Supporting Information:

Carbon, Land, and Water Footprint Accounts for the European Union: Consumption, Production, and Displacements through International Trade.

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Supplementary Materials and Method

Environmentally Extended Multiregional Input-Output Models

In order to keep things simple, the methodological explanation in the following paragraphs is based on a single-region input-output system; however the principle is the same in multiregional models. Input-output (IO) models are made up of matrices describing transactions between actors within an economy. Rows represent product groups while columns represent the industry, government, or household sectors which consume them. Transactions are generally accounted for in monetary terms; however some IO tables based on mass or energy transactions have been constructed.

An environmentally extended IO model constitutes a complete inventory of all economic transactions and selected environmental interventions of individual sectors within a specified region during a period of time, most commonly for a country on an annual basis. An environmentally extended IO model is generally made up of four matrices: the intermediate transactions matrix (Z), the final demand matrix (Y), the value added matrix (W), and the environmental extensions matrix (F), which can also include direct environmental interventions by households (F^{hh}) if applicable. In symmetric IO tables, an economy is modeled as consisting of *n* industries (we will assume the IO table is industry-by-industry, but they can also be product-by-product), *d* categories of final consumers, *w* types of production factors, and *f* types of environmental interventions. Z (*n*-by-*n*) is a square matrix of intermediate transactions where rows represent sales from each of the *n* industries included in the system, while columns represent each industry's purchases, so that an element z_{ij} gives industry *j*'s total purchases from industry *i*. Each column of Y (*n*-by-*d*) contains the purchases made by a specific group of final consumers, such as households and government, from each industry. Y also contains columns for tracking changes in stocks, changes in inventories, capital investments, and exports. Entries in Y describe purchases by consumers which do not produce output that re-enters the economy.

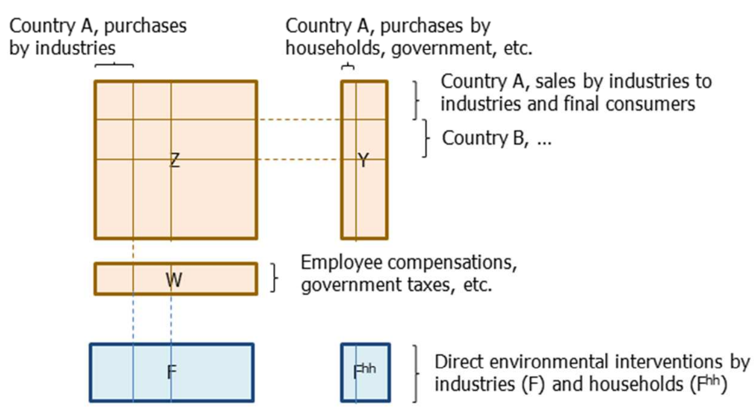

Figure S-1. Generic multiregional input-output tables with environmental extensions.

The rows of W (*w*-by-*n*) represent labor payments, taxes, subsidies, and operating surplus and the columns represent industries or product groups. For environmental analysis, the W matrix is rarely used. The F (*f*-by-*n*) matrix represents environmental interventions of each economic sector. It has one row for each included kind of intervention, such as CO_2 emissions, energy use and so on, and one column for each industry, such that its columns correspond to the columns of Z. In addition, there might be an additional matrix F^{hh}, representing direct environmental interventions by final consumers, e.g. CO_2 emissions from gas stoves in households.

Using these matrices a model can be constructed which allows the calculation of the total economic transactions and environmental interventions occurring along all supply chains associated with the production of a basket of products and services:

The total output (x) from all the industries in the economy over the defined time period can be calculated using Z and y, a column vector of total final demand, equal to the row sum of Y:

$$x = Zi + y$$

where i is a column vector of ones (for the summation of rows across columns of the matrix). Next we define a direct requirements matrix (A):

$$A = Z\hat{x}^{-1}$$

Each element (a_{ij}) of A represents the purchases of product/service (*i*) required by industry/service sector (*j*) to produce one unit of its output. Substituting into the previous eq. (1) we obtain the following:

$$x = Ax + y$$

Solving for x yields

$$x = (I - A)^{-1}y$$

where I is the identity matrix. Note that this equation holds not only for the original x and y but through the Leontief inverse $L = (I - A)^{-1}$ the total supply chain output (x*) associated with an arbitrary demand vector (y*) can be calculated.

