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# Drivers of the virtual water trade

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[1] Through the international trade of food commodities, countries virtually export or import the water used for food production, known as "virtual water." The international trade network thus implies a network of virtual water flows from exporting to importing countries. The purpose of this study is to identify some controlling factors of the virtual water network by means of multivariate regression analyses, or gravity laws, as often named in economics. Starting from the FAOSTAT database, we reconstruct 25 years (1986–2010) of international virtual water trade values; we then analyze the dependence of the exchanged fluxes on: population, gross domestic product, arable land, virtual water embedded in agricultural production and dietary demand, and geographical distance between countries. Significant drivers are identified for each country considering separately export and import fluxes; temporal trends are outlined and the relative importance of drivers is assessed by a commonality analysis. Results indicate that population, gross domestic product and geographical distance are the major drivers of virtual water fluxes, with a minor (nonnegligible) contribution given by the agricultural production of exporting countries. Such drivers have become relevant for an increasing number of countries throughout the years, with an increasing variance explained by the distance between countries and a decreasing role of the gross domestic product. The worldwide adjusted coefficient of determination of fitted gravity-law model is 0.57 (in 2010), and it has increased in time, confirming the good descriptive capability of selected drivers for the virtual water trade.

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## 1. Introduction

[2] Food production is by far the largest form of societal water consumption, while only a smaller fraction of water is spent for drinking, household or industrial usage [*Falkenmark et al*., 2004; *Hanjra and Qureshi*, 2010]. Through the international trade of food commodities, countries virtually export or import the water used for food production, known as "virtual water" [*Allan*, 1998]. Virtual water flows associated to food trade are remarkable and they have been estimated to be as large as $2-3 \times 10^{12}$ m$^3$/yr [*Hoekstra and Hung*, 2002; *Chapagain and Hoekstra*, 2004; *De Fraiture et al*., 2004; *Oki and Kanae*, 2004]. This means that 2% of the global precipitations above land is used to produce commodities for export [*Hoekstra and Chapagain*, 2008].

[3] International trade of food is considered vital for the food security of many countries [*Hanjra and Qureshi*, 2010] but it has implications on world water resources. Trade in water-intensive commodities generates water saving for the importing countries and relieves the pressure on the nation's own water resources, in those areas where freshwater is relatively scarce. This can contribute to increase the efficiency in the use of the world's water resources [*Hoekstra and Chapagain*, 2008; *Konar et al*., 2012] and to prevent water crisis from degenerating into famine, water wars and massive migrations of people. However, it has been found that trade is not generally based on water solidarity [*Seekell et al*., 2011] and that an increasing lack of self sufficiency of many countries may reduce societal resilience to drought [*D'Odorico et al*., 2010].

[4] Virtual water fluxes associated to food trade [e.g., *Hoekstra and Hung*, 2002; *Carr et al*., 2012] provide valuable environmental and economic information. Analysis of virtual water trade, complemented by water footprint accounting and a comprehensive sustainability assessment, may support the formulation of integrated policy options, addressing issues of climate change or efficient use of resources [e.g., *Vanham*, 2013; *Steen-Olsen et al*., 2012]. Appropriate policies are mandatory to face the world water crisis, which has led the United Nations to conclude that water scarcity will be the major constraint to increase food production over the next decades [*UNDP*, 2006]. The understanding of structures and governing factors (drivers) of virtual water trade, thus, aims at contributing to the knowledge for building well-informed regulations.

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[5] Very recently, some studies have investigated the structure and evolution of the virtual water network [*Konar et al*., 2011; *Carr et al*., 2012; *Dalin et al*., 2012; *Carr et al*., 2013], highlighting its development, with the rapid increment of exchanged fluxes and the dynamical structure of nodes and links. Other analyses have highlighted the power-law relationship between the volume of virtual water traded and the number of trade connections of each nation [*Konar et al*., 2011], or the spatiotemporal dynamics of the network as organized in communities [*D'Odorico et al*., 2012]. *Suweis et al*. [2011] used a simple model to describe the topological and weighted properties of the virtual water trade network assuming the gross domestic product and yearly rainfall on agricultural areas at each node (countries) as sole drivers, whereas *Tamea et al*. [2013] introduced the average distance traveled by virtual water as a measure for the analysis of globalization in the virtual water trade.

[6] There is also a vast environmental-economy literature about the evaluation of water footprint of food supply chain. A "top-down" approach based on Input-Output matrices is typically applied in that field [e.g., *Daniels et al*., 2011], where water management data are associated to industrial sectors and downscaled according to the economic value of products [see, e.g., *Guan and Hubacek*, 2007]. This approach, and in particular the Multiregional Input-Output version (MRIO), allows environmental impacts through complex international supply chains to be tracked, but it describes only aggregated products and sectors [*Steen-Olsen et al*., 2012]. Higher level of detail, suitable for analyzing the production and trade of agricultural products, can only be reached with a "bottom-up" approach, i.e., using raw data of production/trade for each product of interest multiplied by a virtual water content. A comparison between the top-down and the bottom-up approach has been performed by *Feng et al*. [2011] who highlighted the discrepancy of the two approaches in the evaluation of national water footprint of consumption. The (classical) bottom-up approach remains the best option for evaluating the water embodied in bilateral trade [*Lenzen*, 2009] and it is thus used in the present paper.

[7] In this framework of increasing interest and activity, the controlling factors of the global virtual water fluxes are yet to be adequately identified; this is the purpose of the study presented here. Starting from the Food and Agriculture Organization statistical database (FAOSTAT), we reconstructed 25 years (1986–2010) of international trade data for 309 crops and animal products. Using the country-specific virtual water content of each product [*Mekonnen and Hoekstra*, 2010a, 2010b], food trade data for each commodity were converted into virtual water trade values and added together to obtain for each year the total virtual water transferred between pairs of trading partners.

[8] The conceptual framework of gravity laws, which are often used to explain network fluxes in fields such as trade, transportation, and migration [e.g., *Anderson*, 1979; *Bergstrand*, 1985], has been adopted here to investigate the factors driving the trade of virtual water. We focused on the dependence of the exchanged fluxes on: population, gross domestic product, arable land, virtual water embedded in agricultural production and dietary demand, and geographical distance between countries. This framework allows us to identify the significant drivers of virtual water trade and to geographically map the controlling factors for each country, as well as to outline their temporal trends and to analyze their relative importance by commonality analysis.

## 2. Data

[9] We use 25 years of international trade data from the FAOSTAT database (http://faostat.fao.org/), where data are available for each country and year for 309 crops and animal products. A trade matrix is reconstructed for every product, $m$, and every year, where the export of product $m$ from country $i$ to country $j$ is stored in the $(i, j)$ element of the matrix. Details about the matrix construction and country arrangements are detailed in *Carr et al*. [2012, 2013].

