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Analysis

# Ecological footprint of nations: Comparison of process analysis, and standard and hybrid multiregional input–output analysis

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ABSTRACT

The ecological footprint (EF) is an indicator of human requirements on bio-productive land, an essential but limited resource, which use is related to environmental burden. In this article, we compare three methods for calculating national EF: a) the process analysis represented by Global Footprint Network (GFN) accounts; b) a standard environmentally extended multi-regional input–output model (EE-MRIOM); and c) a hybrid EE-MRIOM. The process analysis accounts for total domestic production and international trade of selected products. A standard EE-MRIOM further accounts for the upstream footprint of all traded products, but has a low resolution of relevant products in available datasets. The hybrid EE-MRIO method assessed here traces the primary biomass products in physical units through environmental extensions. Our results show that the standard MRIO model might introduce a significant error due to low resolution and poor data quality. The hybrid MRIO approach provides more accurate results than the standard MRIO method since it applies data from additional sources on a more detailed level. The process analysis underestimates the footprint of imports and exports as it ignores trade in services and other products as well as the upstream flows of products included in the analysis.


## 1. Introduction

The global socio-economic metabolism has reached unsustainable levels of resource consumption and waste generation (Ellis et al., 2010; Krausmann et al., 2013; Rockström et al., 2009) and requires a continuously increasing amount of environmental resources and absorption capacity for emissions and waste. Consequently, a planetary-scale critical transition is likely to be approaching (Barnosky et al., 2012) and tools are thus needed to detect early warning signs and quantify the effects on ecosystems of a growing human metabolism. Therefore, indicators of environmental sustainability are becoming increasingly important for policy makers who need a basis for measuring progress and setting policy goals to prevent further detrimental effects (BIO Intelligence Service et al., 2012; Eurostat, 2011; Moldan et al., 2012).

Environmental problems are ultimately driven by the consumption of products and services (Tukker and Jansen, 2006), which emphasizes the value of consumption based indicators, often denoted as footprints. Footprint type indicators assign responsibilities for environmental interventions from producers to final consumers. The ecological footprint (EF) has become a popular indicator of socio-economic requirement on bio-productive land (Wackernagel et al., 2002) and it has been widely applied by many researchers and adopted by several governments. Despite its popularity, the standard method for calculating national EF developed by Global Footprint Network (GFN) based on process analysis has been criticized for inconsistent treatment of internationally traded products (Kitzes et al., 2009; Wiedmann and Barrett, 2010). GFN uses data from FAOSTAT (for biomass-based products) and UN COMTRADE (for commodities) and its method thus only tracks primary and derived products captured by these databases. This data serves as a basis to account for the bio-productive land requirements embodied in international trade of the country (imports and exports of bio-productive land requirements) (Kitzes et al., 2008). The traded products consist of all the primary products plus selected secondary and tertiary products, mainly directly derived from the primary products. An inconsistency stems from the fact that only selected products are included in FAO (Food and Agriculture Organization of the United Nations) statistics and thus in the accounting for EF of traded products. Furthermore, another drawback is the limited production chain considered for footprint calculation, which introduces

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potentially significant truncation error, i.e. an error introduced by leaving part of the supply chain out of the analysis (Lenzen, 2001; Majeau-Bettez et al., 2011). For example, the ecological footprint of internationally traded shoes is considered zero in the current version of GFN accounts, since the land requirements related to feeding cows in order to get leather is too far in the supply chain to be considered for the trade analysis under the process analysis.

Environmentally extended multiregional input–output analysis (EE-MRIOA) is the state of the art in the construction of consumption based accounts of national greenhouse gas emissions (national carbon footprints) (Hertwich and Peters, 2009; Peters et al., 2012), since it is capable of accounting for greenhouse gas emissions embodied in all traded products including their nearly complete production chains,[1] and applying country-of-origin production technology on imported products (Wiedmann, 2009). The main disadvantage of EE-MRIOA is its sector and product aggregation, as all products and economic sectors are aggregated into broad groups, which are subsequently assumed to be and treated as homogeneous. Calculating EF through the IO method therefore implies that the several hundred different internationally traded products tracked by GFN would be aggregated into just a few product groups in order to benefit from the inclusion of all traded products. Historically, GFN has opted to maintain the highest possible product resolution, based on the argument that the benefits would not justify the cost (Wiedmann et al., 2007).

Galli et al. (2012) recently defined a footprint family of indicators covering carbon, ecological and water footprints. The authors argued that a common and consistent calculation framework is desirable in the calculation of these indicators. Furthermore, Ewing et al. (2012) proposed a methodological framework to account for ecological and water footprint using EE-MRIO method, but keeping the same level of detail for primary biomass products as the GFN's process analysis. This method was further applied by Steen-Olsen et al. (2012) and Weinzettel et al. (2013). The advantage of this framework covers the possibility to join the footprint family of indicators under the common framework, the application of standard analytical procedures available in IO analysis and alleviate the disadvantage of aggregating the primary products into a few groups (Galli et al., 2013). This method is easier than a full disaggregation of the MRIO dataset, since only the use structures for these products are distinguished and the dimensions of the core MRIO dataset does not increase above a level manageable by a current standard PC.

The aim of this article is to compare and analyze the differences between national EF calculation through process analysis (represented by GFN accounts), the MRIO method in which land use is linked to the producing sector (standard MRIO method, applied for example by Yu et al. (2013) and Wilting and Vringer (2009)), and the method proposed by Ewing et al. (2012) in which the environmental extension is composed of primary biomass products, which are linked to consuming sectors (hybrid MRIO, applied by Weinzettel et al. (2013) and Steen-Olsen et al. (2012)).[2] We compare these methods on an example of national ecological footprint in 2004. We further emphasize some advantages of the hybrid MRIO approach in respect to process analysis. While a comparison of a MRIO analysis and process-based analysis has been previously provided by Feng et al. (2011) for the national water footprint, this is to our knowledge the first article performing such comparison for national EF values and constituting land types.

[1] Strictly speaking, the standard input–output analysis excludes consumed capital, as it is part of value added, and therefore the upstream requirements of the capital are not part of the results, if any special treatment is not applied (see for example Peters and Hertwich, 2006. The importance of imports for household environmental impacts. J. Ind. Ecol. 10, 89–109. or Schoer et al., 2012. Raw material consumption of the European union — concept, calculation method, and results. Environmental Science & Technology 46, 8903–8909.)

[2] The names "hybrid" and "standard" MRIO are based on a report by Giljum, Lutter, Bruckner and Aparcana, 2013. STATE-OF-PLAY OF NATIONAL CONSUMPTION-BASED INDICATORS. SERI, Vienna. While there is no standard for MRIO, we use this wording to distinguish MRIO from the hybrid MRIO and refer to MRIO as standard MRIO.

