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Analysis

# Environmental Footprints of Agriculture Embodied in International Trade: Sensitivity of Harvested Area Footprint of Chinese Exports

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A R T I C L E I N F O

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A B S T R A C T

Consumption-based accounting seeks to link a population's lifestyles to their environmental impact. Input-output analysis (IOA) serves well in this approach as it covers all traded products, their full supply chains and explicitly delineates final consumption. However, using IOA comes at the expense of precision due to aggregation error. There has been a recent discussion on the plausibility of IOA results of agricultural pressures. We look at the harvested area footprint of Chinese exports, open the black box of the results of IOA and provide a detailed composition of the footprint. This helps to understand whether its size is a result of the poor precision of IOA methods, or whether it is based on plausible production patterns of the exported products.

We hybridize the EXIOBASE database, identify the most important exported products, apply structural path analysis in order to identify the most important production nodes in their production paths and apply a sensitivity analysis over the model.

We show that the results of the hybrid MRIO method are generally robust to assumptions. Our results indicate that while the uncertainty of the sign of net trade footprint can be high, the uncertainty of national environmental footprint accounts is low.

## 1. Introduction

Environmentally-extended multi-regional input-output (EE-MRIO) analysis offers a means to understand the broad system of socio-economic metabolism. It can be used to trace the drivers for environmental pressure through the global economy and to allocate environmental pressures to final consumers, covering the complex supply chains of international trade. It has been applied in many environmental applications, such as emissions of greenhouse gases (Peters et al., 2011), land use (Weinzettel et al., 2013), water use (Steen-Olsen et al., 2012), biodiversity loss (Lenzen et al., 2012), etc. However, EE-MRIO is not a panacea, as there are many assumptions, uncertainties and limitations included in its use (Miller and Blair, 2009). Furthermore, it is a top-down approach that while covering the whole economy, necessarily aggregates similar products into product groups that may introduce *aggregation error* when products differ in certain properties. The application of EE-MRIO to specific sectorial or trade related questions further accentuates aggregation errors.

There has been a recent discussion on the precision and accuracy of MRIO based results for national footprints with environmental pressures primarily in the agricultural sector (e.g. land, water, biodiversity footprints). Kastner et al. (2014) criticise MRIO models as presenting counter-intuitive results in comparison to physical trade studies. In their example, physical trade matrices generally show China to be a net importer of “embodied” cropland, whereas MRIO results generally show China to be a net exporter. This was also visible in earlier work by Peters et al. (2012), Fig. 12. Weinzettel et al. (2014) focus on an analysis of the quantitative differences between input-output and physical trade methods, Schaffartzik et al. (2015) focus on the discussion of conceptual differences. While Schaffartzik et al. argue that “*these two types of approaches may produce diametrically opposed results for the land requirements associated with one country's final demand*” (p. 704), Weinzettel et al. show that this argumentation is true for net trade only, not for the national footprint. Hubacek and Feng (2016) argue that each method is suitable for different purpose, but the discussion is limited to aggregate results and a description of the conceptual differences. Moran et al. (2016) examined the suitability of MRIO for a detailed analysis of embodied biodiversity impacts on a product level and concluded that MRIO is suitable to identify the hotspots for environmental footprints within the socio-economic metabolism, which helps to focus further

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research.

Our current paper advances this discussion on agricultural footprints as we analyze the results from an EE-MRIO approach in the case of harvested area footprint of China. We open the black box of the results of IOA and provide a detailed composition of the footprint. This helps to understand whether its size is a result of the poor precision of IOA methods, or whether it is based on plausible production patterns of the exported products. We (a) look at the current situation of Chinese trade and at the use of agricultural crops in the Chinese economy, (b) provide a sensitivity analysis of the results, and (c) provide a detailed analysis of the footprint of Chinese exports. We focus on Chinese exports as China due to the recent discussion in the literature (Hubacek and Feng, 2016; Kastner et al., 2014) and because China is a large exporter of manufactured products, which generally involve complex production chains in which the errors can propagate and distort the final results. This work is relevant to all environmental footprints originating mainly from agriculture.

## 2. Materials and Methods

### 2.1. Definitions

One key concept that is sometimes misconstrued is the notion of "embodiment". The embodied impact is the impact caused in the supply chain of a product – it is often used for emissions, and includes impacts resulting from the production process of a good or service, e.g. $CO_2$ emitted in electricity generation is said to be "embodied" in the electricity used to power a light. The embodied impact can be calculated at different points along a production chain. Generally, the aim of calculating embodied impacts is to stop burden shifting (Wood and Steen-Olsen, 2013) – hiding environmental impacts up the supply chain. There is a synonymy to functional units in life-cycle assessment – in economy-wide approaches; the functionality is often the livelihood of a population in a certain year (potentially denoted by beyond-GDP indicators such as "happy life years"). An "embodied" approach is central to and synonymous with all "footprint" type analyses. It has a clear difference to material and substance flow type analysis, which look at the material content of an element in a product, such as the aluminium in a car (Nakajima et al., 2011). The concept of embodied impact has found to be useful in conceptualising our indirect reliance on the natural systems that support us – especially as consumers get more disconnected from basic means of production.