[10] The country-specific virtual water contents of crops and animal products are available from *Mekonnen and Hoekstra* [2010a, 2010b]. The considered contents include the contributions of rainfall (green water), surface water and groundwater (blue water) and are time averaged over the period 1996–2005. Given all virtual water contents and considering the exporting country $i$ as the producing country, trade data for each product are converted into virtual water data and summed up over the 309 items $m$ to obtain the total virtual water transferred between pairs of trading partners in a given year. Virtual water trade data are thus organized in 25 matrices, one for each year between 1986 and 2010, whose $(i, j)$ element represents the virtual water flux from country $i$ to country $j$. Matrices are nonsymmetrical because of network directionality, that is flux from $i$ to $j$ is different than flux from $j$ to $i$.

[11] The number of countries, considered as nodes of the virtual water network, changes from year to year according to political-administrative arrangements (e.g., the collapse of Soviet Union and Yugoslavia). In the present analysis, only nations with more than one million inhabitants (about 160) are considered, in order to neglect minor fluxes pertaining to poorly populated countries, where trade may be driven by very peculiar socioeconomic factors.

[12] Explanatory variables used in the gravity-law model are: population ($P$), virtual water of per-capita agricultural production ($WP$), virtual water of per-capita dietary demand ($WD$), per-capita gross domestic product ($GDP$), distance between countries ($D$), and per-capita arable land ($A$). These variables represent a selection of major factors impacting the trade flows and the demand/supply of food and, thus, virtual water trade; they are also chosen for being available with the same spatial coverage and temporal resolution of the virtual water data. Data sources are as follows.

[13] The population ($P$) of each country and for each year in the period 1986–2010 is taken from FAOSTAT, as well as the arable land ($A$), intended as the land under agricultural crops, for each country and year.

[14] Per-capita gross domestic product ($GDP$) for each country and year is available from the National Accounts Main Aggregates Database (http://unstats.un.org/unsd/snaama/dnllist.asp). Due to a different processing of data with respect to FAOSTAT, dissolved countries like former Soviet Union, Yugoslavia Federation and Czechoslovakia are ceased 1 year before than in population and virtual water data sets. In order to restore a common framework,

values of gross domestic product of countries resulting from dissolution, in the first year have been summed up and the sum assigned to the country before dissolution.

[15] The virtual water of agricultural production (*WP*) of each country and year is calculated multiplying the quantity of each agricultural good, *m*, produced by a country (as available from FAOSTAT) by the country-specific virtual water content, $WC_m$ (*i*) and summing up over all products to give the "national footprint of production" [e.g., *Hoekstra and Hung*, 2002]. Here, only a subset of the 309 trade products were considered in order to avoid double accounting of primary and secondary products (for more details and list of products, see *Tamea et al*. [2013]).

[16] The virtual water of dietary demand (*WD*) represents the average volume of freshwater that is used to produce the goods and services consumed by the people of that country ("national footprint of consumption," *Hoekstra and Hung* [2002]). The mean value of the per-capita virtual water demand ($m^3$/yr/cap) for each country in the period 1996–2005 are taken from *Mekonnen and Hoekstra* [2011, Table VIII, volume II].

[17] Finally, the distance between countries (*D*) is organized in a time-invariant matrix of geographical distances measured between the most populated cities of the considered countries, as retrieved from the Cepii database (accesible at http://www.cepii.fr/anglaisgraph/bdd/distances.htm).

## 3. Gravity-Law Models and Comparison Methods

[18] Gravity-law models are often used to explain fluxes occurring in trade networks [e.g., *Bergstrand*, 1985]. These models are based on relationships which formally resemble the law of universal gravitation, that is

$$F_{i,j}=\beta_0 \cdot \frac{v_i \cdot v_j}{d_{i,j}^2}, \tag{1}$$

where $F_{i,j}$ is the exchanged flux between the nodes *i* and *j*, $v_i$ and $v_j$ are values of the relevant variable at the two nodes *i* and *j*, and $d_{i,j}$ is the distance between the nodes. In the second half of the 20th century the economists proposed to apply the functional law (1) to international trade flows, but also to "social interactions," like migration or tourism.

[19] Gravity laws can be generalized using a monomial relation,

$$F_{i,j}=\beta_0 \cdot v_{1,i}^{\beta_1} \cdot v_{2,i}^{\beta_2} \cdot v_{1,j}^{\beta_3} \cdot v_{2,j}^{\beta_4} \cdot \ldots, \tag{2}$$

where $v_{1,i}$, $v_{2,i}$, $v_{1,j}$, $v_{2,j}$ are the explanatory variables for describing the flux $F_{i,j}$, and $\beta_0$, $\beta_1$,... are the model parameters. A major advantage of gravity-laws lays in the multiplicative nature of the equations, which can be managed as linear multivariate regressions between the logarithms of fluxes and of explanatory variables. Model parameters are then interpreted as regression coefficients and can be estimated with the ordinary least square method.

[20] Given the complexity of the virtual water network, a global relationship describing all exchanged fluxes as a function of importers' and exporters' characteristics proved to be inadequate (see section 4). Thus specific models describing the virtual water import and export of each country are necessary and we look at two gravity laws per country: one describing the export as a function of the characteristics of destination countries, and one describing the import as a function of the characteristics of source countries (scheme in Figure 1). Identifying the exporting country by *i* and the importing country by *j*, two different estimates are given for the virtual water flux from node *i* to node *j* ($F_{i,j}$), as a function of the explanatory variables, i.e.,

$$F'_{i,j}=\beta_{0,j} \cdot p_j^{\beta_{1,j}} \cdot wp_j^{\beta_{2,j}} \cdot wd_j^{\beta_{3,j}} \cdot gdp_j^{\beta_{4,j}} \cdot d_{i,j}^{\beta_{5,j}} \cdot a_j^{\beta_{6,j}}, \quad j \in \Omega_d(i), \tag{3}$$

$$F''_{i,j}=\beta_{0,i} \cdot p_i^{\beta_{1,i}} \cdot wp_i^{\beta_{2,i}} \cdot wd_i^{\beta_{3,i}} \cdot gdp_i^{\beta_{4,i}} \cdot d_{i,j}^{\beta_{5,i}} \cdot a_i^{\beta_{6,i}}, \quad i \in \Omega_s(j), \tag{4}$$

where *p*, *wp*, *wd*, *gdp*, *d* and *a* are values of the explanatory variables indicated by the corresponding capital letters, $\Omega_d$ (*i*) is the set of destination countries of the exports of *i* and $\Omega_s$ (*j*) is the set of source countries of the imports of *j*. Equation (3) expresses the demand's pull for export, describing the trade flow $F_{i,j}$ as a function of destination characteristics; this is referred to as the *export law*. Similarly, equation (4) expresses the supply's push for import, describing the trade flow $F_{i,j}$ as a function of source characteristics, and this is referred to as the *import law*.

[21] Gravity laws change in time since the trade matrices, as well as most explanatory variables, are different year by year. Within the proposed framework, relationships with mixed importer-exporter variables (i.e., addition of exporters' variables in (3) and importers' variables in (4)) cannot be considered because such additional regressors would be invariant in country-specific relationships (3) and (4).

