soybean production (Fearnside, 2001), has important impacts on the water cycle (Shukla *et al.*, 1990).

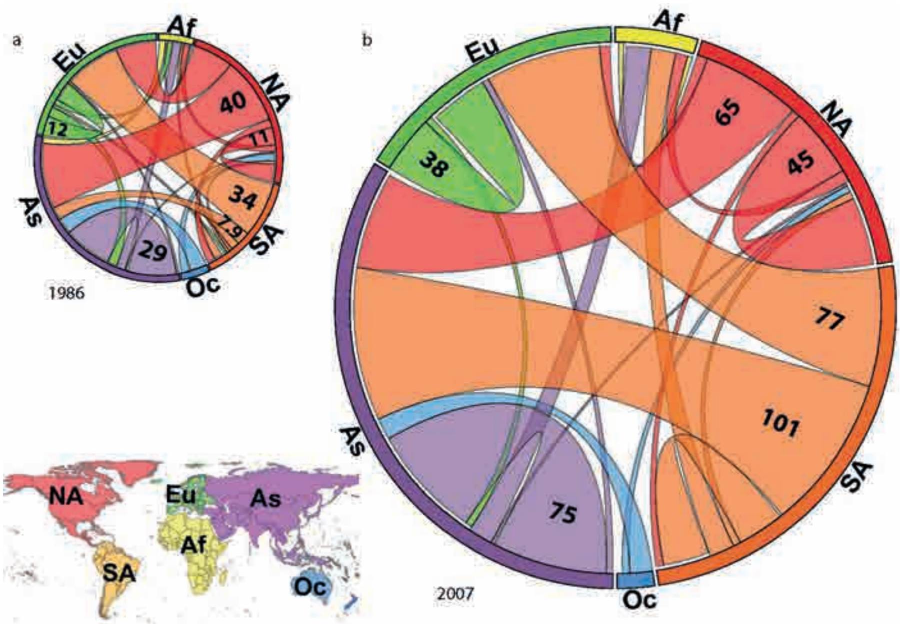

Figure 1. Virtual water flows between the six world regions: Africa (Af), North America (NA), South America (SA), Asia (As), Europe (Eu), and Oceania (Oc). Panel a: Regional VWT network in 1986. Panel b: Regional VWT network in 2007. Numbers indicate the volume of virtual water trade in billion of cubic meters (km^3), and the links' color corresponds to the exporting region. The regional map at the bottom left provides a key to the color scheme and acronyms of regions. The circles are scaled according to the total volume of VWT. Note the large difference between total VWT in 1986 (259 km^3, panel a) and 2007 (567 km^3, panel b). Taken from Dalin *et al.* (2012a).

We have quantified the important changes in the water and food systems as linked through trade. The imprint of globalization and trade policies are evident in the dynamics of the global virtual water trade network (Figure 1). Importantly, the food trade has become more efficient in terms of global water resources use over time, highlighting the important role of international trade in driving efficient allocation of resources.

Structure and controls of the global virtual water trade network over time[4]

We have shown food trade has increasingly saved water over time (Dalin *et al.*, 2012a; Konar *et al.*, 2012), as countries with low agricultural water productivity tend to import food from more productive countries. These global water savings exist even though water is usually not a strong driver of international trade. Thus, it is important to understand the major factors controlling water transfers through international food trade, or global virtual water trade.

Suweis *et al.* (2011) built a fitness model that reproduces the global structure of the international VWT network in 2000 using a few controlling variables: national GDP, rainfall, and agricultural area. This model can be used to predict the future global structure of the network under climate

