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Modeling the future evolution of the virtual water trade network: A combination of network and gravity models

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A B S T R A C T

The paper investigates how the topological features of the virtual water (VW) network and the size of the associated VW flows are likely to change over time, under different socio-economic and climate scenarios. We combine two alternative models of network formation –a stochastic and a fitness model, used to describe the structure of VW flows- with a gravity model of trade to predict the intensity of each bilateral flow. This combined approach is superior to existing methodologies in its ability to replicate the observed features of VW trade. The insights from the models are used to forecast future VW flows in 2020 and 2050, under different climatic scenarios, and compare them with future water availability. Results suggest that the current trend of VW exports is not sustainable for all countries. Moreover, our approach highlights that some VW importers might be exposed to “imported water stress” as they rely heavily on imports from countries whose water use is unsustainable.

1. Introduction

Virtual water (VW) is an indicator measuring the volume of water used to produce a good, implicitly “embedded” into a such good (Allan, 1998) and represents a useful concept to identify the amount of water resources associated with international trade flows. Since its inception, the VW concept has inspired a flourishing literature on how to address global water scarcity vis-à-vis commodity production and consumption in a variety of disciplines. For a comprehensive review on this issue, see Antonelli and Sartori (2015).

The aim of this paper is to provide alternative projections about the future evolution of the international bilateral VW flows both in the medium- (2020) and in the long-run (2050), and to relate them to future water availability in order to assess their sustainability.

Several recent works have applied network analysis to investigate the properties and evolution of the network resulting from bilateral VW flows. We refer to two broad classes of network models to describe the network and to forecast its future evolution. The first is based on a preferential attachment mechanism (Barabási and Albert, 1999; Riccaboni and Schiavo, 2010) whereby nodes accumulate new links in proportion to the number of links they already have (a “rich get richer” mechanism). The second is a fitness-dependent model in which the ability to connect depends on an intrinsic characteristic of each node (a “good get richer” mechanism; see Caldarelli et al., 2002; Garlaschelli and Loffredo, 2004; Suweis et al., 2011; Dalin et al., 2012).

We start by testing which models better reproduce the relevant topological characteristics of the VW trade network: this is done comparing the simulated network stemming from the models with the data on the basis of a number of standard topological measures. We then investigate the ability of the models to match the characteristics of the individual nodes. Adding this layer of

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analysis to the investigation on the global properties of the network represents, *per se*, a contribution to the literature.

Subsequently, we focus on the intensity of bilateral flows (as opposed to their mere existence), described by a gravity model of trade. This is an empirical framework whose ability to predict trade intensity is well-known in the economic literature (Anderson and van Wincoop, 2003; Head and Mayer, 2015).

Finally, we combine these models to produce projections about the future evolution of the network of VW flows in 2020 and 2050 under alternative scenarios. These projections are related to future water availability to assess the degree of water stress associated with the VW flows implied by the models. We find that the current trend of VW exports is not sustainable for all countries. Moreover, our network approach allows us to capture possible indirect effects: some importing countries may be prone to “imported water stress” as they rely on VW flows coming from countries whose trade patterns put high pressure on available water resources.

Our study improves and expands upon recent studies that have applied complex network analysis to study the topology (Sartori and Schiavo, 2015), the geography (Konar et al., 2011) and the temporal evolution of VW trade as a global network (Suweis et al., 2011; Carr et al., 2012; Dalin et al., 2012). First of all, our analysis is based a total of 309 agricultural goods up to the year 2010; second, new country characteristics are tested in the fitness model. Third, two alternative models are used to simulate the topology of the VW network and are compared in terms of their performance. Finally, the size of future VW flows is predicted by means of a gravity model of trade.

The paper proceeds as follows. The next Section briefly describes the data and the methodology used to replicate the binary structure of the VW network and the intensity of each flow. Section 3 describes the performance of the different models, whereas Section 4 builds on the results in order to generate future projections of VW flows in 2020 and 2050. The last Section discusses the implications of these projections in terms of direct and indirect water stress.