## 2. Methods

### 2.1. National Ecological Footprint Through Process Analysis (GFN's Accounts)

#### 2.1.1. General approach

According to GFN, a nation's EF ($EF_N$) is calculated based on direct requirements on domestic bio-productive land[3] ($EF_P$, production perspective EF, comprising all land utilized domestically) from which the EF of exported products ($EF_{EX}$) is subtracted and to which the EF of imported products ($EF_{IM}$) is added:

$$EF_N = EF_P + EF_{IM} - EF_{EX}. \tag{1}$$

The EF is composed of six different land types (cropland, forest land, fishing grounds, grazing land, built-up land, and carbon uptake land) which are expressed in a common unit of "global hectares" (gha) based on the bio-productivity of each land type (Borucke et al., 2013; Galli et al., 2007). The global hectare is defined as a hectare of land with world-average bio-productivity. The direct requirements on domestic bio-productive land ($EF_P$) are calculated through "primary products", i.e. the products directly extracted from nature, e.g. wheat, corn, grass, etc. The ecological footprint ($EF_i$) of a single primary product i is defined as:

$$EF_i = \frac{P_i}{Y_{Ni}} \times YF_{NL} \times EQF_L. \tag{2}$$

And the direct requirements on domestic bio-productive land ($EF_P$) are calculated as a sum over all primary biomass products i:

$$EF_P = \sum_i \frac{P_i}{Y_{Ni}} \times YF_{NL} \times EQF_L \tag{3}$$

where $P_i$ is the physical amount of primary product i, $Y_{Ni}$ is the country (N) and product specific yield, $YF_{NL}$ is the country and land type (L) specific yield factor, and $EQF_L$ is the land type specific equivalence factor. Each primary product is associated with one land type. The interpretation of this equation is that $P_i/Y_{Ni}$ converts the physical amount of product into actual land requirements, the yield factor YF converts the actual land into world average land of the respective land type and the equivalence factor then converts that into area of world average bio-productivity, measured in global hectares. The yield factor YF is defined as:

$$YF_L = \frac{\sum_{i \in U} A_{LWi}}{\sum_{i \in U} A_{LNi}} \tag{4}$$

where i is the index over all primary products (set U) of the respective land type produced in the given country, $A_{LWi}$ is the area associated to each primary product i if the world average yield was applied and $A_{LNi}$ is the area associated to each primary product i in the studied country. In other words, the nominator accounts for the area which would be needed to produce all the primary products produced in a given country if they were produced with world average yields, and the denominator presents the total area actually used to grow all the primary products within the country. In this sense, for each of the six considered land types, the yield factor tells us how bio-productive the national land is in comparison to the world average land bio-productivity.

[3] Sometimes denoted as "direct or production footprint" because it is directly used for the domestic production of goods and services. The term "production footprint" is confusing, because it does not refer to footprint (it does not cover any upstream requirements), but it only comprises the direct requirements on bio-productive land within the country in question.

Based on Eq. (4), current GFN's national accounts simplify Eq. (3) into the form:

$$EF_P = \sum_i \frac{P_i}{Y_{Wi}} \times EQF_L. \tag{5}$$

Implying the following equation for an ecological footprint ($EF_i$) of a single primary biomass product i:

$$EF_i = \frac{P_i}{Y_{Wi}} \times EQF_L \tag{6}$$

where $Y_{Wi}$ is the world average yield of product i. The simplification introduced by Eq. (6) is valid only in three cases: (a) all primary products of the specific land type are produced on land with equal ratio of world average yield and domestic yield; (b) the total national EF of the given land type is calculated from the production perspective as in Eq. (5) (the results can differ for individual primary products, but the sum over all primary products will be the same); (c) when only a single product is assumed to be produced by the given land type. In the current GFN's accounts, (c) is the case for all land types except cropland. However, GFN applies this simplification also on individual primary crop products traded internationally, which results in an unknown error for national cropland EF.

*2.1.2. Ecological Footprint of Internationally Traded Primary Products Through the Process Analysis (GFN's Accounts).* As the EF (GFN's process analysis) aims to track the amount of regenerative capacity embedded in a given product with a limited underlying data, all traded primary products are assumed to be produced with world average yields (Galli et al., 2007) and the corresponding requested area is then converted to productivity weighted global hectares. The EF of traded primary biomass products is therefore calculated using Eq. (6). Moreover, only the direct land requirements are considered for planting the crops. This simplification implies that all primary products traded internationally are assumed to have the same EF per unit of weight. Note that this is not an intentional feature but rather a result of the simplification.

*2.1.3. Ecological Footprint of Processed Traded Products Through the Process Analysis (GFN's Accounts).* GFN's current methodology only accounts for the EF of a limited number of processed traded products[4] using a process type analysis with a limited number of considered upstream steps in the production chain. In the calculation of EF of non-primary traded products (henceforth referred to as derived products), such as bread, yields $Y_D$ of the derived products are calculated from the yields ($Y_P$) of the primary products using extraction rates:

$$Y_D = Y_P \times EXTR_D \tag{7}$$

where $EXTR_D$ is a technical conversion factor giving the amount of the primary product required per unit of the secondary product, e.g. how much wheat is used for the production of 1 kg of bread.

In the case of more products being produced from one primary input, the technical conversion factor can be written as:

$$EXTR_D = \frac{TCF_D}{FAF_D} \tag{8}$$

where $FAF_D$ is the footprint allocation factor, which allocates the footprint of a primary product between simultaneously derived products according to the $TCF_D$ (technical conversion factor)—or weighted prices. The economic value of derived products represents their relative contributions to the incentive for the harvest of the primary product (Kitzes et al., 2008), see also Weinzettel (2012) and Ardente and Cellura (2012). While physical laws determine the set of feasible processes, the economic and other laws created by humans determine which of these processes will be employed in the production of goods and services. The equation for the footprint allocation factor of a derived product is:

$$FAF_D = \frac{TCF_D V_D}{\sum TCF_i V_i} \tag{9}$$

where $TCF_i$ and $V_i$ is the technical conversion factor and the market price, respectively, of each simultaneously derived product and $V_D$ is the market price of allocated product. For a production chain with only one derived product, then, $FAF_D$ is 1 and the extraction rate equals the technical conversion factor provided by FAO. For more details on the EF of different land types see (Kitzes et al., 2008).

In summary, there are three simplifications applied within the GFN's National Footprint Accounts with regard to imported and exported products: (a) nearly all internationally traded products are treated as being produced by world average productivity and technology,[5] (b) only a limited number of internationally traded products is considered, (c) only a limited number of upstream supply chain steps is considered.

### 2.2. Standard EE-MRIO Method

Environmentally extended multi-regional input–output analysis has recently been used in order to assign responsibilities for environmental interventions to final consumers and to analyze international trade with respect to embodied environmental interventions, e.g. (Hertwich and Peters, 2009; Lenzen et al., 2012). Environmental interventions are linked to the producing sectors within the environmental extension matrix and they follow the production chain through the Leontief inverse matrix, based on flows of the aggregated product groups (Hertwich and Peters, 2009). The basic equation of a standard EE-MRIO is:

$$EF_N = F(I - A)^{-1} y_N \tag{10}$$

where $EF_N$ is the national EF embodied in the total national final demand of products $y_N$, F is the environmental extension matrix (direct EF of sectors) normalized per unit of sector output, I is the identity matrix and A is a technical coefficients matrix. The matrix $(I - A)^{-1}$, commonly referred to as the Leontief inverse, gives the total output by all sectors per unit final demand of each product group, including indirect (upstream) activities, i.e. activities of the whole production chain. Eq. (10) serves to account for upstream (indirect) requirements related to the purchased products. Direct requirements on bio-productive land by final consumers have to be addressed separately in both standard and hybrid MRIO.