However, an "embodied impact" is not a tangible quantity. It implies some sort of allocation to drivers or notion of "responsibility" of a tangible emission or land use to the products or functions that are outputs of the product system. This allocation can be done by different methods (Loiseau et al., 2012; Majeau-Bettez et al., 2014), and based on different characteristics (Ardente and Cellura, 2012; Pelletier et al., 2014; Weinzettel, 2012). This latter point introduces certain problems for different fields – while allocation via physical relationships is often accepted (allocate the impact of the cow to the demand for leather shoes), those via non-physical relationships is less accepted, e.g. the activities of a hired marketing company to promote a car are seldom included in a conventional process life cycle assessment of a car. As a result, researchers have approached the problem by disaggregating product groups to groups with similar characteristics (Wood, 2011), using mixed unit-tables to choose a unit to best represent product characteristics (Weisz and Duchin, 2006), or to create hybrid tables where part of the allocation is done via a physical satellite system, and part is done via the MRIO (Weinzettel et al., 2014). There is no observation of an embodied impact, just various ways to increase precision towards a meaningful capture of burden shifting. In the following, we introduce some of the methodological technicalities of such hybridisation.

### 2.2. Methods - Hybrid MRIO Method

MRIO approaches cover the system boundary of the economy – any valued good and service is included (Weinzettel et al., 2014). As the data requirements of describing industrial production (**S** for environmental or other factor inputs and **L** for inputs of processed goods and services) are substantial, the tractability of data becomes more difficult, and products are always aggregated into broader product groups.

Earlier work of Weinzettel et al. (2014) showed that standard MRIO may not be suitable for accounting of environmental footprints of agriculture due to low product resolution of the existing datasets and that more effort should be directed towards primary crops and their processing, possibly using a hybrid MRIO framework as proposed by Ewing et al. (2012).

For exploring the supply chain impacts of exported goods presented in detail below, Ewing et al. (2012) proposed a hybrid EE-MRIO model in which primary crops are allocated to the economic sector of the MRIO table according to their first use and not production.

The footprint **E** of a final demand **y** is calculated through the following equation:

$$\mathbf{E} = \mathbf{C} * \mathbf{S_p} * \mathbf{L} * \mathbf{y} + \mathbf{C} * \mathbf{y_p} \tag{1}$$

where $\mathbf{S}_\mathrm{p}$ is the physical use matrix of primary crops by economic sectors per unit of sector output (tonnes per euro), **C** is the characterisation matrix to convert the primary crops measure in tonnes into specific footprints – in our case into harvested area, therefore, **C** in our case is the reciprocal of a yield as reported by FAOSTAT (FAO, 2015), $\mathbf{y_p}$ is a vector of primary crops consumed directly by final demand. Of note is that compared to Eqs. (3)–(5), $\mathbf{S}_\mathrm{p}$ contains actual agricultural products, and not the environmental pressure (whether it be land area or mass of harvested products) of the products. $\mathbf{S}_\mathrm{p}$ also only contains primary crops further transformed in the economy, and not processed crops or livestock; $\mathbf{y_p}$ contains the direct consumption of crops. Hence, the hybridisation occurs by splitting $\mathbf{y_p}$ from total crops, and handling them exogenous to the IO model. For a calculation of international trade it is suitable to split the impacts per unit into direct footprint, i.e. the harvested area of primary crops $\boldsymbol{Q}^{dir}$ and indirect impact per unit $\boldsymbol{Q}^{ind}$ of all products (non-primary crops do not have direct footprint):

$$\boldsymbol{Q}^{ind} = \mathbf{C}^* \, \mathbf{S_p}^* \mathbf{L} \tag{2}$$

$$\boldsymbol{Q}^{dir} = \mathbf{C} \tag{3}$$

Then embodied impacts in exports $E_{h,r}{}^{exp}$ and imports $E_{h,s}{}^{imp}$ are calculated as a sum of indirect impacts calculated through the economic processing (subscript $m$) and the direct impacts calculated through the direct physical trade (subscript $p$):

$$E_{h,r}^{exp} = Q_{m,r}^{ind*} \sum_s B_{m,r,s} + Q_{p,r}^{dir*} \sum_s B_{p,r,s} \tag{4}$$

$$E_{h,s}^{imp} = \sum_r Q_{m,r}^{ind*} B_{m,r,s} + \sum_r Q_{p,r}^{dir*} B_{p,r,s} \tag{5}$$

### 2.3. Integrating Commodity Balance for Primary Crops

The hybrid MRIO applied here is based on a product-by-product MRIO table distinguishing 200 products compiled under the industry technology assumption and based on the EXIOBASE (v2.2, year 2007) database (Tukker et al., 2013; Wood et al., 2014; Wood et al., 2015). It treats the international trade based on country-by-country international trade data and the domestic first use of primary crop products, such as wheat, maize, etc. as extensions based on commodity balance sheets of the FAOSTAT database. The primary crop products produced within each country are allocated to their first users globally.