A normalized environmental extension matrix (F) can be defined that gives environmental interventions by sector per unit output, by dividing total annual emissions etc. by total production, to arrive at a matrix with e.g. kg CO_2 emitted per dollars' worth of aluminum produced by the aluminum industry:

$$F = F_r\hat{x}^{-1}$$

The F matrix can be used to calculate total environmental interventions associated with an arbitrary final demand of products (y*):

$$E^* = F(I - A)^{-1}y^*$$

Where E* is a vector of total environmental interventions resulting from the whole production phase of the arbitrary demand vector y*.

In order to accurately represent trade flows and the economic structure involved in the production of imported products, an IO model combining several national-level IO tables through the use of international trade data is required. Such an international multiregional input-output (MRIO) table depicts interdependencies between domestic and foreign sectors with different production technology, resource use and pollution intensities and is regarded as a methodologically sound approach for the enumeration of environmental impacts from consumption. Using MRIO instead of a single region IO table does not change anything of the general concept of IOA, with the exception of international trade. Therefore, all exports are not part of final demand in MRIO model, but are allocated to the users in other regions. Exports to industries abroad are included in Z, while only when exports are used for final consumption in the receiving economy they are part of the final demand matrix. In an MRIO with *m* regions, the dimensions of the matrices would increase with the factor *m* where applicable (see Fig. 1).

Model Construction

The environmentally extended multiregional input-output (MRIO) system constructed and used for the present analysis is based on the Global Trade Analysis Project Database Version 7 (GTAP 7) [1]. The GTAP 7 database models the total global economy in 2004 as 113 geographical regions, composed of 94 individual countries and 19 aggregate regions. GTAP is based on datasets provided by a worldwide network of national dataset providers as well as the UN Commodities Trade Database. The process of constructing a multiregional input-output database from the GTAP 7 database is described in [2]. The construction of the extensions that was used for the present analysis is thoroughly documented in [3]. The following overview is based on similar descriptions in [3] and [4].

Both water and land use is largely determined by agricultural and forestry production. Primary crop and forestry products refer to non-processed products that are directly harvested. In this article, the term *primary product* always refers to such (biological) products. Ecological and Water footprint accounts currently available have high product level detail on such products. This kind of detail is normally not available in IO systems, a shortcoming that could lead to serious aggregation errors. Therefore, the environmental extension matrix should be based on these primary products distinguishing their country of origin with the same level of detail as is used for standard footprint accounting and which is different from the MRIO system. Therefore we distinguish two systems: the monetary (MRIO) system and the physical (footprint – environmental extension) system. These systems differ regarding detail in primary crop and forestry products classification and country aggregation. Furthermore, the two systems track trade flows in different units, monetary (Euros) and physical (tons or m^3), respectively. The monetary system follows MRIO classification, while the physical system follows the classification required for footprint calculations, in this particular case the FAOSTAT classification system.

The information about the origin and type of primary product has to be kept in order to calculate the footprints in a proper manner. Two types of information regarding the use of specific primary products by MRIO sectors and regions can be available. The first one comprises production and international trade of primary products; the second comprises information on direct use of some primary products by specific MRIO sectors, for example the use of products as seed by their producing industry. It is usually not possible to distinguish the country of origin for each particular primary product which is consumed by a specific sector within the consuming country, but the overall composition of supplying countries for each primary product is well distinguished. Since detailed information on the use of all primary products by all individual sectors of the MRIO model is generally not available, the allocation of the rest of primary products to individual sectors within MRIO regions can be done using the appropriate monetary flows within the MRIO model (the monetary flow of the respective product group of the respective region). This is generally done by the Leontief inverse in the standard approach as well, but using the same patterns for all products of one product group. The advantage of this approach is the distinction of the consuming region for individual primary products and utilizing specific data on the use of some primary products such as feed and seed by MRIO sectors. For example, if more primary products are aggregated in one MRIO product group and only one primary product is traded internationally, this detail will be kept by this approach. The distinction in the use of the rest of primary products within the same MRIO product group for intermediate consumption and final demand will not be addressed since its distribution within the same region is based on the monetary flows only.