In the standard MRIO method which can be applied for EF calculation, the EF of all primary products would be allocated to their producing sector in the environmental extension matrix, e.g. all wheat is allocated to the wheat producing sector. This can be done in two different forms with identical results. The EF of all primary products produced by each sector can be allocated directly to this sector, or alternatively, the primary products produced by the sectors can be allocated to the producing sectors and converted into EF using a characterization matrix C containing the conversion factors for individual primary products:

$$EF_N = CP_P(I - A)^{-1} y_N. \tag{11}$$

In this case the F matrix is replaced by a multiplication of a matrix C and a matrix $P_P$, which contains primary product assigned to respective producing sectors. Matrix C contains factors to convert the weight of

[4] GFN's choice of the traded products to be included in the calculation is not arbitrary, but depends on the products reported by the databases from which trade statistics are taken (Borucke et al., 2013).

[5] This is understandable for imported products, since GFN uses information on total imports from FAOSTAT, but it is applied also for exported products, when the country of origin is known and country specific factors can be applied.

**Table 1**
Summary of the three approaches as investigated in this paper.

| | GFN's process analysis (2010 edition) | Standard MRIO | Hybrid MRIO |
|---|---|---|---|
| Global coverage | YES | YES | YES |
| Units in tracking production chain | Physical | Monetary | Physical (for primary biomass products) and monetary for all other products |
| Allocation | Economic value[a] | Economic value | Economic value |
| Re-exports | Included[b] | Excluded | Excluded |
| Number of products considered for international trade | 169 specific primary biomass products >150 specific derived products | 57 product groups covering the whole economy | 169 specific primary biomass products 57 product groups covering the whole economy |
| Number of regions considered for international trade | 238 UN countries | 113 regions for international trade | 238 UN countries for international trade of primary biomass products 113 regions for the trade of all other products |
| Productivity and technology assumed | Global average[c] | Country specific | Country specific |
| EF of a single primary product | $EF_i = (P_i / Y_{wi})\ EQF_L$ | $EF_i = (P_i / Y_i) \cdot YF_{LN} \cdot EQF_L$ | $EF_i = (P_i / Y_i) \cdot YF_{LN} \cdot EQF_L$[d] |
| National EF | $EF_N = EF_P + EF_{IM} - EF_{EX}$ | $EF_N = CP_P(I - A)^{-1}y_N$ | $EF_N = CP_C(I - A)^{-1}y_N + Cy_{Np}$ |

[a] GFN uses physical quantities to assign EF of product to their users, but if two products are produced from one product, allocation based on economic value is applied.
[b] Re-exports are excluded from the national EF by the calculation procedure, but they are included for international trade, which is important for this comparison.
[c] Except for carbon uptake land EF for exported products, which reflects country specific $CO_2$ intensity of energy use.
[d] If not specifically stated otherwise.

primary products into corresponding EF and it therefore contains coefficients derived either from Eqs. (2) or (6). We used only Eq. (2) for the standard MRIO method in this comparison.

The standard MRIO approach implies the same sales structure for all the primary products produced by one economic sector distinguished by the underlying MRIO system. This means that all primary products are assigned to the using sectors and countries through the Leontief inverse based on the monetary flows within the MRIO dataset for the respective product group. For example, if maize and barley correspond to the same product group of the MRIO system, their sales structure is the same as for this broader product group. As a result, for both products the same share will be allocated to exports, irrespective of the differences in the export values reported by FAOSTAT.

### 2.3. Hybrid EE-MRIO Method

The level of detail currently used by GFN's process analysis for internationally traded products would be substantially reduced in the standard EE-MRIO method (taking into account the product detail within the available MRIO datasets, such as GTAP,[6] WIOD,[7] EXIOBASE,[8] EORA[9]). In this article we assess the hybrid MRIO method developed by Ewing et al. (2012) in which the primary biomass products are linked to the consuming sectors. This enables the application of a different sales' structure for each primary product, irrespective of the product groups within the MRIO model. This means that each primary product can be assigned to the using sectors and countries based on its specific data irrespective of the monetary flows within the MRIO dataset. The environmental extension therefore represents the intermediate consumption of primary products distinguished by region of origin. Eq. (10) for the footprint calculation has to be extended to cover the direct footprint of the primary products $y_{Np}$ (expressed in physical units) included in the final demand vector $y_N$ and the matrix $P_P$ is replaced by matrix $P_C$, which contains primary products assigned to the first consuming sectors worldwide:

$$EF_N = CP_C(I - A)^{-1}y_N + Cy_{Np}. \quad (12)$$

The matrices C, I, A and $y_N$ have the same meaning as for the standard MRIO method. Within the hybrid calculation setup for EF it is possible to distinguish international trade of the primary products at the same level of detail as for the GFN's process analysis, since the number of elements of the environmental extension matrix is in general unlimited. Furthermore, matrix C has the same role and shape as in the standard MRIO method and it can be based on Eq. (2) since the origin of each primary product is known and therefore no simplification is needed. In order to show the difference introduced by the simplified Eq. (6), both Eqs. (2) and (6) are implemented and applied in the hybrid MRIO approach.

In the current version of our hybrid EE-MRIO model, primary crops, forestry and fish products are incorporated into the EE-MRIO model as described above to account for cropland, forest land and fishing grounds EF. Data on international trade and specific use by some economic sectors are used for crops, data on international trade is used for forestry products and no additional data is used for fish products (due to data availability), which means that this approach is equivalent to the standard EE-MRIO approach for fish products, as only the MRIO sales' structures are applied.

Grazing land, built-up land and carbon uptake land EF are treated in different ways. Requirements on domestic grazing land are allocated directly to producing, i.e. livestock sectors according to their total monetary output, since no additional data was available for the disaggregation. Built-up land is allocated to domestic sectors based on more detailed classification provided by the Corine land cover dataset (Bossard et al., 2000), other datasets as stated in the report (Weinzettel et al., 2011) and using total sector output for more detailed disaggregation. Carbon dioxide emissions are allocated to the emitting sectors as it is done in the national carbon footprint calculations and other environmentally extended input–output analyses focused on emissions. For additional information on hybrid EE-MRIO method and data, please see Weinzettel et al. (2011).

For more detail on the comparison methodology for hybrid EE-MRIO model see the Supporting Information (text part).

### 2.4. Summary of the three approaches

Summary of the three approaches as investigated in this paper is provided in Table 1.