First, the total country consumption of each crop from each country is estimated based on FAOSTAT bilateral trade data and production data. FAOSTAT production data provides the total supply of crops by countries and the trade data is combined to connect producers of primary crops with their users removing re-exports from the bilateral trade flows in a similar way to Weinzettel et al. (2012) and Kastner et al. (2011).

Second, for the allocation of primary crops within the consuming countries we utilize the FAOSTAT commodity balance sheets (**B**). The commodity balance sheets distinguish for each crop reported $p$ five categories $c$ on the different uses (food, feed, processing, other uses and seed). We link those categories $c$ to the MRIO sectors $m$ and within these groups of sectors the primary crops are allocated proportionally to monetary sales structure of the parent product within the MRIO system. E.g. barley intended for feed in Germany according to FAOSTAT commodity balance sheet is allocated to all livestock sectors and distributed across those sectors using monetary sales structure of “Other cereal crops”. This linking can be described mathematically as a three-dimensional concordance matrix $G_{p,c,m}$, where each $\Sigma_c G_{p,c,m}$ sums to 1. The final matrix $\mathbf{F}^b$ (for each crop $p$ allocated to use by each IO sector $m$) is calculated as

$$F^b_{p,m} = \sum_c B_{p,c}{}^* \boldsymbol{G}_{\boldsymbol{p,c,m}} \tag{6}$$

And subsequently in coefficients (where $x_m$ is product output):

$$S^b_{p,m} = \frac{F^b_{p,m}}{x_m} \tag{7}$$

We worked with 186 primary crop products in the same level of detail as available within the most widely used dataset FAOSTAT. As the commodity balance sheets **B** reported by FAOSTAT have lower product resolution than the primary crops, we apply the ratio of the parent product to all primary crops belonging to the same product group.

The calculation of direct and indirect impacts, as well as impacts embodied in trade then proceed as per the hybrid MRIO model presented in Section 2.2, Eq. (6), albeit using $\boldsymbol{S^b}$ for $\mathbf{S_p}$.

### 2.4. Sensitivity Analysis

#### 2.4.1. Reference Model

We take as a reference a hybrid MRIO model set up in a similar way as the model presented earlier by Weinzettel et al. (2014), however, compiled for the year 2007 EXIOBASE 2 dataset. This model is simpler than the model described in Section 2.3, since it does not utilize the data from commodity balance sheets as it only applies data on international trade from the FAOSTAT database. All other allocations are based on the monetary flows of parent MRIO product groups. We call it a reference model as it represents an earlier version of the model (Steen-Olsen et al., 2012; Weinzettel et al., 2013) and provides a basis on the comparison of the newly integrated FAOSTAT commodity balance data.

#### 2.4.2. Food Model

There is one important caveat in linking FAOSTAT style commodity balances to sectors used in national accounts – and that relates to the specification of food consumption, as food is consumed in all economic sectors and therefore it contributes to the footprint of products produced by those sectors. Kastner et al. (2014) argue that there is no agreement whether or not the footprint of food paid for by companies should be accounted as an impact of the company that can then be passed through the supply chain to final goods produced, or whether all food consumed by humans should be considered a final good. An example may be whether a conference lunch is included in the footprint of university research, or whether it is only included in the footprint of the attendees. In physical trade approaches, no food impacts are included in the footprint of produced products, which is not in line with classification of intermediate and final goods as proposed under the System of National Accounts. Regardless, we do a sensitivity analysis for these differing approaches in order to connect physical trade and MRIO results.

In order to estimate the role of food footprint included in the products exported from China, and to provide a good basis for the analysis of the results we create a sensitivity model in which we allocate primary crops consumed as food according to FAOSTAT to households, restaurants and hospitals using the monetary flows of the corresponding product groups. This eliminates the use of all agricultural and food in all manufacturing processes including food processing, and therefore gives a lower bound to the total embodied export of agricultural food. That is, the exported MRIO processed food products carry no footprint of primary crops directly entering those sectors. The remaining footprint of processed MRIO food products is then due to feed used in livestock products embodied in food, seed and other uses of primary products embodied in the exported food products.

#### 2.4.3. Livestock Models – Animal Balances

Because of the importance of the livestock sector in the consumption of primary crops, we further created four sensitivity models by adjusting the sales structure of livestock products within the EXIOBASE database according to FAOSTAT livestock commodity balance sheets converted into monetary units using prices from the FAOSTAT, with two corrections for missing and unrealistic data from Prodcom (Eurostat, 2012). All the adjustments for the Livestock sensitivity models are done for China only due to the data availability reasons, and the results are therefore discussed only with the connection to Chinese exports.

In the first livestock sensitivity model denoted as “Livestock 1” we adjust the sales structures of Chinese livestock products according to FAOSTAT livestock commodity balance sheets distinguished by four EXIOBASE product groups.