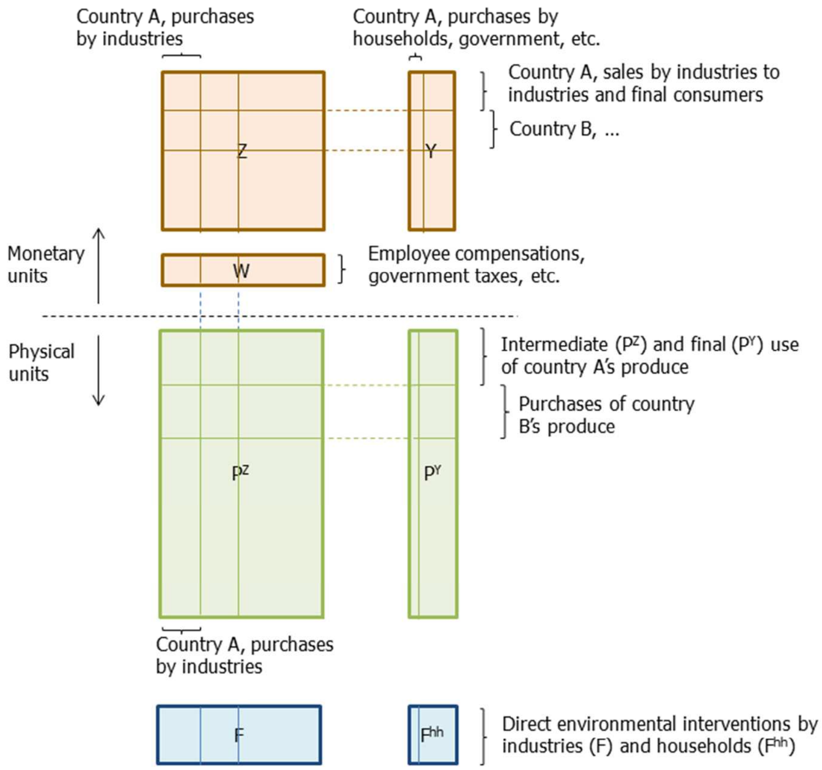

Figure S-2. Sketch of the constructed EE-MRIO model including the additional physical system (green)

Constructed according to the preceding description, the P^Z and P^Y matrices track 179 primary products from producing country to the sector and region that first uses them. Hence they both have 179 (primary products) times 238 (countries) rows. P^Z has columns corresponding to the columns of Z, while P^Y has columns corresponding to the columns of Y, see Fig. S-2. The units are metric tons for agricultural products, and m^3 for forestry products. Upon construction, these matrices were treated as regular environmental extensions, where the environmental intervention is the amounts used of individual primary products. Following a column down through the matrices Z, P^Z, and F in Fig. S-2, one can infer the purchases made by that particular sector from all sectors (Z), its total use of primary products of all 179 types and produced in all 238 countries (P^Z), and its total CO_2 emissions etc. (F). Using a set of coefficients that convert each primary product produced in each country to a corresponding set of land and water footprints, one copy of P^Z and P^Y can be created from each footprint type. Due to the extensive matrix sizes and the computational capabilities required, these matrices were constructed and subsequently aggregated across primary products. Note that this does not change any results since the matrices, once constructed, are static.