[22] Virtual water fluxes and explanatory variables are converted into their logarithm of base 10 then, for each country and year, the regression coefficients $\beta_0$,...,$\beta_6$ are estimated. The least square method is initially applied to estimate the seven coefficients of each multivariate relationship (3 and 4), provided that at least seven trade links are active for the given country and year. Then a Student's *t* test with a 5% significance level is applied to identify the significant variables, i.e., those with a corresponding $\beta$ coefficient significantly different than zero. Finally new

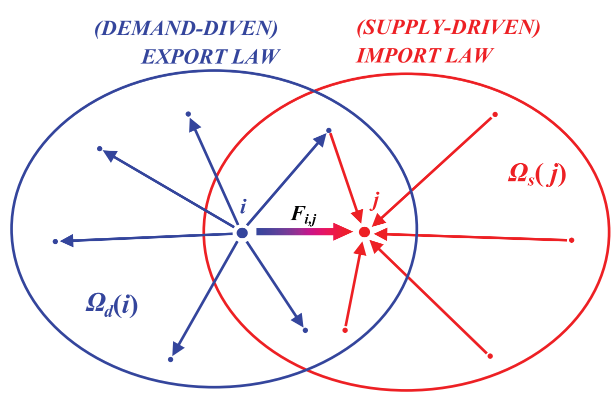



**Figure 1.** Scheme of the two sets defining the gravity law for export (3) and the gravity law for import (4), in blue and red, respectively.

regression coefficients are evaluated using only the statistically significant variables; in case that none of the variables were significant, the only coefficient remaining ($\beta_0$) is taken as the mean flux.

[23] The local adjusted coefficient of determination, $R^2_{adj}$, is used to describe how well each multivariate regression for a given country in a given year fits the data. Global adjusted coefficient of determination are also built to assess the overall (worldwide) performance of gravity-law models; the coefficient for the export law is calculated as

$$R_e^2 = 1 - \frac{\sum_{i,j} \left(\mathrm{Log}\, F_{i,j} - \mathrm{Log}\, F'_{i,j}\right)^2}{\sum_{i,j} \left(\mathrm{Log}\, F_{i,j} - \langle \mathrm{Log}\, F_{i,j} \rangle\right)^2} \cdot \frac{n_{F'_{i,j}} - 1}{n_{F'_{i,j}} - n_\beta}, \quad (5)$$

where $\langle \mathrm{Log}\, F_{i,j} \rangle$ is the mean logarithm of non-null fluxes exchanged worldwide in a given year for which an estimate $F'_{i,\ j}$ is available, $n_{F'_{i,j}}$ is the overall number of estimates $F'_{i,\ j}$ built with (3), and $n_{\beta_i}$ is the overall number of significant coefficients of export laws (3). Similarly, the global adjusted coefficient of determination for the import law, $R_i^2$, is calculated as in (5) with $F''_{i,\ j}$ instead of $F'_{i,\ j}$. These coefficients of determination enable the comparison between countries and the analysis of temporal trends both at the country scale and worldwide.

[24] Drivers of the virtual water trade are assessed with a temporal and spatial analysis of the significance of each variable. In order to investigate the relative importance of explanatory variables and how this changes in time, a "commonality analysis" (also called "element analysis") is performed [e.g., *Newton and Spurell*, 1967]. This is a statistical tool for determining the partitioning of variance into the contributions given by each regressor in a multivariate linear regression. Considering a multivariate regression between a dependent variable $F$ and a set of regressors $v_1$, $v_2$, $v_3$,. . ., the variance of $F$ can be explained partly by the contribution of each regressor alone (unique contribution) and partly by the joint contribution of such regressor with all other correlated variables. Focusing on the *unique contribution* $U(v_1)$ of regressor $v_1$, this is the fraction of additional variance explained by such variable when it is entered last in a regression and represents the marginal contribution of $v_1$ to the regression model, neglecting the correlation with other regressors. $U(v_1)$ can be quantified by

$$U(v_1) = R^2_{F(v_1,v_2,v_3,\ldots)} - R^2_{F(v_2,v_3,\ldots)}, \quad (6)$$

where $R^2_{F(v_1,v_2,v_3,\ldots)}$ is the coefficient of determination in the regression of $F$ with all regressors $v_1$, $v_2$, $v_3$,. . . and $R^2_{F(v_2,v_3,\ldots)}$ is the coefficient of determination in the regression of $F$ with regressors $v_2$, $v_3$,. . .. Unique contributions can be both positive or negative, with negative sign indicating that such variable decreases the regression quality confounding the variance explained by another regressor [*Capraro and Capraro*, 2001]. Comparing the unique contributions to the gravity-law models for virtual water trade allows additional insight into the relative importance of explanatory variables of the model and enables the detection of temporal trends.

## 4. Results and Discussion

[25] A global multivariate regression, expressing all exchanged fluxes as a function of both importers' and exporters' variables, resulted in a maximum (along the years) adjusted coefficient of determination of 0.34. The inadequacy of such result and the scarce representativeness of the global model suggest that considered variables (see section 2). control the virtual water fluxes in different ways in each country.

[26] This section presents and discusses the application of gravity-law models to the import and export of each country, with an initial example of results related to one single country followed by the application to the whole world, with the aim of identifying the major drivers, their relative importance and their evolution in time.

### 4.1. The Case of a Single Country: Italy

[27] First of all, gravity laws are applied to the virtual water trade of Italy, which is one of the major virtual water importers in the world as detailed in *Tamea et al*. [2013]. Results of such application are given in Figure 2 and include regression coefficients for the export law (3) and import law (4) from 1986 to 2010, and the corresponding adjusted coefficients of determination ($R_e^2, R_i^2$).

[28] The virtual water export of Italy is strongly dependent on importers' population and gross domestic product ($\beta_{1,j}, \beta_{4,j} \simeq 1$), as well as on the distance of importers, to which fluxes are negatively correlated ($\beta_{5,j} \simeq -1.5$). The virtual water of importers' production ($\beta_{2,\ j}$) was significant and negative at the beginning of the time span, but then became nonsignificant and the corresponding exponent are set to zero; the loss of such driver may have been influenced by the development of the European Union's Internal Market and the increased export fluxes toward countries with abundant agricultural production. Apart from few occasional exceptions, other importers' variables are not significant for Italian export and do not contribute to relationship (3).

[29] The virtual water import of Italy is positively correlated with exporters' population, agricultural production and gross domestic product. For most of the time span, GDP of other countries has had a lower coefficient for import ($\beta_{4,i} \simeq 0.5$) than for export, but in most recent years (about after 2000) it sharply increased reaching similar values nowadays. Italian virtual water import has a marked negative correlation with the exporters' virtual water demand ($\beta_{3,\ i}$), and to a lesser extent with their distance and arable land; exporters' distance ($\beta_{5,i} \simeq -0.8$) has a lower absolute-valued coefficient than importers' distance but a weak trend seems to bring the two values closer to one another also for this variable.