In the second livestock sensitivity model denoted as “Livestock 2” we adjust the sales structures of Chinese livestock products according to the sum of all the livestock products available in the FAOSTAT livestock commodity balance sheets. The reason for the aggregation of all FAOSTAT livestock products is the difficulty with precise linking of FAOSTAT product categories to EXIOBASE, which may introduce some errors in the previous sensitivity model.

In the other two sensitivity models we start with “Livestock 2” model consider an uncertainty of the FAOSTAT livestock commodity balance sheets and we decreased (“Livestock 3”) and increase (“Livestock 4”) the “other uses” by 20%, i.e. as the original value in sensitivity model “Livestock 2” is 27% for “other uses”, in “Livestock 3 it is adjusted to 22% and in “Livestock 4” it is adjusted to 32%. The other categories are modified to match 100% in total.

## 3. Results

### 3.1. Agricultural Crops in Chinese Economy

Before looking at the MRIO results for Chinese harvested area footprint, we explore the starting point and look at Chinese commodity balances from FAOSTAT and physical trade across the whole Chinese economy from Comtrade (United Nations Statistics Division, 2012). Here, exports of agricultural products are roughly 30 Mt, imports 70 Mt, exports of food products are 30 Mt and imports are 32 Mt, exports of manufactured goods, 600 Mt, imports 350 Mt. Without looking at the embodied cropland content of manufactured goods and services, the size of the export of food products relative to agricultural exports already implies that significant embodied exports would occur here which would not be necessarily captured by statistics that do not systematically cover processed food products. Trade of textiles and associated products are also an important issue here, and Comtrade data (United Nations Statistics Division, 2012) shows a large export surplus

**Table 1**
Cropland harvested area (million hectares) of the main uses of top 10 most important crops in China (calculated from the FAOSTAT commodity balance sheets after correction for net trade).

| | Food | Processing | Feed | Others | Seed |
|---|---|---|---|---|---|
| Maize | 1.9 | 1.0 | 20.9 | 5.3 | 0.3 |
| Rice, paddy | 24.9 | 0.0 | 2.5 | 0.4 | 1.1 |
| Wheat | 20.3 | 0.0 | 1.6 | 0.6 | 0.9 |
| Soybeans | 1.0 | 6.9 | 0.6 | 0.0 | 0.2 |
| Vegetables, fresh nes | 7.7 | 0.0 | 0.7 | 0.0 | – |
| Seed cotton[a] | – | 1.3 | 0.3 | 4.3 | 0.04 |
| Rapeseed | 0.0 | 5.3 | 0.2 | 0.0 | 0.1 |
| Potatoes | 3.4 | 0.5 | 0.4 | 0.0 | 0.2 |
| Groundnuts, with shell | 1.3 | 2.3 | – | 0.0 | 0.1 |
| Sweet potatoes | 1.8 | – | 1.8 | 0.0 | 0.0 |
| Total | **62.3** | **17.3** | **29** | **10.6** | **2.9** |

[a] Note that in the MRIO model we apply an economic allocation (Pelletier et al., 2014; Weinzettel, 2012) to split the harvested area between cottonseed and cotton lint, i.e. the harvested area of seed cotton is allocated to cotton seed and cotton lint based on the relative value added of the two agricultural processes, which results in allocating about 73% of harvested area to cotton lint and 27% to cottonseed. Waste is allocated proportionally to all listed uses.

over imports (16.6kt export, 3.7kt import).

Looking closer at the source of the agricultural products, Table 1 shows an overview of the most important primary crops and their uses in China according to the commodity balance sheets of FAOSTAT, converted to hectares (see Eq. (3)). It covers about 75% of total Chinese harvested area. Nearly 10% of this area is used in non-food applications, therefore, becoming part of supply chains of non-food products and another 24% is used as feed, therefore ending up in supply chains of food (e.g. milk and meat) and non-food (e.g. leather) products. As China is a large exporting country (up to 50% of domestic production of some product groups is intended for exports in monetary terms), it is not surprising that a substantial part of this footprint ends up in exports.

From these results we can make preliminary conclusion that significant cropland is embodied in further processing and feed. Part of it will be used in food production as well (Kastner et al., 2014), but there is also a significant net export of manufactured goods, including textiles, which would embody some of the aforementioned uses. The commodity balances derived from FAOSTAT are used as a starting point for the MRIO analysis. We now turn to MRIO work to make the link between the two.

### 3.2. Sensitivity Analysis of Hybrid MRIO Results

The general results for footprint of Chinese consumption, imports and exports are presented in Table 2 for all the sensitivity models. It can be seen that the results for Chinese national harvested area footprint are quite robust across all the models, ranging between 163 and 168 million hectares of harvested cropland (range of variation of about 3%). Only the "commodity balance MRIO" model shows China as a net exporter of harvested area. Uncertainty work from MRIO models is scarce, but Lenzen et al. (2010) find stochastic uncertainties in the order 5–10% for greenhouse gas emissions of the UK. If we take a simplistic assumption of 5% relative error for the footprints of imports and exports, this results in an absolute error of the net trade which is larger than the net trade itself. Therefore, we may conclude that the result for the net trade is highly uncertain and any solid conclusion regarding its sign cannot be made. However, as the net trade is small relative to the national footprint, China appears to be quite self-sufficient regarding harvested area.