2. The network of virtual water trade flows: data and methodology

The network representation of the global trade system is a graph made by N nodes (countries), connected by links that represent bilateral (virtual water) flows. The network is represented by a square matrix W_N (dimensions $N \times N$), where exporters are in rows and importers in columns. International trade gives rise to a weighted and directed network, in which the link direction goes from the exporting to the importing country, and the weight of each link is given by the volume of virtual water flowing between any country-pair. Each cell w_{ij} captures the VW flow from country i to country j, with $w_{ii}=0$ by construction. The (horizontal) sum over row i is the total amount of VW exports of country i, while the (vertical) sum over column j is the total amount of VW imports of country j. We can derive a binary, unweighted version of the network by disregarding the information on link weights (i.e. the size of the flow) and simply accounting for the presence/absence of a trade connection. In this case, the NxN binary matrix A_N is called an adjacency matrix and its generic element a_{ij} is either one or zero depending on whether countries i ad j are connected or not.

The VW content of a good is the volume of water that is used to produce it (Allan, 1998). When a good is traded, its VW content is implicitly traded as well: VW trade thus refers to the cross-border flows of VW implied by international trade. A VW flow is obtained by multiplying the estimated country-specific VW content of each (agricultural) good by the registered volume of trade. Food production and international trade data for a total of 309 agricultural goods (i.e. crops and animal products) over the period 1995–2010 are obtained from the FAOSTAT database, while Mekonnen and Hoekstra (2011) provide estimates of the country-specific VW content of the various goods. Among existing studies, Konar et al. (2011) and Dalin et al. (2012) use a different method to determine the virtual water content of goods, namely the H08 global hydrological model by Hanasaki et al. (2008). For each single year, aggregate VW trade is obtained by summing the flows relative to the 309 individual goods. Our analysis includes 190 countries, listed in Table A1 of the Appendix A. [1]

Beside trade data, we also use information on the endowments of agricultural land (from FAOSTAT), long-term (average) annual precipitations, total renewable water resources (from AQUASTAT), GDP (in constant 2005 USD) and population (taken from the World Bank database). Projections about GDP and population are taken from the Shared Socioeconomic Pathways (Riahi et al., 2017).[2]

3. Replicating the observed network of virtual water trade

In this Section we employ a battery of models to replicate the main features of VW trade observed in the data. First, we use two simple models of network formation to describe the binary structure of VW trade, i.e. the presence of absence of a link between any two countries (Sections 3.1 and 3.2). Second, we compare the relative performance of gravity and fitness models to describe the intensity of bilateral trade flows (Section 3.3). Building on these results, Section 4 will present projections about the future evolution of VW trade under the baseline scenarios regarding the expected evolution of economic, demographic and environmental variables, whereas Section 5 will discuss the implications for this and other alternative scenarios illustrated in the Supplementary Material.

3.1. A stochastic model of network growth based on preferential attachment

Riccaboni and Schiavo (2010) develop a generalized version of the Barabási–Albert model to describe the dynamics and growth of weighted networks, and show that the model correctly replicates several features of international trade data. Although the VW trade network displays structural characteristics that are different from those analyzed in Riccaboni and Schiavo (2010), their modeling strategy is flexible enough to accommodate such differences. Since we focus on the binary network structure, the model boils down to a preferential attachment mechanism adjusted to allow for both entry of new nodes and the random allocation of some links.

The model starts with a given number of nodes (N_0) and assumes that at each time $t=\{1,\ldots,M\}$ a new link among two nodes arises. Each new link is assigned to either existing or new nodes according to the following procedure:

- with probability a the new link is assigned to a new (i.e. not previously existing) source node, whereas with probability $(1-a)$ it is allocated to an existing node i;
- in the latter case, the probability of choosing any existing node i is a linear combination of a random assignment and a preferential attachment mechanism. In particular, letting b identify

[1] For a detailed and exhaustive description of the way the virtual water content of the goods and the virtual water trade flows were computed, we refer to Carr et al. (2012, 2013) and Tamea et al. (2014). The Supplementary Material reports the list of products considered in computing the virtual water flows.

[2] The dataset is available at https://tntcat.iiasa.ac.at/SspDb. We use projections based on the OECD-SSP2 scenario labeled "middle of the road", that corresponds exactly to the medium variant of the new IIASA-VID-Oxford projections on population, which combines medium fertility with medium mortality and medium migration, and the Global Education Trend education scenario (see KC and Lutz, 2014, Dellink et al., 2015, and Riahi et al., 2017 for more details).

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