When the footprints are implemented this way into the F matrix, it is necessary to account separately for direct footprints (E_{DIR}) of primary products included in the final demand (y) and all indirect footprints (E_{IND}) of all products included in the final demand (y) using the following equations:

$$E_{DIR} = F^{hh}y$$

$E_{IND} = F(I - A)^{-1}y$

Land footprint coefficients

The land footprint describes the equivalent land and ocean area utilized by humans to derive usable biomass products, i.e. products of economic interest to people [5, 6]. This land and ocean area is weighted according to its current productivity by converting it into an equivalent area of global average productivity, measured in units of global hectares [7]. The land footprint distinguishes five different land types, namely: cropland, forest land, pasture, built up land and marine area, each with a specific, world-average productivity.

The direct land footprint (LF_D) is calculated as:

$LF_D = A_{LN} \cdot YF_{LN} \cdot EQF_L$

Where A_{LN} is the area of land type L used in country N, YF_{LN} is a country and land type specific yield factor, which converts the area A_{LN} in country N into world average area of the respective land type and EQF_L is a land type specific equivalence factor, which converts the former result into an area with a global average productivity. For each individual primary biomass product, A_{LN} is calculated as P_{LN}/Y_{LN}, where P_{LN} is the physical amount of product harvested and Y_{LN} is the country specific yield for the land type L producing that product.

The yield factor is derived as:

$$YF_{LN} = \frac{\sum_{i \in U} A_{LWi}}{\sum_{i \in U} A_{LNi}}$$

Where i is an index over all primary biomass products (set U) harvested from the land type L in country N, A_{LWi} is the area associated to each primary biomass product using world average yields and A_{LNi} is the area associated to each primary biomass product i in the studied country.

Country specific yields, production volumes and international trade data are retrieved from FAOSTAT database [8], yield factors and equivalence factors are retrieved from database of Global Footprint Network [7].

Water footprint coefficients

Water Footprint estimations (green, blue and grey) of primary crops are taken from the study by Mekonnen and Hoekstra [9]. The green, blue and grey Water Footprints of primary crops are estimated in a spatially-explicit way. Calculations are done by taking a high-resolution approach, estimating the Water Footprint of the crops at a 5 by 5 arc minute grid.

The green and blue Water Footprint of a crop (WFcrop, m3/ton) is calculated as the green or blue component in crop water use (CWUi, m3/ha) divided by the crop yield (Y, ton/ha) where i indicates the component of Water Footprint, green and blue.

$$WF_{proc,i} = \frac{CWU_i}{Y}$$

The green and blue components of crop water use (CWU, m3/ha) are calculated by accumulation of daily evapotranspiration (ET, mm/day) over the complete growing period:

$$CWU_i = 10 \times \sum_{d=1}^{lgp} ET_{i,d}$$

Where ETi,d represents evapotranspiration by type, i, either green or blue and by day, d. The factor 10 is used to convert mm into m3/ha. The summation is done over the period from the day of planting, d=1, for the entire length of growing period (lgp) until harvest.

The grey water footprint of a primary crop (WFcrop,grey, m3/ton) is calculated as the chemical application rate per hectare (AR, kg/ha) times the leaching rate (α) divided by the maximum acceptable minus the natural concentration for the pollutant considered (cmax – cnat, kg/m3) and the crop yield (Y, ton/ha).

$$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{max} - c_{min})}{Y}$$

Grey water footprints are measured based on the (human-induced) loads that enter into freshwater bodies, not on the basis of the loads that can finally be measured in the river or groundwater flow at some downstream point. Since water quality evolves over time and in the course of the water flow as a result of natural processes, the load of a certain chemical at a downstream point can be distinctly different from the sum of the loads that once entered the stream (upstream). The choice to measure the grey water footprint at the point where pollutants enter the ground- or surface water system has the advantage that it is relatively simple – because one does not need to model the processes that change water quality along the river – and safe – because water quality may improve along the flow of a river by decay processes, but it is unclear why one should take improved water quality downstream as an indicator instead of measuring the immediate impact of a load at the point where it enters the system. While the grey water footprint indicator thus does not account for natural processes that may improve water quality along the water flow, it does also not account for processes that consider the combined effect of pollutants, which may sometimes be greater than what one may expect on the basis of the concentrations of chemicals when considered separately. In the end, the grey water footprint strongly depends on ambient water quality standards (maximum acceptable concentrations), which is reasonable given the fact that such standards are set based on the best available knowledge about the possible harmful effects of chemicals including their possible interaction with other chemicals.