It can be seen that the different assumptions regarding the treatment of food related crops within the MRIO model have only a marginal impact on the result of national footprint, but it has a substantial impact on the results of international trade, as it changes the footprint of Chinese exports about one quarter. This is caused mainly by two factors: (a) excluding processed food products from the footprint analysis of international trade; (b) excluding food products consumed by factories producing goods not directly linked to food, such as machinery. This impacts in the same way the exports of all countries, resulting in lower imports to China in this model. However, the effect is smaller for imports due to their product structure (mainly raw materials and less manufactured products). The effect of excluding processed food products from the footprint analysis of traded goods would be considered to be strongest, due to the large volumes of export of processed food products (see Section 3.1).

In terms of sensitivity of results to the individual products, we correspondingly see a decrease in impact in all food related im/exports in the food model, and an increase in impact in all non-food related im/exports. Results are generally stable across models – with most products changing in the order of ± 20%. Exceptions include chemicals and to a lesser extent plastics – which is sensitive to the allocation of agricultural items to its supply chain or not; for the food model, these products are allocated a greater share of the supply chain impacts.

### 3.3. Composition of Footprint of Exported Goods

The aim of this section is to further investigate the intricacies of current MRIO through a structural path analysis in order to identify the most important nodes in the specific production chains and a crop composition of the footprint of these nodes. One of the disadvantages of MRIO is that in achieving full economy-wide coverage, precision can be lacking. Generally we find reasonably high stochastic errors at the product group level. Work done for the UK carbon footprint found manageable uncertainties at national level, but much higher uncertainties for individual products (Lenzen et al., 2010). When focussing on a particular crop extraction, these uncertainties are also likely to be significant.

In Table 3 we provide the results of structural path analysis (Peters and Hertwich, 2006) for the top 3 exported products (extended in the Supporting Information to top 10 products) with the highest harvested area footprint using the food sensitivity model in order to eliminate the footprint of food consumed within the production chains as discussed in Section 2.4.2. Furthermore, for the purpose of structural path analysis we set all diagonal elements of the MRIO table to zero, which has no influence on the overall results of the footprints, but it suppresses the internal loops of all sectors within the results of the structural path analysis, e.g. the process chain "textiles – textiles – textiles" is summed into "textiles" together with all such process chains of any length.

We cover only nodes with contribution over 0.2 million hectares and the top 5 crops. The table starts with the total harvested area footprint of total exports and continues with the most important exported products highlighted in bold. The rows in non-emphasized letters have the following meaning. The first column includes the production path – the last product is the product to which manufacturing the primary crops are allocated. The composition of those crops is reported in the third column. We report the relative contribution of each crop next to its name. The second column shows the relative contribution of the path to the footprint of the exported product. The last column shows the footprint covered by the specific description – i.e. the production path and the presented crops.

The exported product group with the highest harvested area footprint is Textiles, which footprint results mainly from the use of cotton lint directly in textiles manufacturing. The most surprising result is the appearance of "raw milk" in the list, contributing about 15% of the total textile footprint, and similar for wearing apparel. Leather and associated products are co-produced in the animal husbandry industry, such that an allocation must be made from the impacts of cattle farming to the milk, meat and leather produced. If an industry technology assumption (Majeau-Bettez et al., 2016) is used to create a symmetric input-output table we are assuming each industry has its own specific way of production, irrespective of its product mix, see (Eurostat, 2008),

**Table 2**
The harvested area Chinese national footprint and the footprint of Chinese imports and exports calculated by all the sensitivity models of the hybrid model (unit: million hectares of harvested crop area).