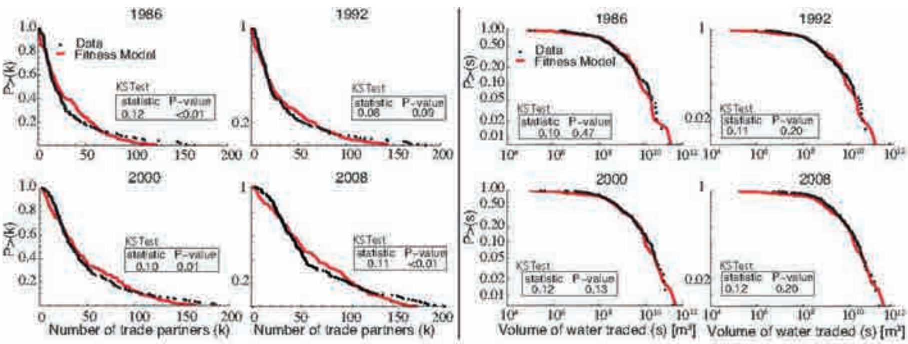

Figure 2. Exceedance probability distribution of the undirected node degree (*k*, panel a) and strength (*s*, panel b): comparison of data and model results in 1986, 1992, 2000 and 2008, using GDP and RAA, respectively. The similarity between data and model is confirmed by a Monte-Carlo Kolmogorov-Smirnov test; test results are shown in the "KS test" box. Taken from Dalin *et al.* (2012b).

[4] Additional findings, as well as detailed material and methods, can be found in the published article (Dalin *et al.*, 2012b) and its appendix.

and socio-economic changes. Here we compare the structure of the empirical network each year with the structure obtained from the fitness model using input variables specific to each year. Finally, we show the predicted structure of this network under socio-economic and climate scenarios.

In the undirected version of the network, a node's degree is the number of export and import partners of each country and a node's strength is the nation's volume of virtual water exports and imports. We find that the distribution of node degree is well fit by an exponential distribution every year. Similarly, the distribution of node strength is well fit by a stretched exponential distribution every year, presenting larger heterogeneity than the node degree distribution. This reflects the dominance of a few countries concentrating large parts of the global VWT volume.

To model the nodes' degree and strength, we attribute to each node two fitness variables: one based on the country's annual GDP (time series from 1986-2008 (The World Bank, 2012)) and the other on the nation's long-term average annual rainfall (Aquastat, 2010) and agricultural land area (time series from 1986-2008 (Food and of the United Nations (FAO), 2010)). The two fitness variables assigned to each node i, normalized GDP and normalized Rainfall times Agricultural Area (RAA), are used to characterize the undirected network properties in each year from 1986-2008. Both for node degree and node strength, we observe that the model and data match closely for all years studied (Figure 2).

In the directed version of the network, each node has two weighted properties: in-strength, s_{in} (i.e. import volume), and out-strength, s_{out} (i.e. export volume). To characterize the asymmetry of the directed and weighted network, the fitness variable assigned to each node needs to be different whether the country participates in the trade as an exporter or as an importer. Thus, in this paper (Dalin *et al.*, 2012b), we choose for the first time two different fitness variables for exporting and importing nodes. As RAA represents well the nation's potential to produce and thus export food, we use this variable for exporting nodes (y), and for importing countries, we choose a variable related to food demand, represented by the national population (z). We then attributed to each link directed from i to j a weight based on y_i^n and z_j^n. Using this procedure, we obtain a close match between the modeled and observed distributions of directed strengths over the period. Thus, simple node properties such as rainfall, agricultural area and population allow us to model the two distinct distributions of exports and imports in the network.

Having shown the good performance of the fitness model to reproduce the statistical properties of the network using a few external variables, we apply this model to predict the future structure of the network under different scenarios for the year 2030.

We observe that the difference between projected node strength distributions with the driest and with the most humid climate scenario appears to be negligible. Both rainfall projections correspond to an increased strength of all countries, particularly for dominant nations. Indeed, the projected strength distributions present remarkably large tails, implying that the dominance of a few countries in the network will increase and the heterogeneity among nations will grow.

We have shown that our fitness model reproduces well the topological and weighted properties of the undirected and directed virtual water trade network via food trade over a time-period of significant changes (1986-2008), assuming as sole controls each nation's GDP, rainfall on agricultural area, and population. The population variable is shown for the first time to reproduce the crucial directed flows of virtual water over time. The simplicity of these input variables implies that future scenarios may be easily run to predict the future global structure of the global VWT network. The tendency for a few countries to concentrate most virtual water trade flows has been observed in the past, in particular with the emergence of China as a major importer (Dalin *et al.*, 2012a). We found that the distribution of network flows is expected to become increasingly heterogeneous, and, thanks to our directed network modeling framework, that a few importing countries are likely to concentrate a significant portion of virtual water trade through food commodities.

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