Uncertainties, limitations, and subjectivity

Following the "Driver, Pressure, State, Impact, Response" (DPSIR) framework, the assessment of sustainability can be subdivided into more manageable tasks of analyzing drivers (e.g., population increase), pressure (e.g., GHG emissions), environmental state (e.g., atmospheric GHG concentration, mean global temperature), impacts (e.g., more frequent severe weather events), and responses (e.g., emission taxes, energy efficiency programs). In this study we quantify pressures, thus avoiding the difficult following task of assessing the overall consequences on the environment. Especially for land and water use, the impacts are mostly local, and would depend fundamentally on specific knowledge about the local conditions. For instance, the blue water footprints calculated here is a sum of water consumption in all parts of the world, without considering the water availability at the point of extraction. Still, even though all the blue water use is aggregated in the WF_b indicator, the model keeps the detailed information. This facilitates impact assessments based on the footprint accounts.

Even the pressure accounting however, is not straightforward. The matters of how to directly quantify pressures on the climate, and on biological and freshwater resources, are not definitively settled, and our method involves some weighting and subjective choices. For instance, the carbon footprint (CF) is perhaps the least disputed among the three indicators, but even here we weight emissions of CO_2, CH_4, N_2O, and various fluorinated greenhouse gases (F gases), into tons of CO_2-equivalents, using weights that depend on the time horizon chosen. Furthermore, we do not include biogenic CO_2 emissions, though Cherubini et al. [10] point out that these too have a forcing effect during their atmospheric lifetime. The Ecological Footprint (EF), since its introduction two decades ago, has become popular as a sustainability indicator. However, it has also been criticized for being too simplistic, see [11]. The land footprint (LF) used here is defined as a subset of the EF, where we exclude energy land (carbon uptake land). The energy land is not land that is used as such; it is a certain area of forest land required to be left unused to store carbon to counteract CO_2 accumulation in the atmosphere due to anthropogenic emissions. This area is directly derived from CO_2 emission accounts; however, since these are already counted in the CF in this analysis, we did not include this part of the EF. Regarding water use, it is immediately obvious that some water use can hardly be said to have any harmful effects at all, if the extraction rate is modest and water is abundant, while extensive water consumption in water stressed regions is another story. The water footprint (WF) [12] does not account for this, but counts all water equally, which has spurred some debate [13-17].

There are several sources of uncertainty in our analysis. There are some inherent uncertainties to MRIO analyses; this relates to the aggregation of products and industries required when keeping complete records of national economies, and to the fundamental assumption that monetary transaction record can be used to represent physical flows. Moreover, there is also the question of the validity of the underlying data. The GTAP database is based on voluntary data submissions from a network of partners, and the quality of the submitted data is not always certain [2]. The physical extension matrices we constructed for this model were based on data from the FAOSTAT database, which suffers from similar data quality challenges. Finally, a limitation to our analysis is the vintage of the datasets. The model year is 2004, since this is the reference year for the GTAP 7 database. However, the GTAP 8 database has recently been released, with 2004/2007 as reference years [18].