| | Commodity balance MRIO | Reference MRIO | Food[b] MRIO | Livestock 1 | Livestock 2 | Livestock 3 | Livestock 4 |
|---|---|---|---|---|---|---|---|
| National footprint China | 163.0 | 167.1 | 167.4 | 167.9 | 166.6 | 167.1 | 166.2 |
| Imports MRIO | 43.4 | 49.3 | 40.2 | 43.4 | 43.4 | 43.4 | 43.4 |
| Exports MRIO | 45.1 | 46.8 | 37.6 | 40.1 | 41.5 | 41.0 | 41.9 |
| Net trade MRIO (surplus, ex - im) | 1.7 | − 2.4 | − 2.7 | − 3.2 | − 1.9 | − 2.3 | − 1.5 |
| Net trade error[c] | 4.4 | 4.8 | 3.9 | 4.2 | 4.2 | 4.2 | 4.3 |
| Production | 164.7 | 164.7 | 164.7 | 164.7 | 164.7 | 164.7 | 164.7 |
| National footprint products | | | | | | | |
| Food products nec | 36.1 | 45.6 | 11.6 | 36.8 | 36.5 | 36.5 | 36.4 |
| Vegetables, fruit, nuts | 30.0 | 32.2 | 36.2 | 30.0 | 30.0 | 30.0 | 30.0 |
| Construction work | 11.2 | 13.2 | 9.4 | 9.8 | 10.4 | 10.3 | 10.5 |
| Hotel and restaurant services | 11.1 | 10.7 | 10.4 | 14.8 | 13.7 | 14.0 | 13.5 |
| Fish products | 10.3 | 6.4 | 7.9 | 10.6 | 10.3 | 10.4 | 10.3 |
| Animal products nec | 3.7 | 1.9 | 2.7 | 1.9 | 2.5 | 2.5 | 2.4 |
| Wearing apparel; furs | 3.6 | 4.2 | 3.0 | 2.9 | 3.0 | 2.9 | 3.0 |
| Health and social work services | 3.5 | 4.4 | 5.4 | 3.7 | 3.7 | 3.7 | 3.7 |
| Processed rice | 3.4 | 2.9 | 0.3 | 3.5 | 3.4 | 3.4 | 3.4 |
| Meat animals nec | 3.4 | 0.9 | 3.0 | 4.0 | 3.6 | 3.7 | 3.5 |
| Exported products | | | | | | | |
| Textiles | 8.4 | 9.9 | 7.5 | 6.8 | 6.9 | 6.7 | 7.0 |
| Meat animals nec | 4.8 | 1.3 | 4.2 | 4.7 | 4.7 | 4.7 | 4.7 |
| Wearing apparel; furs | 3.1 | 3.6 | 2.6 | 2.5 | 2.6 | 2.5 | 2.6 |
| Food products nec | 2.8 | 3.6 | 0.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| Furniture; other manufactured goods n.e.c. | 2.7 | 2.8 | 1.8 | 0.8 | 1.5 | 1.4 | 1.6 |
| Fish products | 1.9 | 1.2 | 1.5 | 2.0 | 1.9 | 1.9 | 1.9 |
| Chemicals nec | 1.7 | 2.1 | 1.6 | 1.7 | 1.7 | 1.7 | 1.7 |
| Office machinery and computers | 1.7 | 2.2 | 1.5 | 1.6 | 1.7 | 1.7 | 1.7 |
| Radio, television and communication equipment and apparatus | 1.5 | 2.0 | 1.3 | 1.5 | 1.6 | 1.5 | 1.6 |
| Hotel and restaurant services | 1.4 | 1.4 | 1.3 | 1.9 | 1.8 | 1.8 | 1.7 |
| Imported products[a] | | | | | | | |
| PP_soybeans | 10.7 | 10.7 | 10.7 | 10.7 | 10.7 | 10.7 | 10.7 |
| Products of vegetable oils and fats | 9.0 | 6.2 | 7.5 | 9.0 | 9.0 | 9.0 | 9.0 |
| Chemicals nec | 3.4 | 7.9 | 3.7 | 3.4 | 3.4 | 3.4 | 3.4 |
| PP_Cotton lint | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| Processed rice | 2.3 | 1.8 | 0.2 | 2.3 | 2.3 | 2.3 | 2.3 |
| Dairy products | 1.5 | 0.4 | 1.4 | 1.5 | 1.5 | 1.5 | 1.5 |
| PP_Oil, palm | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Plastics, basic | 1.1 | 2.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Beverages | 0.8 | 0.7 | 0.4 | 0.8 | 0.8 | 0.8 | 0.8 |
| Hotel and restaurant services | 0.7 | 0.6 | 1.5 | 0.7 | 0.7 | 0.7 | 0.7 |

[a] It must be noted that items tagged PP_ are primary crops, and the results do not include any upstream impacts of primary crops (e.g. from fertiliser etc.). These are still accounted for, but in the corresponding (aggregate) EXIOBASE product (see Eqs. (4) and (5)).

[b] The food model is a lower bound model that largely excludes further processing of raw foodstuffs, and thus all embodied impacts of domestically consumed products, exports and imports can be considered as a lower bound rather than an accurate estimate (see Section 2.4.2).

[c] Net trade error is calculated as a sum of absolute errors of the footprint of imports and exports, assuming their relative error of 5%. Even though we assume lower bound for this relative error, the error of net trade is higher than the net trade itself.

thus mixing production functions of what would be expected for an individual product. Further, when monetary tables are used, allocation is performed via economic values and high value products such as leather obtain a greater share of the responsibility than if a mass based allocation was applied.

## 4. Discussion and Conclusions

### *4.1. Net Trade Focus*

While the results on national footprint are quite robust across the sensitivity analysis, the results for net trade show that even when controlling for first-order supply-chain information in the allocation of agricultural goods to the economy, there are still enough variability in results to change net-trade of embodied environmental impact from positive to negative. This result can be qualified in the expected uncertainty of all these approaches. To try and determine a net-trade signal well within the uncertainty range of the results, we would argue, is ill-advised.