[30] As shown in Figure 2 (bottom-right plot), the import law (4) has an average coefficient of determination of about 0.5, with minor variations in time and no marked trend. The export law (3) is generally captured better by the proposed gravity-law model, with similar performances at the beginning of the time period and a sharp increase in time of $R_e^2$, up to values higher than 0.7.

### 4.2. Significance of Drivers

[31] Country-based gravity-law models are then applied to all countries; the analysis of regression coefficients and

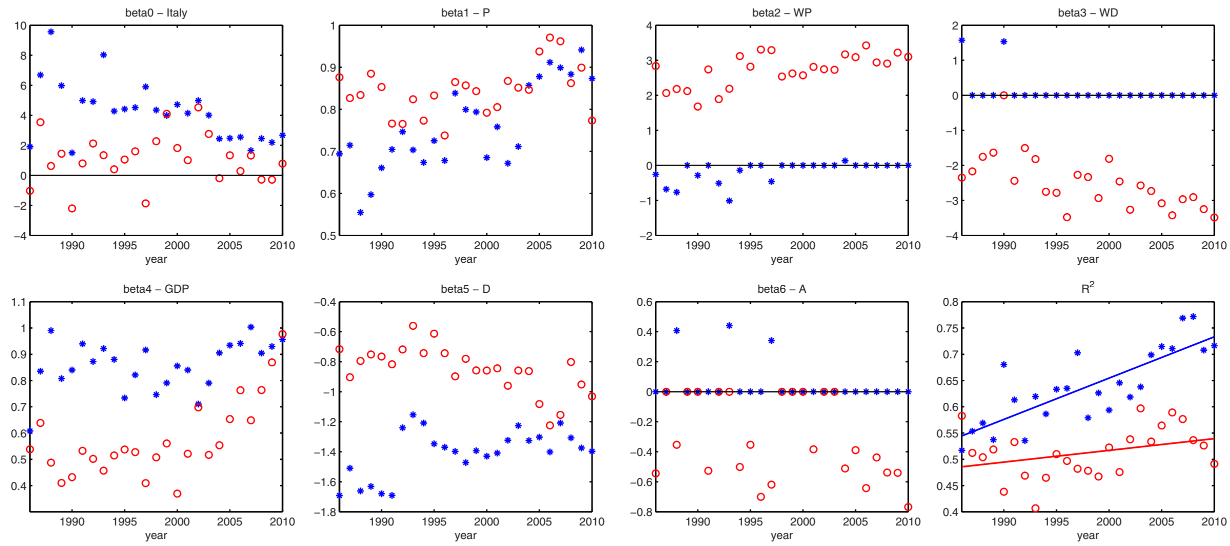



**Figure 2.** Regression coefficients of the export (blue asterisks) and import (red circles) gravity laws for Italy and their evolution in time from 1986 to 2010; the bottom-right plot shows adjusted coefficients of determination of the two laws and their linear temporal trends.

of the significance of explanatory variables at the Student *t* test (5% significance) allows one to find out the controlling factors of the virtual water fluxes for each country (see Figure 3).

[32] Population (P) of both importer and exporter countries plays a major role for the international virtual water fluxes; in all cases the correlation is positive and only very few countries are characterized by gravity-law models where population exponents are not significantly different than zero.

[33] The virtual water of agricultural production (WP) is a major driver of the import law, i.e., the agricultural production of source countries markedly influences, with a positive correlation, the virtual water imports. Production of destination countries, on the other hand, is significant in some African, Central European and Southern Asian countries, but the varied sign of correlation indicates an uncertain influence on the export law. In particular, countries such as Spain, Poland, Finland, Iran, China, Niger, Chad and Democratic Republic of the Congo, export larger virtual water volumes toward countries with higher WP, thus toward countries which seem to be richer in water. This fact may indicate that (i) blue countries export specific goods that, for climatic or commercial reasons, can only be grown there and not in the importing countries despite water abundance, or (ii) there are political/commercial agreements that drive goods exchange and are not related to water availability.

[34] The virtual water of dietary demand (WD) is a broad negative driver of the import law, i.e., the higher is the virtual water demand of source countries, the lower is the flux imported from them. Some countries with a nonsignificant coefficient appear to be concentrated in South America and in the arid regions of Africa, Middle East and Asia. On the other hand, virtual water demand of destination countries surprisingly appears not to have a clear influence on the export, since few countries have a significant non-null exponent and this can have variable sign. Only Russian Federation, China and Australia are major countries whose export is directly correlated to the demand of destination countries.

[35] The gross domestic product (GDP) is a major positive driver of virtual water fluxes, especially when considering the GDP of exporting countries (import law), indicating that almost all countries import larger virtual water volumes from rich countries. The GDP of importing countries is significant mainly as a positive driver, that is, countries tend to export more toward richer countries, although in some countries of Asia and Africa it has a negative correlation or it is not significant at all. In these "red" cases (Russian Federation, Ukraine, Algeria, Libya, Somalia, Mongolia, and Myanmar) virtual water exports are smaller toward richer countries, which apparently could be justified by country-specific political conditions.

[36] The distance (D) between countries is the major driver with negative correlation, in both import and export laws, indicating that the closer are countries, the larger are the exchanged fluxes.

[37] The arable land (A) is an overall negative driver. When destination countries are considered (export law), this indicates that export fluxes are higher toward trading partners with less arable land, and this occurs with few exceptions (Norway, Germany, Mongolia, Botswana, Mauritania, and some countries with a nonsignificant coefficient). However, where import law is found to have a negative correlation with arable land, this indicates that import fluxes are larger from trading partners with less arable land, which is quite unexpected.

[38] Finally, it is also interesting to see how the significance of different variables has changed in time. To this purpose, Figure 4 shows the number of countries for which each variable is significant (positively and negatively correlated) from 1986 to 2010, where the last year corresponds to the situation depicted in Figure 3. It can be seen that the role of variables in the import relationship is marked: either widespread positive (P, WP, GDP) or widespread