## 3. Data

The general data source for national EF calculation is the statistical database of the Food and Agriculture Organization of the United Nations (FAOSTAT), which includes production and international trade of agricultural products. The data on international trade of crops includes two datasets, one on imports (country by country) and one on exports (country by country). However, these two datasets are not compatible for several reasons documented by FAOSTAT. Furthermore, these datasets are not compatible with total exports and total imports provided by FAOSTAT and utilized in the current version of GFN's National Footprint Accounts. There are several options how to deal with this inconsistent data, however, we opted to remove some obvious errors, including cases where the reported exports were larger than the

[6] www.gtap.agecon.purdue.edu.
[7] www.wiod.org.
[8] www.exiobase.eu.
[9] www.worldmrio.com.

domestic production plus imports, and where total trade reported was exactly ten times larger or smaller than the sum of the detailed trade. After this initial adjustment, we applied a method used by Weinzettel et al. (2012) on the electricity trade within Europe in order to remove re-exports. The constraints for this treatment were the domestic production and an estimate of the domestic consumption (domestic consumption = domestic production + imports − exports). The source and destination country for international trade is derived as a result of this method. A similar method was applied by Kastner et al. (2011) on agricultural products.

This procedure results in some differences between the GFN's process analysis and hybrid MRIO method. GFN calculates the EF of imports and exports of a country based on total imports and total exports reported by FAOSTAT, while MRIO model uses this data together with data on detailed international trade. The system could have been designed to keep both total imports and total exports of each country equal to values applied by GFN. However, it could be desirable at least to limit the total exports to total domestic supply plus total import, a condition often violated within the underlying data. While constructing the hybrid MRIO model we decided to work with a balanced system, in which world total imports match world total exports, i.e. all exports end in some consuming country and vice versa, which explains the differences between the two systems.

A multiregional input–output table was constructed from the GTAP 7 (Narayanan and Walmsley, 2008) database based on the procedure suggested by Peters et al. (2011a). The data on carbon dioxide emissions is available in the underlying GTAP database and it was adjusted to match the CDIAC dataset (http://cdiac.ornl.gov/).

For more details on data and its treatment see Weinzettel et al. (2011).

## 4. Results[10]

### 4.1. National Ecological Footprints: Production and Consumption Perspective

National ecological footprints allocate the appropriation of bio-productive land from the whole production chain to the country of final consumption. They are based on direct demand on domestic bio-productive land expressed in global hectares. This measure should be equal in all three methods. However, there are some minor differences due to underlying data. Therefore, we first show the comparison of national total direct demand on domestic bio-productive land expressed in global hectares, the unit of ecological footprint, in Fig. 1. We refer to this as the “production perspective”.

The production perspective is nearly identical for the two MRIO models, while it differs for the GFN's calculation method mainly for the carbon uptake component of EF. This is only due to a difference in the raw input data used to calculate the carbon uptake EF: while GFN extracts carbon emission data from the International Energy Agency (IEA), the UN-Comtrade database, and CDIAC, both MRIO models are calibrated to match the CDIAC dataset.

In Fig. 2 we compare national EF (consumption perspective) obtained by the three methods. The differences are larger, in a range of tens percent. While the footprint of the US seems to be underestimated by the process analysis, this method overestimates the footprint of China. The overall results for Brazil are very close, but there are differences for individual land types. The differences in the consumption perspective are affected by the differences in the underlying data shown in Fig. 1 and by net footprint of the traded products, which means that the errors in imports and exports, respectively, can in some cases cancel each other. Therefore, in the next section we focus on a detailed analysis of the footprint of imported and exported products for individual land types.

### 4.2. Cropland EF of Imports and Exports

Since the production perspective should give equal results, the differences among the three models in national footprints should result from international trade only. The results for cropland EF of internationally traded products are displayed in Table 2 and visualized in Figs. 3–6. Table 3 summarizes the definitions of the different product classes (primary, secondary, etc.). (See Table 1.)

We refer to upstream production processes (e.g. electricity generation) as processes which are needed for the production. We refer to indirect land use as land use in the upstream processes in the production chain, such as land use to grow biomass used for electricity generation used for baking bread.

The international trade of primary biomass products should be equal for the process analysis and the hybrid MRIO method. The difference between standard and hybrid MRIO methods for ecological footprint of internationally traded primary crops shows the aggregation error or the error introduced by different prices for domestically consumed and internationally traded primary crops or the poor quality of the underlying data of the standard MRIO method and therefore also the improvement of the standard MRIO method by the hybridization. There are some differences between the process analysis and the hybrid MRIO method due to a simplification by GFN regarding the calculation of the footprint of traded commodities, as GFN applies world average yields and no yield factors, while the MRIO method applies country specific yields and yield factors. Therefore, we also show the results calculated with the hybrid MRIO model using world average yields and no yield factors (MRIO hybrid Yavg in Figs. 3 and 4). However, the results of the hybrid MRIO model also differ from the process analysis due to underlying data inconsistencies and assumptions used while constructing the hybrid EE-MRIO model.

The results show that for some countries, such as the US, Japan, Canada, and the Russian Federation the hybrid method improves substantially the treatment of international trade compared to the standard MRIO method. For example, the hybrid MRIO method reports 127 million gha for EF of exported primary crop products of USA, matching quite well will 117 million gha reported by the process analysis, while the standard MRIO method reports 162 million gha. The differences between the hybrid MRIO and the process analysis are influenced by two factors: (1) re-exports are excluded from the hybrid MRIO method, but not from the process analysis; (2) we adjusted the underlying data for the hybrid MRIO method as documented in the data section. It is not possible to judge which data is “more correct”.

The overestimation of cropland EF related to international trade of primary crop products calculated by the standard MRIO method for the Russian Federation and Nigeria most probably stems from underlying data regarding satisfaction of domestic needs by domestic and imported products and an overestimation of the international trade. More of the domestically produced products are exported and more primary crop products are imported instead. Such flaws can potentially introduce an extensive error to the footprint calculation. The same may be true for the cropland EF of derived products, as shown in Figs. 5 and 6.

International trade of secondary and tertiary products is presented in Figs. 5 and 6 together with the footprints not included by the GFN's process analysis at all (upstream footprints of primary products, denoted as PP upstream, secondary and tertiary products, denoted as SP upstream, and footprint of other products — not considered by GFN's process analysis due to data availability and denoted as OP). See Table 3 for an overview of these terms.

[10] The complete set of results is provided in the Supporting information. Here we present only selected results in order to highlight the differences between individual methods. Furthermore, the Supporting information includes underlying data for all the graphs presented in the main document in a tabular form.