### *4.2. Monetary Versus Physical IO Table*

Monetary input-output method has been criticised for using economic allocation, as opposed to physical allocation in physical input-output models. However, whether physical or monetary units in aggregated systems, such as the input-output analysis better reflect the upstream requirements of the different products aggregated into one group cannot be stated without a deep analysis and the answer will differ from product to product and for different environmental footprints. If a production process of one product uses more bioenergy than another product with the other inputs identical, its price and land footprint will be higher while its mass might be the same. Here we can posit that the most important limitation of the IOA is an aggregation of products and industries into broader groups, which are treated as being homogenous. An additional drawback of this method stems from the compilation of the input-output table, and the more general discussion of "allocation" (Majeau-Bettez et al., 2014). A company producing more useful product outputs is included in one economic sector and additional assumptions are needed to allocate the products the company

**Table 3**
Composition of cropland harvested area footprint of exports, hybrid MRIO, lower estimate (continues in Supporting Information).

| Production node in a specific path (> 2%) | Contribution of this node (hectares, %) | Crop composition of the footprint of this node (the top 5 crops) | Covered by the specific description (hectares) |
|---|---|---|---|
| Total exported footprint | 24,577,961 | Total covered by all listed contributions | 11,840,353 |
| Textiles: exported footprint | 4,400,301 | Covered by listed flows | 3,456,406 |
| Textiles | 51.6% | Cotton lint 93%, Ramie 3%, flax fibre 1.4%, rice 0.6%, rubber natural 0.6% | 2,238,768 |
| Textiles – raw milk | 11.9% | Maize 80%, forage products nec 4.3%, soybeans 2.9%, rice 1.9%, wheat 1.8% | 475,985 |
| Textiles – animal products nec | 6.2% | Maize 46%, wheat 20.6%, forage products nec 9.4%, soybeans 5.9%, rice 5.1% | 237,352 |
| Textiles – animal products nec - cattle | 3.9% | Maize 81.4%, wheat 6.2%, forage products nec 4.3%, millet 1.7%, buckwheat 1.2% | 162,688 |
| Textiles – raw milk – cattle | 3.2% | Maize 81.4%, wheat 6.2%, millet 1.7%, buckwheat 1.2%, forage products nec 4.3% | 133,488 |
| Textiles – pig | 2.8% | Rice 32.3%, forage products nec 30.8%, maize 24.4%, wheat 5.6%, sweet potatoes 1.1% | 116,062 |
| Textiles – chemicals nec – products of vegetable oils and fats | 2.2% | Soybeans 42.7%, rapeseed 29.3%, Groundnuts, with shell 13.4%, cotton seed 6.9%, sunflower seed 2.8% | 92,063 |
| Meat animals nec: exported footprint | 4,046,278 | Covered by listed flows | 3,727,067 |
| Meat animals nec | 93.0% | Maize 86.2%, wheat 4.3%, millet 1.8%, buckwheat 1.3%, 1.1% oats | 3,563,597 |
| Meat animals nec – food products nec | 2.9% | Soybeans 31.1%, rapeseed 21.4%, groundnuts, with shell 9.7%, Maize 8.7%, barley 6.3% | 90,588 |
| Meat animals nec – cattle | 1.9% | Maize 81.4%, wheat 6.2%, millet 1.7%, buckwheat 1.2%, forage products nec 4.3% | 72,882 |
| Wearing apparel; furs: exported footprint | 1,588,086 | covered by listed flows | 863,328 |
| Wearing apparel; furs - textiles | 33.2% | Cotton lint 93%, Ramie 3%, flax fibre 1.4%, rice 0.6%, rubber natural 0.6% | 519,863 |
| Wearing apparel; furs – textiles – raw milk | 7.6% | Maize 80%, forage products nec 4.3%, soybeans 2.9%, rice 1.9%, wheat 1.8% | 109,711 |
| Wearing apparel; furs – raw milk | 5.6% | Maize 80%, forage products nec 4.3%, soybeans 2.9%, rice 1.9%, wheat 1.8% | 80,840 |
| Wearing apparel; furs – textiles – animal products nec | 4.0% | Maize 46%, wheat 20.6%, forage products nec 9.4%, soybeans 5.9%, rice 5.1% | 55,265 |
| Wearing apparel; furs – animal products nec | 2.6% | Maize 46%, wheat 20.6%, forage products nec 9.4%, soybeans 5.9%, rice 5.1% | 35,922 |
| Wearing apparel; furs – textiles – animal products nec – cattle | 2.1% | Maize 81.4%, wheat 6.2%, millet 1.7%, buckwheat 1.2%, forage products nec 4.3% | 31,616 |
| Wearing apparel; furs – textiles – raw milk – cattle | 2.0% | Maize 81.4%, wheat 6.2%, millet 1.7%, buckwheat 1.2%, forage products nec 4.3% | 30,110 |

uses to its outputs. Depending on the assumption applied, this may result in distorting inputs within the production chain of some products (Majeau-Bettez et al., 2016).

While we currently use monetary units to represent flows of products and services, the whole concept can be applied with physical units as well. However, such an application is currently limited by available data.