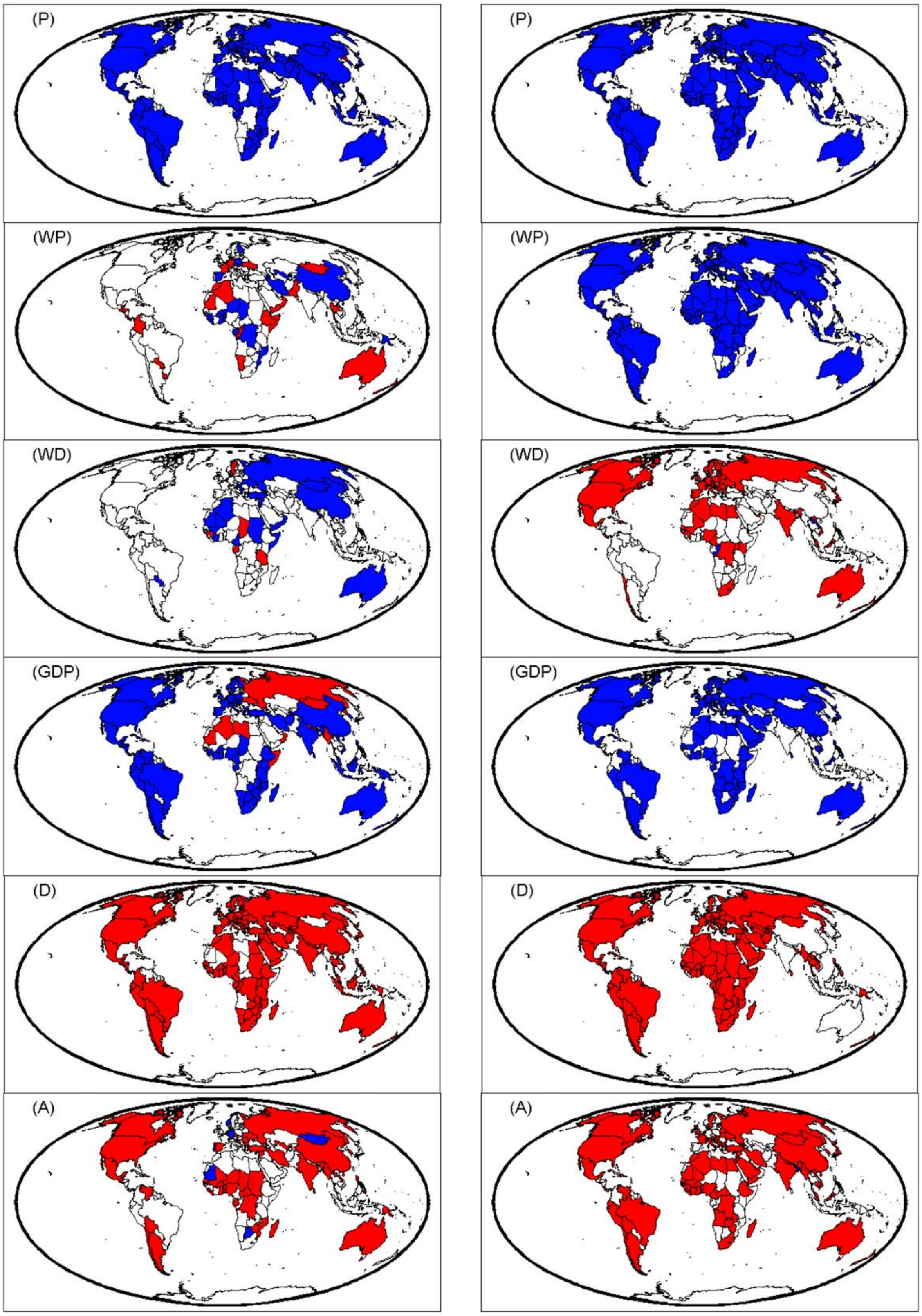



**Figure 3.** Significance of each variable in the (left) export laws and (right) import laws for the world countries in 2010; positive and significant exponents are in blue, negative and significant exponents in red, and nonsignificant exponents in white.

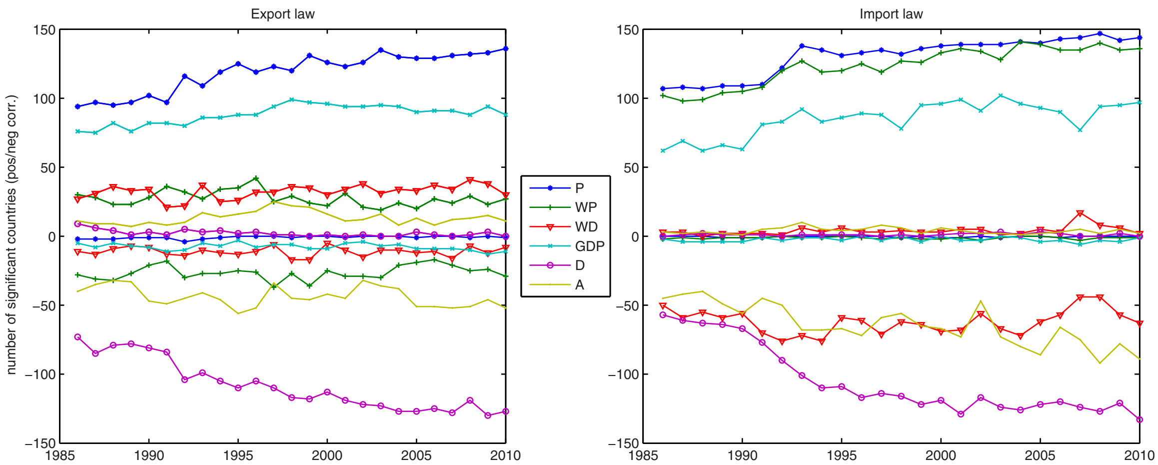



**Figure 4.** Number of countries, in time, for which each variable is significant with positive or negative exponent (indicated by a positive and negative number, respectively).

negative (WD, D, A), without intermediate situations; moreover, the number of countries with significant variables is increasing for both positively and negatively correlated variables. Significance of explanatory variables in the export relationship is more variegated, with predominance of P and GDP (positive correlation) and D (negative correlation), although a number of countries show some dependence on the other variables, with both positive and negative correlation. Temporal trends indicate a clearly increasing number of countries for which the major drivers are significant, while no trends are found in the other drivers, suggesting that they may represent occasional and country-specific contributions without a marked role at the global scale. The increasing importance of distance as a negative driver can partly be explained by the temporal increase in the number of network nodes [*Carr et al.*, 2012]. This structural change in the network results in a decreasing average distance traveled by virtual water [*Tamea et al.*, 2013] which possibly entails an increase of significance of such driver.

### 4.3. Commonality Analysis

[39] The Student *t* test assesses if a regression coefficient is significantly different than zero, thus if the explanatory variable is relevant to the regression or not; however, nothing can be said about the relative importance of variables. This can be evaluated through the results of the commonality analysis, performed here on the gravity-law models of all countries.

[40] Figure 5 shows the box plots of unique contributions *U* of each variable in all countries in 2010. The sample sizes of each box is given by the number of countries having such variable in the fitted gravity model, that is the sum of positive and negative numbers (without sign) of Figure 4 in year 2010. It can be seen (Figure 5) that median contributions to the export law provided by population, GDP and distances are around 0.15–0.2, whereas production, demand, and arable land give a median contribution equal or below 0.05. Variability of contributions reflects and confirms their relevance, with larger interquartile ranges