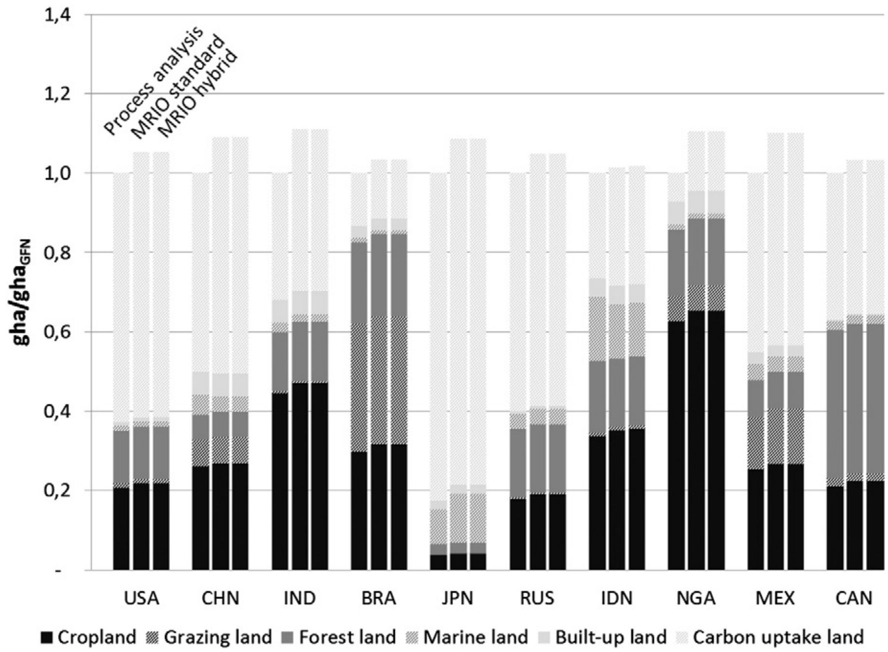


**Fig. 1.** Production perspective — national direct requirements on domestic bio-productive land (the columns are scaled relative to process analysis, which is set to 1). The country codes are: USA — United Sates of America, CHN — China, IND — India, BRA — Brazil, JPN — Japan, RUS — Russia, IDN — Indonesia, NGA — Nigeria, MEX — Mexico, CAN — Canada. These codes are used identically in all the following graphs.

The footprint of secondary products differs substantially for the process analysis and the hybrid MRIO method (note that we exclude the standard MRIO model from this comparison as it provides misleading results for primary crops). It is very difficult to judge which method provides more accurate results for secondary products. For example, the EF of one ton of bread is calculated using world average bread production and physical units under the process analysis, while it is calculated using country specific, but sector average technology, where many different products are aggregated, and using monetary units within the hybrid MRIO method. However, it can be seen that ignoring the footprint of other products and the upstream footprints of the products considered by GFN is a substantial drawback of the process analysis.

In order to partially respond to Kastner et al. (2014) we focus on Chinese exports, which are considerably higher under the hybrid MRIO approach in comparison to the process analysis due to an inclusion of more processed products. The most important exported products are textiles and food products (secondary product according to our classification), which account for about 21% and 14% respectively of total exported cropland (the percentages in this paragraph refer to results of the hybrid MRIO), and leather products and wearing apparel (other

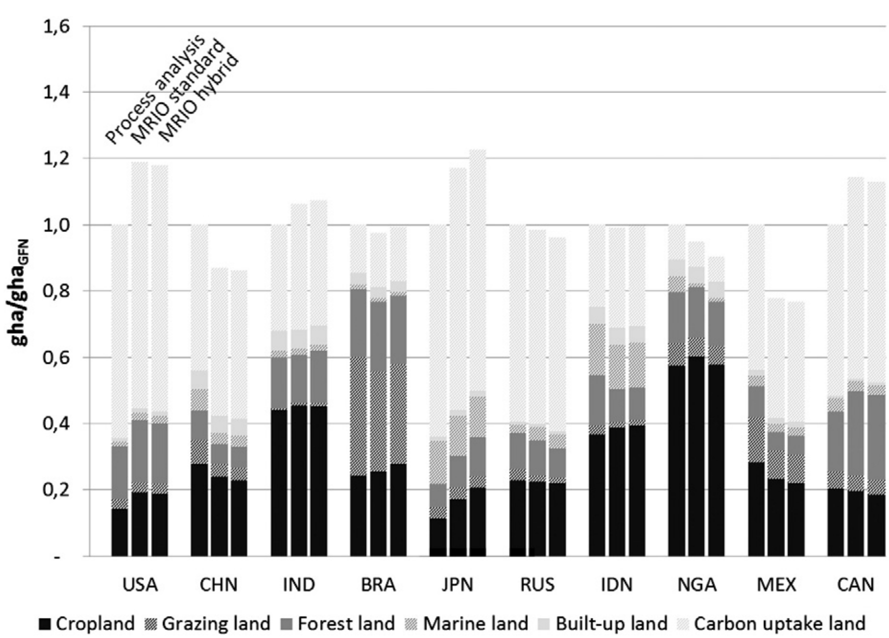


**Fig. 2.** National EF: National requirements on bio-productive land from the consumption perspective (the columns are scaled relative to the process analysis, which is set to 1).

**Table 2**
Comparison of cropland EF of internationally traded products (million gha, year 2004).

| | USA | CHN | IND | BRA | JPN | RUS | IDN | NGA | MEX | CAN |
|---|---|---|---|---|---|---|---|---|---|---|
| *Cropland EF of imported products (total)* | | | | | | | | | | |
| Process analysis | 57 | 98 | 18 | 12 | 60 | 24 | 18 | 6 | 43 | 16 |
| MRIO hybrid | 108 | 79 | 11 | 12 | 89 | 197 | 15 | 36 | 31 | 17 |
| *Cropland EF of imported primary crop products* | | | | | | | | | | |
| Process analysis | 21 | 50 | 7 | 7 | 37 | 5 | 8 | 3 | 23 | 5 |
| MRIO hybrid, world average yields | 18 | 48 | 6 | 7 | 37 | 5 | 8 | 3 | 23 | 4 |
| MRIO hybrid | 15 | 53 | 6 | 7 | 36 | 5 | 9 | 4 | 22 | 4 |
| MRIO standard | 35 | 29 | 7 | 12 | 58 | 119 | 11 | 113 | 21 | 14 |
| *Cropland EF of imported secondary and other products* | | | | | | | | | | |
| secondary products, process analysis | 37 | 47 | 10 | 4 | 23 | 19 | 10 | 3 | 20 | 11 |
| secondary products, MRIO hybrid | 36 | 9 | 2 | 2 | 27 | 109 | 3 | 13 | 4 | 6 |
| primary products upstream, MRIO hybrid | 3 | 2 | 1 | 0 | 2 | 19 | 1 | 6 | 1 | 1 |
| secondary products upstream, MRIO hybrid | 16 | 3 | 1 | 0 | 8 | 36 | 1 | 1 | 2 | 2 |
| other products, MRIO hybrid | 38 | 12 | 2 | 2 | 15 | 27 | 2 | 13 | 3 | 5 |
| *Cropland EF of exported products (total)* | | | | | | | | | | |
| Process analysis | 208 | 24 | 22 | 75 | 2 | 10 | 31 | 3 | 5 | 54 |
| MRIO hybrid | 162 | 123 | 27 | 73 | 5 | 192 | 18 | 33 | 11 | 56 |
| *Cropland EF of exported primary crop products* | | | | | | | | | | |
| Process analysis | 117 | 11 | 8 | 39 | 0 | 7 | 5 | 2 | 3 | 38 |
| MRIO hybrid, world average yields | 119 | 10 | 8 | 41 | 0 | 7 | 5 | 0 | 2 | 35 |
| MRIO hybrid | 127 | 10 | 9 | 40 | 0 | 7 | 5 | 0 | 2 | 37 |
| MRIO standard | 162 | 21 | 11 | 32 | 0 | 119 | 6 | 115 | 6 | 55 |
| *Cropland EF of exported secondary and other products* | | | | | | | | | | |
| secondary products, process analysis | 92 | 12 | 14 | 36 | 1 | 3 | 26 | 1 | 2 | 16 |
| secondary products, MRIO hybrid | 16 | 40 | 8 | 15 | 0 | 105 | 3 | 12 | 3 | 10 |
| primary products upstream, MRIO hybrid | 4 | 3 | 1 | 3 | 0 | 20 | 0 | 6 | 1 | 3 |
| secondary products upstream, MRIO hybrid | 4 | 27 | 2 | 7 | 1 | 34 | 2 | 1 | 2 | 3 |
| other products, MRIO hybrid | 10 | 44 | 6 | 8 | 4 | 27 | 7 | 14 | 4 | 4 |
| *Net trade primary products (import − export)* | | | | | | | | | | |
| Primary products, process analysis | −96 | 39 | 0 | −32 | 37 | −2 | 3 | 1 | 20 | −33 |
| Primary products, MRIO hybrid, Yavg | −102 | 37 | −2 | −34 | 37 | −2 | 3 | 3 | 21 | −31 |
| Primary products, MRIO hybrid | −112 | 43 | −3 | −33 | 36 | −2 | 3 | 4 | 19 | −33 |
| Primary products, MRIO standard | −127 | 8 | −4 | −20 | 58 | 0 | 5 | −2 | 15 | −40 |
| *Net trade total (import − export)* | | | | | | | | | | |
| Total, process analysis | −151 | 74 | −4 | −63 | 58 | 14 | −13 | 3 | 38 | −38 |
| Total, MRIO hybrid | −54 | −45 | −15 | −61 | 83 | 5 | −3 | 4 | 19 | −39 |