### 4.3. MRIO Improvement Suggestions

MRIO approaches may always suffer from product aggregation and noise in the production functions used in large scale databases. However, given the current rapid rate of development in MRIO much better datasets might be expected in the near future. To further improve the precision of MRIO results related to agricultural production, we would highlight 3 key areas:

1. Disaggregation of production for domestic markets vs production for foreign markets.
2. Disaggregation of product groups with high embodied impact, and diverging uses (Crops nec, food products nec and chemicals in EXIOBASE are clearly such groups).
3. Treatment of by-products, applying mixed technology assumptions when constructing the input-output tables.

Firstly, increasing detail of product systems investigated helps to separate out noise in the supply chain of products, so that impacts of cotton farming does not end up in meat products. Intertwined with the detail in the product systems is the regional detail, and the difference between production for domestic consumption and exports (Dietzenbacher et al., 2012; OECD, 2016; Su et al., 2013). Increasing regional detail essentially allows for the tracing of production practices of 2 or more different products that would be treated as 1 product at the national level, while often we will have high value products conceptually similar to low value products, but destined for export markets. Of most importance in addressing product system detail is to include detail where both conditions hold: a) upstream impacts diverge between products and b) consumption of products differ within a product group (e.g. household consumption, further processing, export). A third factor that would greatly improve MRIO models for agricultural based issues would be increased knowledge of subsistence farming, and the separation of products to consumers directly.

### 4.4. Input-Output Analysis or Process Analysis?

Input-output analysis is not the only method to estimate the upstream flows and footprints of products, international trade and consumption. Process analysis, also sometimes denoted as a physical trade approach, accounts for upstream flows tracking the production chain process by process upstream from the derived products. It was suggested that the input-output approach yields counterintuitive results by Kastner et al. (2014), as the authors were not able to explain the high differences between physical trade approaches and MRIO approaches for cropland embodied in Chinese exports. They say that they "*make the case for a re-evaluation for the application of this method to account for embodied land and associated environmental impacts*".

The hybrid MRIO method takes the available FAOSTAT data on international trade as a starting point and allocates the usage of the land use according to the monetary flows within the whole economy (Ewing et al., 2012), so that part ends up in domestic final consumption and part in exports. It benefits from the complete coverage of processes within an economy, while the process analysis and physical trade approaches, may benefit from the levels of detail and precision that MRIO derived results will likely never match. As such, they are particularly useful for analysing impacts of specific products. However, MRIO results show that the secondary stages of production do embody large cropland requirements and that analysing direct and first order impacts is not enough (Hubacek and Feng, 2016; Peters et al., 2012; Weinzettel et al., 2014).

Both methods employ and rely on the available data from statistical offices. Perhaps, the input-output data is more complex and therefore more errors can be expected, but in general, errors occur in all datasets and reconciling the FAOSTAT trade statistics is one of the major steps in establishing the hybrid MRIO model. The need for a consistent data in MRIO analysis can be seen as a benefit, as some data errors can be removed during the establishing the hybrid MRIO model. While the results of the MRIO analysis are not perfect (as shown in this article), the method and data are continuously being developed and improvements can be expected (e.g. Wood et al., 2015).

## 5. Conclusions

Our sensitivity analysis shows that the national harvested area footprint of China is quite robust over different assumptions. The treatment of food consumed within production activities influences the footprint of imports and exports, but its effect on the national footprint is modest. Allocating its footprint solely to domestic consumption irrespective of the final destination of the products decreases the footprint of international trade. In contrast to the robustness of the national harvested area footprint for China is the harvested area footprint of the net trade, which has much higher uncertainty. According to our calculations for this particular case the uncertainty is roughly twice as high as the absolute value of the net trade footprint (Table 2).

The deeper analysis of the footprint of Chinese exports shows the types of aggregation errors that occur when investigating single supply chains using input output analysis. In future research we recommend further disaggregation and call for improved treatment of by-products in input-output analysis.

Is China a net importer or exporter of embodied cropland? We cannot say – beyond the fact that under certain assumptions it is a net importer, under another assumptions it is a net exporter. Environmental footprint indicators have to be understood as something notional, which is estimated under specific assumptions and subjective value choices. Estimating upstream environmental impacts requires a model, and there is no observation to derive a true value to validate the models. Therefore, differences in results of different methods will always remain. We argue that ultimately, what matters for the global sustainability is the total environmental footprint of a country, person or product. The net values of trade are important in economics as they make the distinction between loss and profit. However, environmental footprints are intentionally estimated irrespective of national boundaries. From the global sustainability perspective, it makes no sense to compare countries solely based on net trade. Footprint accounting is designed to see beyond burden-shifting. By systematically including economy-wide approaches to our trade and consumption habits, can we be sure that the sustainable livelihoods that we seek to attain aren't just hiding the problem under the cloak of globalisation.

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## Appendix A. Supplementary data

Supplementary data to this article, such as additional results, methodlogical issues and classification of model product groups, can be found in Supporting Information online at https://doi.org/10.1016/j.ecolecon.2017.11.013.

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