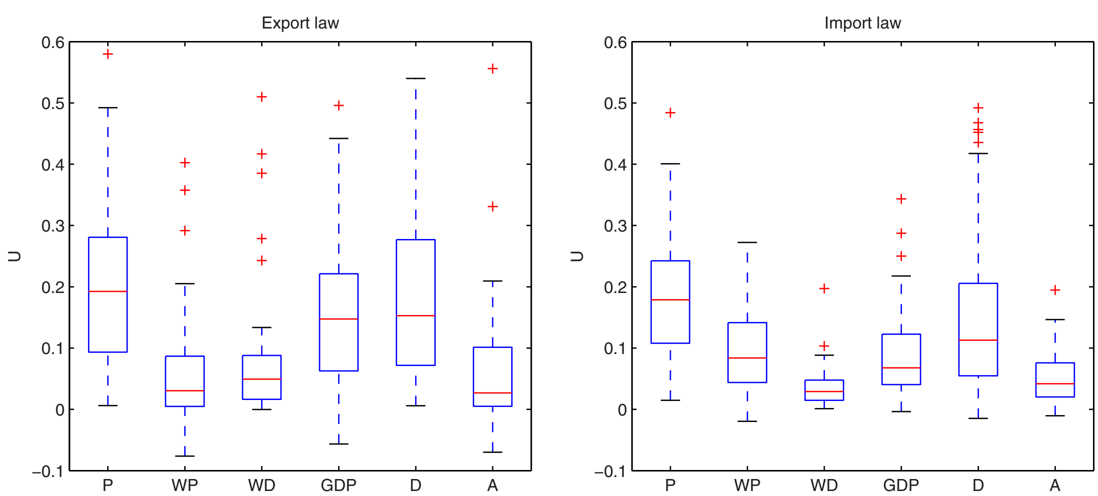



**Figure 5.** Box-plots indicating the unique contribution, *U*, of each variable in the (left) export and (right) import laws in 2010.

centered above 0.15 for P, GDP, and D, and lower ranges for the other variables. WP, GDP, and A have lower tails in the negative set of $U$ values, indicating occasionally "harmful" contributions to the multivariate regressions. For the import law (Figure 5, right plot), a ranking of variables' contributions can be made according to their median and interquartile contributions: population has the highest median and upper quartile, distance has a lower median but larger interquartile range, WP is marginally more relevant than GDP, while arable land and demand give the least contributions to the regression. In general, part of the variability of virtual water fluxes remains unexplained as it is related to driving factors or variables which have not been considered in the present analysis.

[41] Considering the time evolution of unique contributions of the worldwide median values (Figure 6), in the export relationship it is clear that separation between relevant (P, GDP, and D) and less relevant variables (WP, WD, and A) remains marked in time. The relevance of GDP, after a rise in the first decade, settles at the lower edge of relevant drivers, while distance increases its importance in time, although not reaching the values of population. Contributions to the import law are more mixed: the virtual water of production (WP) has a greater role, with respect to the export law, and the GDP has a smaller one. While D and—to a lesser extent—P increase their contribution in time, all other variables weakly decrease it.

[42] Notice from the comparison of Figures 4 and 6 that variables may be significant for a certain number of countries but the portion of variance they explain is made clear only with an investigation of their commonality. For example, virtual water demand, production and arable land in the export law are significant in a non-negligible number of countries, but they give little contribution to explain the variance of export fluxes.

### 4.4. Global Performance of Gravity Models

[43] After having analyzed the role of each explanatory variable in the multivariate regression defining the gravity-law models (3–4), results are now presented in terms of quality of regressions. Fitting capability of the multivariate regression in each country is shown in Figure 7, where country colors reflect values of the adjusted coefficient of determination, $R^2_{adj}$, obtained with the export law (above) and the import law (below).

[44] The virtual water trade of all countries is well described by the gravity models, and countries with a coefficient of determination in the range 0.4–0.8 prevail in the map of export law (Figure 7, top). The export law describes very well the virtual water fluxes exported by European countries, North America and Australia, as well as other major countries such as India, Mongolia, Bolivia and Chile, where $R^2_{adj}$ reaches values between 0.6 and 0.8. For countries resulting from USSR dissolution, China and most of South America, $R^2_{adj}$ of export takes values between 0.4 and 0.6. Fluxes pertaining to African countries are not well reproduced: values of regression coefficient are low (apart from Chad) and results for this continent are very heterogeneous. The scarce representativeness of the proposed model for African countries may be due to the fact that African continent, for its limited access to the global economy, remains only marginally affected by the globalization of freshwater resources [*Carr et al.*, 2012]. Furthermore, the present study does not consider the humanitarian aids, which may be relevant for African countries. In general, it is worth noting that countries where the model is successful are responsible for a large portion of the virtual water flows across the globe. For example, regressions with $R^2_{adj} > 0.6$ describe 1200 km$^3$ of virtual water export, i.e., 44% of the total trade in 2010; such a percentage reveals the success of the gravity-law model proposed.

[45] Temporal trends of the coefficient of determination (see Figure 8) indicate that for some countries the descriptive capability of gravity laws has increased over time. In fact USA, Canada, Russian Federation, China, and Eastern European countries are characterized by a significant increase of both adjusted regression coefficients. There is also a significant improvement of the export law in many European countries, and of the import law in Middle Eastern and South American countries. The case of Italy (shown in Figure 2) confirms the significant increase of descriptive capability for exports (3) and a nonsignificant variation for imports (4).

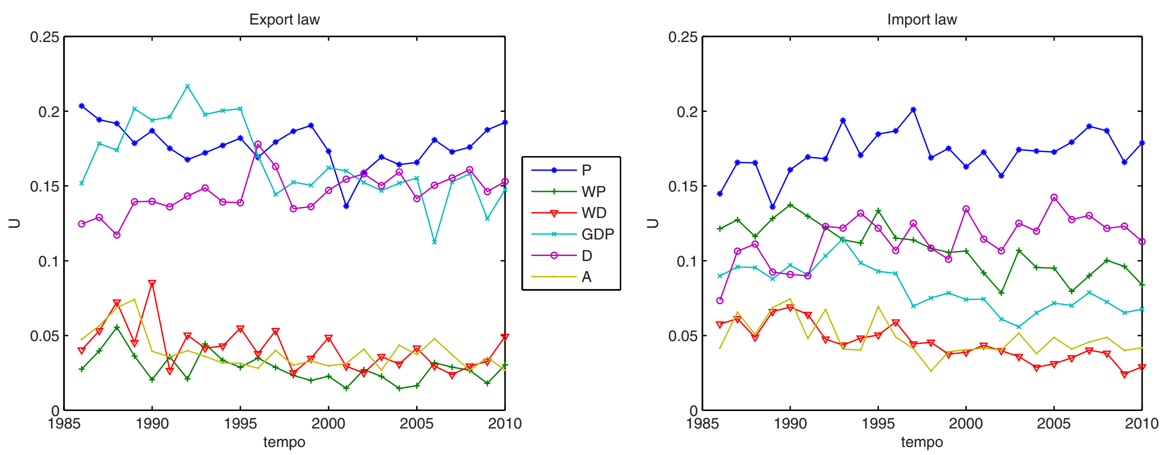
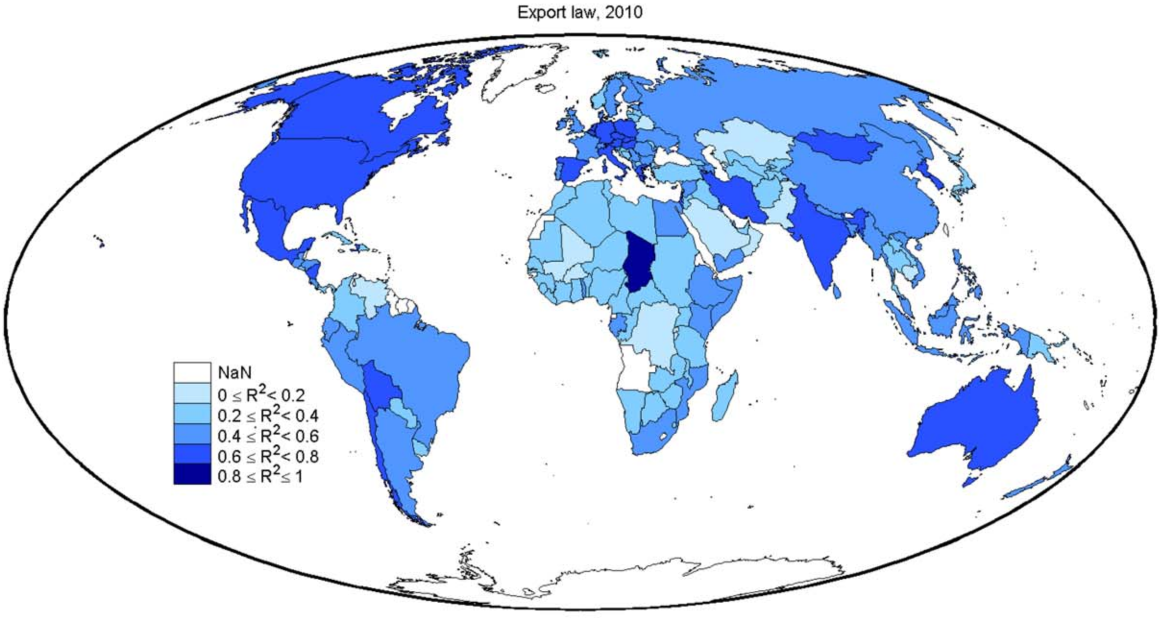