Supplementary Data

Environmental extensions

Environmental extensions describing the land use by economic sectors and final consumption were developed following an approach proposed by Ewing et al. [19]. Actual land use was associated to the harvested primary biomass products, which were allocated to economic sectors of their first use. This approach allowed for the utilization of detailed data on international trade of specific primary crop and forestry products and their use by economic sectors based on information from the FAOSTAT database [8]. Therefore, primary crop and forestry products were treated using the high level of detail included in FAO statistics, while the input-output model with considerably broader product categories was employed to address the trade and consumption of products produced from these primary biomass products and also for primary fish products. In a second step all the primary biomass products were converted into equivalent area using country specific conversion factors. The equivalent area associated to primary biomass products used by individual economic sectors is then allocated to final consumers using the standard input-output equation:

$$L = F \cdot (I - A)^{-1} \cdot Y$$

Supplementary Results

Supplementary Figures

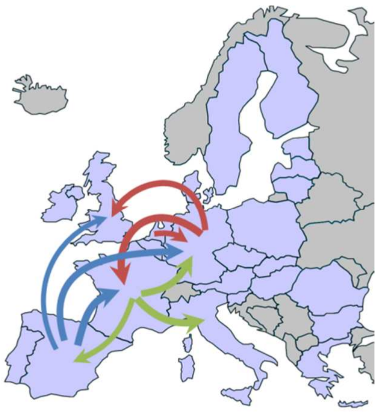

Figure S-3 Top three gross displacements of environmental pressures between EU member states, with arrows pointing in the direction of product flows, i.e. opposite of displacement. Red arrows show CF, green LF, and blue WF_b. For each footprint the arrow thicknesses indicate relative magnitudes.

Supplementary Tables

Description of Tables All descriptions are referring to the tables in the Excel workbook 'Supporting_Information.xls'.

Table S-1 in the worksheet 'Overall_FP' shows the total footprints for each EU country, as well as the EU and world totals. Table S-2 shows the results from the production or territorial perspective, meaning e.g. for WFb - how much blue water is consumed within the borders of each country. The footprint and territorial results are thus the same for the world overall. Overall land footprint results were previously published in ref 1. Population estimates were taken from the GTAP 7 database[2].

Tables S-3 through S-7 show displaced footprints. In the top 28x28 table in each sheet, an element (i,j) shows the total environmental pressures occurring in region i and allocated to final consumption in region j due to international trade. The rather small values on the diagonals (i,i) represent pressures occurring in region i which go into production chains abroad before coming back to the home region for final consumption. An example can be wheat grown in Norway and exported to Sweden as flour where it is used to produce bread which is in turn imported back to Norway for final consumption.

Each value in this top table is then broken down on the top 5 contributing products below. As such there are 28*28 small 5x3-tables, where the first column shows the product consumed, the second shows the footprint attributed, and the third converts this value to a percentage of the total shown in the big table above. Be aware that the breakdown is on products purchased in region j that lead to environmental pressures in region i, hence the products need not directly represent imports between these regions.

Consider this example: In the 'CF_trade' sheet, we see that purchases of "Motor vehicles and parts" by final consumers in Austria led to 47 ktCO2e of emissions in Belgium. This could be caused by Austrians directly importing cars or car parts from Belgium, or it could be that they purchase cars from another country or domestically. For instance we can imagine that part of this came from Austrians buying German cars, and that the German car manufacturer used electricity that was produced by Belgian coal power plants. The only thing we know directly from the table is that the purchases, somewhere in the supply chain, led to these emissions in Belgium.

In both the top tables, as well as in the bottom system of 28*28 small tables, the top 5 values are highlighted in each sheet (excluding exchanges with the aggregated "Rest of the world" region).

Note that the land footprint (LF) is a subset of the Ecological Footprint (EF), and the blue water footprint (WFb) is a subset of the water footprint (WF). The results are for the year 2004.

Tables S-8 and S-9 show the sectors and regions included in the MRIO model, based on the GTAP 7 database.

Tables S-10 and S-11 show the countries and products included in the physical extension matrices.