products according to our classification) which account for 12% and 11% respectively. If we look into primary crops responsible for the footprint of textiles, 26% is seed cotton, followed by maize (14%) and sugar cane (13%). Part of this might be an artifact of the underlying data behind the GTAP database, but it should be noted that the process analysis includes only raw textiles and fibers with the highest footprint of cotton waste which accounts for 94% of the total footprint of textiles within the GFN's accounts. Seed cotton used in the production of exported

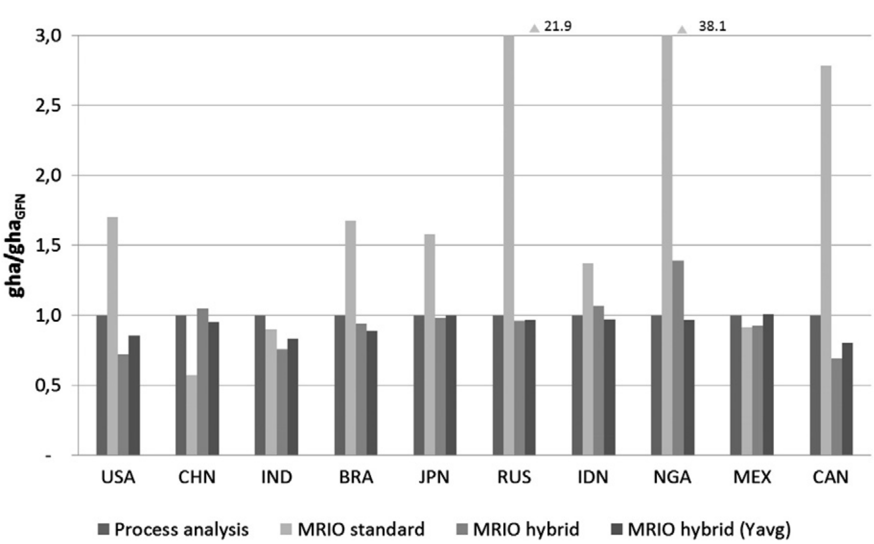


**Fig. 3.** Cropland EF of imported primary crop products (the columns are scaled relative to the process analysis, which is set to 1). Yavg denotes EF calculated with world average yields.

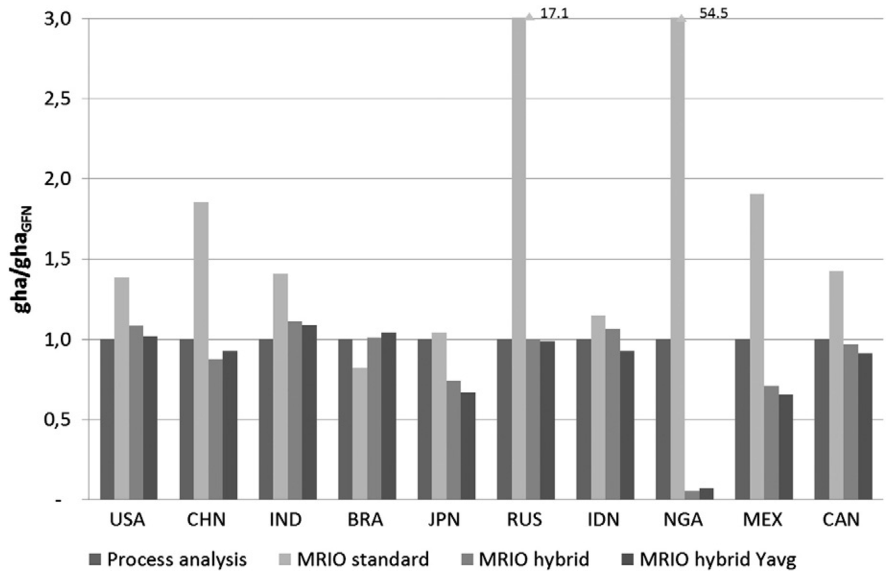


**Fig. 4.** Cropland EF of exported primary crop products (the columns are scaled relative to the process analysis, which is set to 1).

textiles is responsible for about 5.4 million global hectares according to the hybrid MRIO method, while it is responsible for only about 1.6 million global hectares according to the process analysis. Therefore, it seems that the process analysis might be missing an important part of footprint related to textiles. A direct response to Kastner cannot be made at this point, since imports have to be taken into account as well and we are not able to explain why the MRIO results are lower in some cases; it might well be due to insufficient representation of secondary

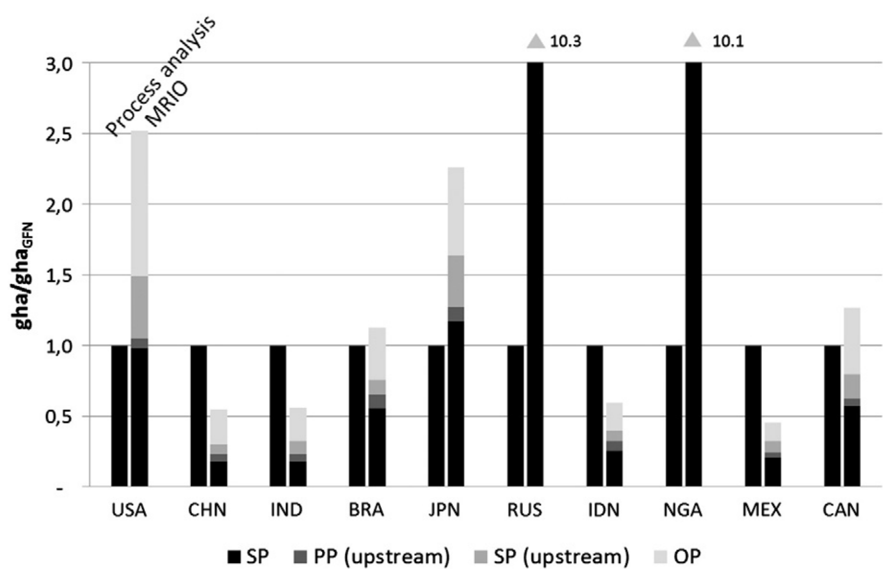


**Fig. 5.** Cropland EF of imported secondary and other products calculated by the process analysis and the hybrid MRIO method (the columns are scaled relative to the process analysis, which is set to 1). SP denotes secondary products, PP (upstream) denotes upstream footprint of primary products, SP (upstream) denotes upstream footprint of secondary products and OP denotes products which are not included in the GFN's process analysis at all.