**Figure 6.** Time evolution of the worldwide medians of the unique contribution, $U$, of each variable in the (left) export and (right) import laws.



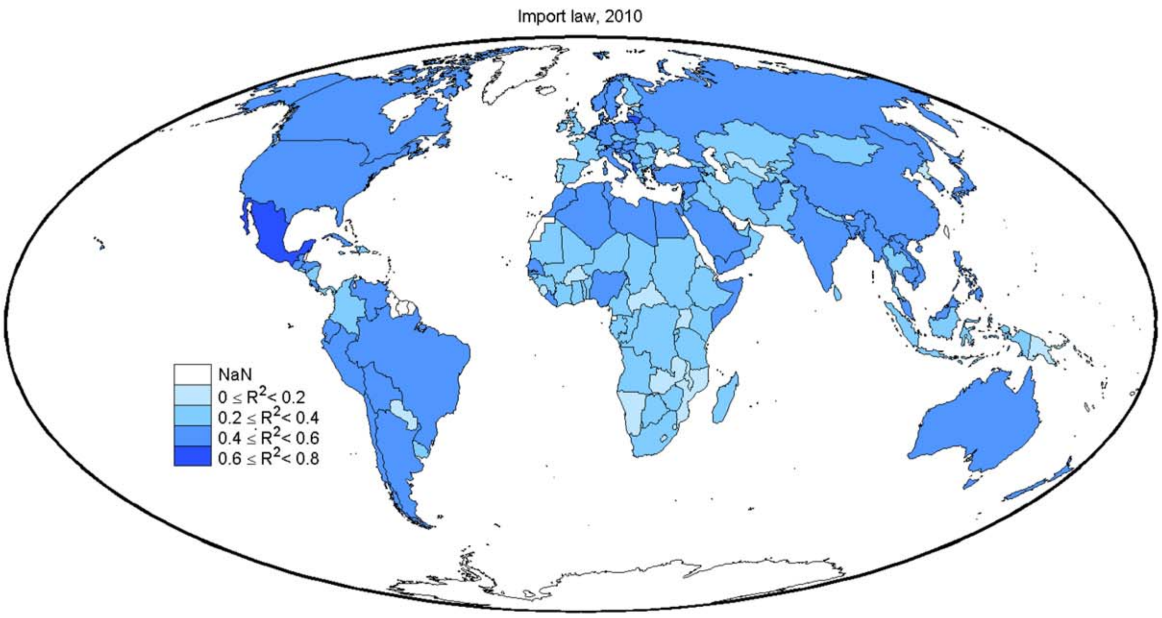




**Figure 7.** Geography of the regression adjusted coefficient $R^2_{adj}$ for the gravity laws (3) and (4) in 2010. Countries with less than one million inhabitants and with less than seven active trade links are in white.

[46] The performance of gravity-law models is finally highlighted by comparing real and estimated virtual water fluxes exchanged by all pairs of countries in a given year, where estimates are computed with the relations (3) and (4). To this purpose, scatterplots are effective in showing the discrepancies between real and modeled fluxes and the general dispersion of points around the bisector line, which identifies the perfect model. Scatterplots in Figures 9a and 9b show the good alignment and the higher density of points around the bisector, indicating the overall good fitting of the gravity-law models. The overall coefficients of determination in 2010 are $R_e^2 = 0.57$ and $R_i^2 = 0.47$ for the export and import law, respectively, and represent the last point of the temporal analysis which follows (Figure 9c). Both coefficients have increased in the 1986–2010 period with positive trends which are significant at the 5% according to the Student's *t* test.

[47] The goodness of fit of the export law is systematically better than the import law, as highlighted by Figure 9 and by the overall darker color in the upper map of Figure 7 when compared to the lower map. This greater descriptive power indicates that while country exports (driven by importers) is well described by the gravity-law models and by the variables considered in this study, country imports (driven by exporters) may need other variables or a different functional model. The better fitting of export, rather