References

1. Narayanan, G. B.; Walmsley, T. L., *Global Trade, Assistance, and Production: The GTAP 7 Data Base*. Center for Global Trade Analysis, Purdue University: West Lafayette, 2008.
2. Peters, G. P.; Andrew, R.; Lennox, J. Constructing an environmentally extended multi-regional input-output table using the GTAP database. *Economic Systems Research* **2011,** *23* (2), 131-152.
3. Weinzettel, J.; Steen-Olsen, K.; Galli, A.; Cranston, G.; Ercin, E.; Hawkins, T.; Wiedmann, T.; Hertwich, E. *Footprint Family Technical Report: Integration into MRIO model*; One Planet Economy Network: London, 2011.
4. Weinzettel, J.; Hertwich, E. G.; Peters, G. P.; Steen-Olsen, K.; Galli, A. Affluence drives the globalization of land use. **Submitted for publication**.
5. Wackernagel, M.; Schulz, N. B.; Deumling, D.; Linares, A. C.; Jenkins, M.; Kapos, V.; Monfreda, C.; Loh, J.; Myers, N.; Norgaard, R.; Randers, J. Tracking the ecological overshoot of the human economy. *Proceedings of the National Academy of Sciences of the United States of America* **2002,** *99* (14), 9266-9271.
6. Haberl, H.; Wackernagel, M.; Krausmann, F.; Erb, K. H.; Monfreda, C. Ecological footprints and human appropriation of net primary production: A comparison. *Land Use Policy* **2004,** *21* (3), 279-288.
7. Ewing, B.; Reed, A.; Galli, A.; Kitzes, J.; Wackernagel, M. *Calculation Methodology for the National Footprint Accounts, 2010 Edition*; Global Footprint Network: Oakland, USA, 2010.
8. FAO, FAOSTAT Database. In Food and Agriculture Organization of the United Nations: Rome, 2010.
9. Mekonnen, M. M.; Hoekstra, A. Y., A global assessment of the green, blue and grey water footprint of crops and crop products. In *Value of Water Research Report Series*, UNESCO-IHE: Delft, the Netherlands, 2010.
10. Cherubini, F.; Strømman, A. H.; Hertwich, E. Effects of boreal forest management practices on the climate impact of CO2 emissions from bioenergy. *Ecological Modelling* **2011,** *223* (1), 59-66.
11. van den Bergh, J. C. J. M.; Verbruggen, H. Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'. *Ecological Economics* **1999,** *29* (1), 61-72.
12. Hoekstra, A. Y.; Hung, P. Q. *Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade*; UNESCO-IHE Institute for Water Education, Delft, the Netherlands: 2002.
13. Ridoutt, B. G.; Pfister, S. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environmental Change* **2010,** *20* (1), 113-120.
14. Pfister, S.; Hellweg, S. The water "shoesize" vs. footprint of bioenergy. *Proceedings of the National Academy of Sciences* **2009,** *106* (35), E93-E94.
15. Hoekstra, A. Y.; Gerbens-Leenes, W.; van der Meer, T. H. Reply to Pfister and Hellweg: Water footprint accounting, impact assessment, and life-cycle assessment. *Proceedings of the National Academy of Sciences* **2009,** *106* (40), E114.
16. Ridoutt, B. G.; Huang, J. Environmental relevance—the key to understanding water footprints. *Proceedings of the National Academy of Sciences* **2012,** *109* (22), E1424.

17. Hoekstra, A. Y.; Mekonnen, M. M. Reply to Ridoutt and Huang: From water footprint assessment to policy. *Proceedings of the National Academy of Sciences* **2012,** *109* (22), E1425.
18. Narayanan, B.; Aguiar, A.; McDougall, R., *Global Trade, Assistance, and Production: The GTAP 8 Data Base*. Center for Global Trade Analysis, Purdue University: 2012.
19. Ewing, B.; Hawkins, T.; Wiedmann, T.; Galli, A.; Ercin, A., E.,; Weinzettel, J.; Steen-Olsen, K. Integrating Ecological and Water Footprint Accounting in a Multi-Regional Input-Output Framework. *Ecological Indicators* **2012,** *23*, 1-8.