**Table 3**
Definition of product classes used in the comparison. The calculation procedures to identify the footprints are included in the supporting information.

| Name | Abbreviation | Explanation | Example |
|---|---|---|---|
| Primary product | PP | Product derived directly from nature | Wheat (extracted and directly traded without transformation) |
| Secondary product | SP | Non-primary product included in process analysis | Bread (processed grains) |
| Other product | OP | Product not included in process analysis | Shoes[a], car[a], services |
| Primary product upstream | PPup | Upstream production chain of the primary product | Seeds for primary products |
| Secondary products upstream | SPup | Upstream production chain of the secondary products | Biomass used to generate electricity used in the production of the secondary product |

[a] Included for carbon uptake land only.

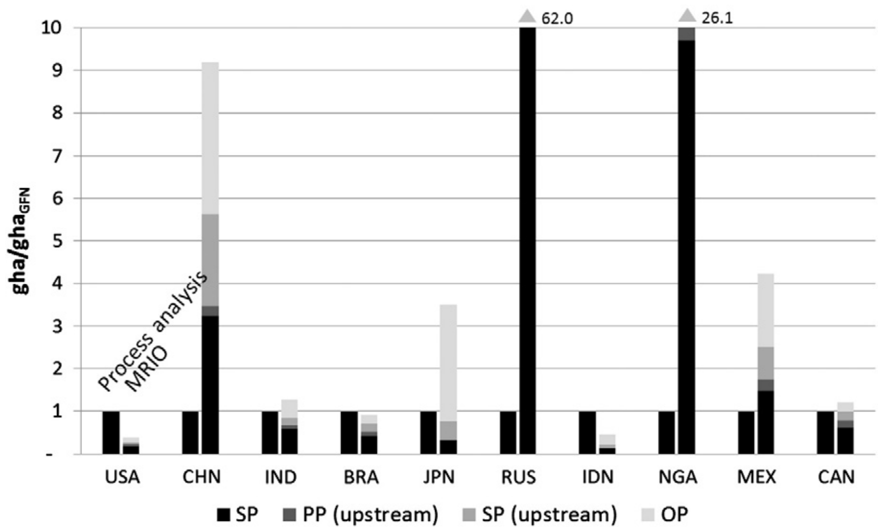


**Fig. 6.** Cropland EF of exported secondary and other products calculated by the process analysis and the hybrid MRIO method (the columns are scaled relative to the process analysis, which is set to 1). SP denotes secondary products, PP (upstream) denotes upstream footprint of primary products, SP (upstream) denotes upstream footprint of secondary products and OP denotes products which are not included in the GFN's process analysis at all.

products within the hybrid MRIO approach or due to different treatment of waste cotton and other products of low economic value but assumed to have high footprint when allocation on the mass basis is applied. But we can directly reply that the process analysis (as applied by GFN but also in general, as these types of analysis are based on the same dataset provided by FAOSTAT) underestimates processed products, such as leather and wearing apparel, since those are currently missing in its trade analysis. Since China imports rather raw materials and exports processed materials and products, the two methods therefore provide counterintuitive results which are implied mainly by insufficient representation of processed products by the process analysis. Note, that if only the trade in primary products is considered, both MRIO approaches show China as a net importer in accordance to process analysis. This was already shown by Peters et al. (2012), who refers to process analysis as apparent consumption due to its omission of the more processed traded products.

The comparison of standard and hybrid MRIO method for primary crops also explains the differences between results for Chinese trade provided by Weinzettel et al. (2013) and Yu et al. (2013) in Kastner et al. (2014) in addition to the different year of analysis, as Weinzettel et al. analyze land use displacement in 2004, while Yu et al. in 2007.

### *4.3. Carbon Uptake Land EF of International Trade*

Carbon uptake land EF is the $CO_2$ footprint multiplied by a constant. GFN's accounts for international trade of physical commodities which are multiplied by an energy multiplier (common for all countries) in order to convert the commodity into energy requirements for its production. The energy is subsequently multiplied by a $CO_2$ multiplier, which is country specific for exports and world average for imports. GFN's application of the process analysis therefore ignores regional differences in the production technology and the trade in services. The aim of the footprint indicators is to assign environmental impacts to the driving processes. Even though services are considered as immaterial products, their footprint should be accounted for, since consumers are considered the driving force not because they consume a physical product, but because there is a monetary flow from the consumer to the producer, which represents the motivation for the producer. Therefore, the logic of these indicators requires accounting for services as well. The graphs in Figs. 7 and 8 show the carbon uptake land EF of imported and exported products, respectively, with the distinction of the MRIO results according to whether the products are included (MRIO A) in the process analysis or not (MRIO B).

It is not possible to decide which method provides more accurate results. MRIO method is preferred in the scientific literature focused on consumption based accounts of $CO_2$ emissions (Davis and Caldeira, 2010; Hertwich and Peters, 2009; Peters et al., 2011b). It applies country specific production technology and considers nearly complete supply chains, while the process analysis partly assumes world average technology and ignores the footprint of services. For some countries (such as USA and Japan) omitting the trade in services might introduce a considerable error.

## 5. Discussion and Conclusion

Environmental footprints[11] of nations are used to show the differences between individual countries regarding the global environmental burdens they impose, considering not only their domestic territory, but assigning environmental burdens to final consumers of products and services from the full supply chains. Building on the methodology introduced by Wackernagel et al. (2002), the Global Footprint Network released the first set of National Footprint Accounts of EF in 2003 using the process-based method referred to in this article as the process analysis.

The environmentally extended MRIO method has become accepted as the standard method for carbon footprint estimation and more recently it has also been used for EF and land footprint accounting. The comparison between process-based and multi-regional input–output methods performed in this article shows that both approaches have their advantages and disadvantages. Here we compared the specific GFN's application of the process analysis with two alternative MRIO methods based on GTAP 7 database.

The standard MRIO method with low product disaggregation, which allocates environmental pressure to the producing sectors, provides implausible results for the EF of primary crop products traded internationally for some countries. This drawback is resolved

[11] Environmental footprint is a general term which refers to a broader concept of all footprints related to environmental issues. Ecological footprint is one particular environmental footprint, or a group of footprints.