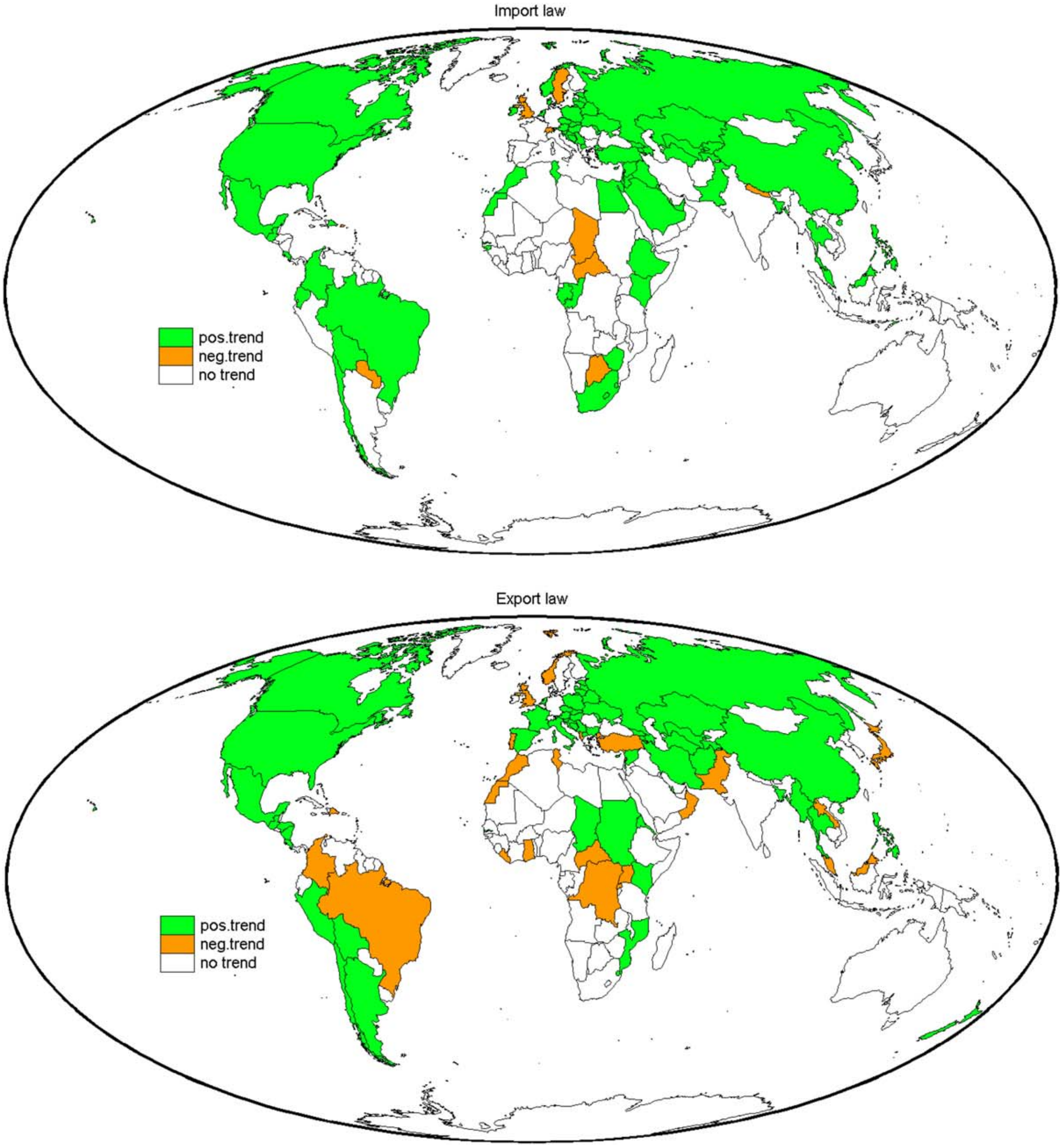



**Figure 8.** Trends of the adjusted coefficient of determination $R^2_{adj}$ of each country during the studied period; significant positive trends are green, significant negative trends are orange, and nonsignificant trends are in white.

than import, may be due to the higher influence on trade flows of destination countries (demand) rather than of source countries (supply). For example, independently of the wealth of a country, its goods are traded only if there are countries which are rich enough to buy them. This economic mechanism is revealed by the comparison of the two plots in Figure 5: contributions of P, D and A are comparable in the two cases, WD and WP compensate each other, while a large difference is found for the GDP, which is found to explain much less variance in the import law than in the export law. The higher influence of GDP of importers, rather than GDP of exporters, provides a possible explanation of the systematic greater quality of the export model for virtual water flows.

## 5. Conclusions

[48] Gravity-law models are simple yet valuable models to describe virtual water fluxes associated to the international trade. Results show that population, gross domestic product, and distance are the fundamental controlling factors of virtual water trade, both for import and for export. Virtual water of agricultural production of exporter countries is also relevant, while the arable land does not give a significant contribution; virtual water of dietary demand does not contribute to explain import fluxes, indicating that water (and food) requirements have a minor impact on trade than other—economic and structural—factors. These results confirm the fact that virtual water trade is currently driven by economic factors rather than water solidarity [*D'Odorico*

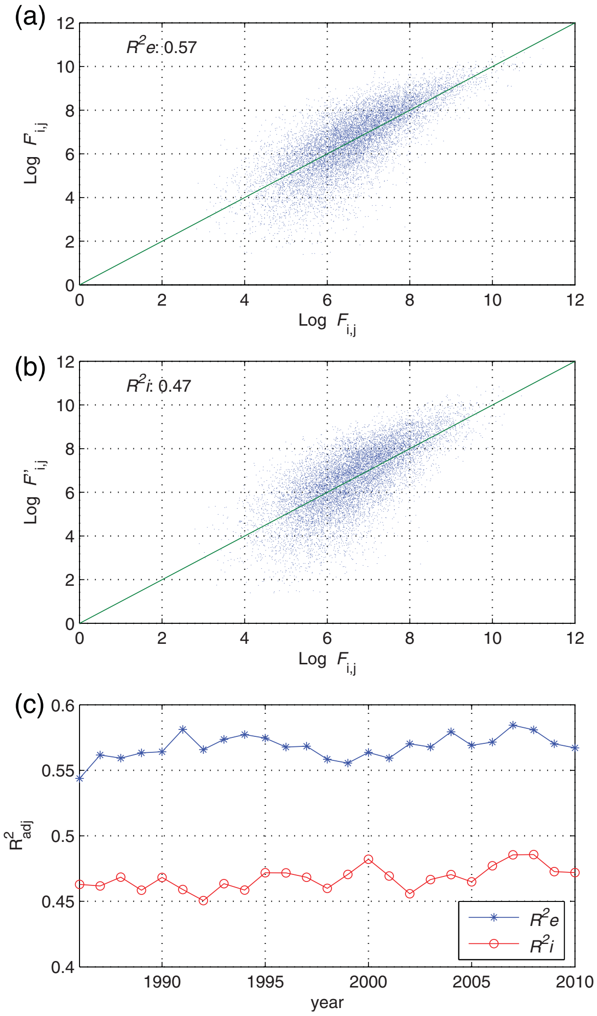



**Figure 9.** Comparison between real ($F_{i,j}$) and estimated virtual water fluxes for year 2010 with (a) the export law ($F'_{i,j}$) and (b) the import law ($F''_{i,j}$). (c) The temporal evolution of the global adjusted coefficients of determination for the two gravity-law models, $R_e^2$ (blue asterisks) and $R_i^2$ (red circles).

*et al.*, 2010]. Descriptive capability of gravity laws is good, with an overall coefficient of determination of 0.57 in 2010, for the whole traded fluxes; in general, export fluxes are better captured than import fluxes, indicating that importers are more determinant than exporters in structuring the trade network and that other variables related to exporting countries may be necessary to explain import laws. The proposed analysis, performed on the trade occurred in years 1986–2010, clears the way to future projections of the virtual water trade and to predictions of international flows based on the dynamics of identified drivers. Future projections of the virtual water trade can be interesting and useful tools for global water resource managers, for policy makers and for socioeconomical researchers.

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