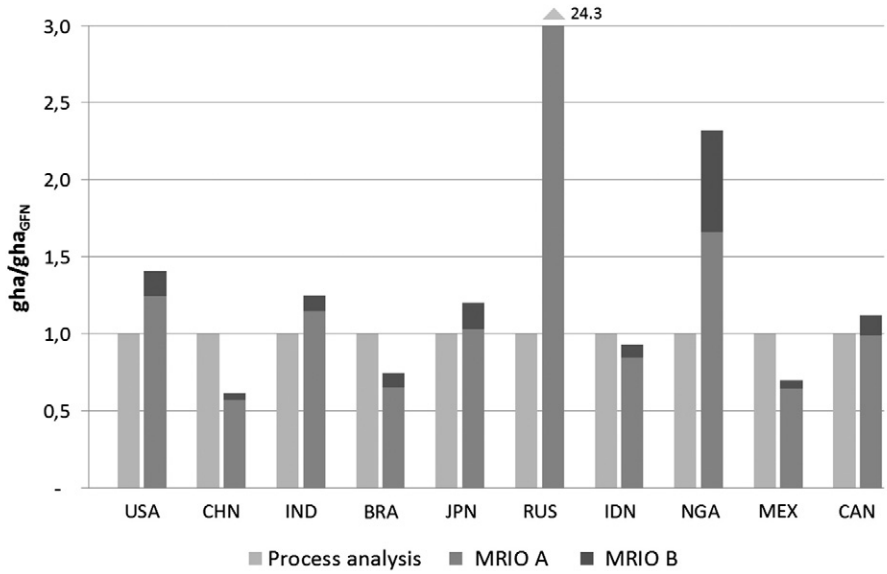


**Fig. 7.** Carbon uptake land EF of imported products (the columns are scaled relative to the process analysis, which is set to 1), MRIO A denotes products covered by the process analysis, while MRIO B denotes products not covered by the process analysis. Both MRIO models are equivalent (there is no hybrid MRIO for this footprint).

by the hybrid MRIO method, which allocates the primary biomass products to their first users using additional information on international trade of individual primary products. This task is more time consuming and requires (but also enables) arbitrary judgments regarding the data quality on international trade due to inconsistencies of the available data. The advantage of this method is the possibility to choose how to resolve these inconsistencies. According to our results, international trade of primary crop products is responsible for a substantial part (about 20%) of total cropland displacement, which highlights the importance of accurate accounting of international trade of primary products and therefore the need for hybridization.

The large differences between standard and hybrid MRIO models for the EF of primary crop products can result from aggregation error; from price variations for domestically used and internationally traded products (problems widely discussed by Schoer et al. (2013)); or from poor quality of data within the underlying GTAP 7 database for the respective sectors. In any case, it is worth to invest effort into exploring additional data on international trade of those products.

The limited number of products tracked by the GFN's process analysis and their limited supply chain considered for footprint calculation result in omitting an important part of the footprint of international trade. This could be improved by including more products into the calculation system of national accounts.

It is difficult to judge the accuracy of the GFN's process analysis compared to the hybrid MRIO method. The process analysis utilizes higher level of detail for the calculation of secondary and tertiary products, while applying mostly world average yields and production technology, while the hybrid MRIO method applies country specific yields and technology, but on a less detail level, assuming sector average technologies. Taking into account that the aggregation error for the hybrid MRIO method for secondary products can be of a similar order of magnitude as the aggregation error of the standard MRIO method for primary

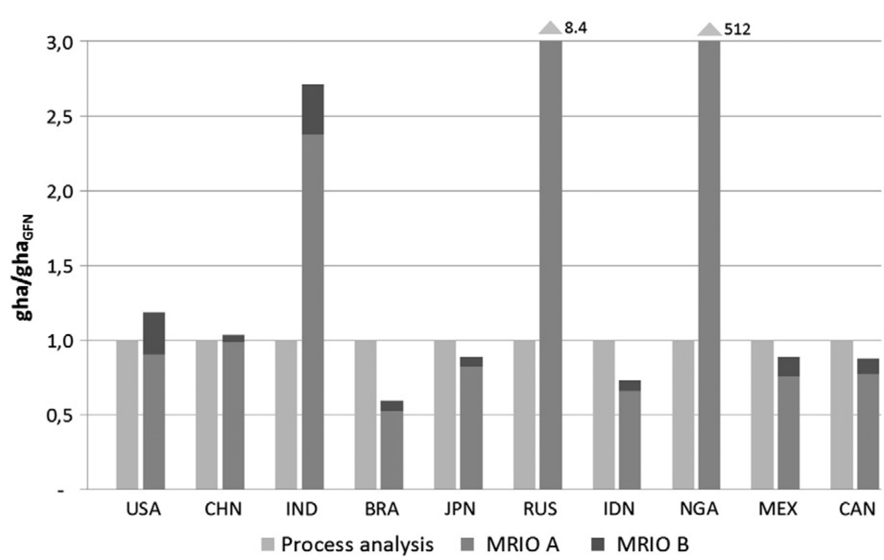


**Fig. 8.** Carbon uptake land EF of exported products calculated by the process analysis and MRIO method (the columns are scaled relative to the process analysis, which is set to 1), MRIO A denotes products covered by the process analysis, while MRIO B denotes products not covered by the process analysis. Both MRIO models are equivalent (there is no hybrid MRIO for this footprint).

crop products, the hybrid MRIO method should be further improved in order to get a higher level of detail for secondary products. While a full disaggregation of the MRIO table should be preferred from the methodological point of view, a direction towards more hybridized approach (not applied in this comparison) is suggested by Ewing et al. (2012). This is an important step, since MRIO method is currently preferred in the scientific literature on national environmental footprints. Further development of more disaggregated MRIO datasets and models can be expected in the future.

The MRIO method (both the standard and hybrid version) provides many options for further analysis of the results, such as structural path analysis, contribution analysis, or structural path decomposition analysis. It also provides an option to link a consuming region with a producing region, an option currently missing in GFN's application of the process analysis, which only looks at imports from the world and exports to the world for each considered nation (this drawback can be partially avoided by using bilateral trade data in the process analysis as well). Furthermore, while the process analysis only works with total imported and exported footprint, the MRIO method also provides results in the form of imported footprint for domestic final demand and exported footprint from the domestic territory (both excluding imported footprint used for production of exported products), which is currently not possible for the process analysis, as it is currently not possible to distinguish which imports are used for production of exports using the process analysis.

Although this has not been considered in the comparison performed in this article, availability of data on a yearly basis can play an important role in the selection of indicators and methods of their calculation. Until recently, MRIO models (e.g., GTAP 7 and GTAP 8) were only available for a very limited number of years (one, two or three), usually with a time lag of at least three years, while the trade data which the process analysis relies on for the calculation of footprint embedded in trade are available on a yearly basis (from 1961 up to 2008). Being able to track trends in the human demand for the Earth's regenerative capacity is currently among the main advantages of the process analysis. However, new MRIO datasets, such as Eora, are becoming available on a yearly basis as well (Lenzen et al., 2013), and others can be expected to follow.

The two key issues favoring the process analysis in the past – product detail and data availability on a yearly basis – can potentially be addressed by the implementation of a hybrid EE-MRIO model based on the MRIO dataset available in a time series. As such, a more prominent use and dissemination of MRIO-based National Footprint Accounts can be envisioned in the near future, at least for a calibration of the process analysis.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2014.02.020.

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