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Methodological and Ideological Options

Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption

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ABSTRACT

The consumption of internationally traded goods causes multiple socio-environmental impacts. Current methods linking production impacts to final consumption typically trace the origin of products back to the country level, lacking fine-scale spatial resolution. This hampers accurate calculation of trade and consumption footprints, masking and distorting the causal links between consumers' choices and their environmental impacts, especially in countries with large spatial variability in socio-environmental conditions and production impacts. Here we present the SEI-PCS model (*Spatially Explicit Information on Production to Consumption Systems*), which allows for fine-scale sub-national assessments of the origin of, and socio-environmental impacts embedded in, traded commodities. The method connects detailed production data at sub-national scales (e.g., municipalities or provinces), information on domestic flows of goods and in international trade. The model permits the downscaling of country-to-country trade analyses based on either physical allocation from bilateral trade matrices or MRIO models. The importance of producing more spatially-explicit trade analyses is illustrated by identifying the municipalities of Brazil from which different countries source the Brazilian soy they consume. Applications for improving consumption accounting and policy assessment are discussed, including quantification of externalities of consumption, consumer labeling, trade leakages, sustainable resource supply and traceability.

1. Introduction

Sustainability science increasingly recognizes the growing importance of global teleconnections in driving local social–ecological dynamics (Liu et al., 2013; Meyfroidt et al., 2013). A key aspect of these teleconnections is the unprecedented increase in material flows entering international trade in recent decades (Krausmann et al., 2009; Wiedmann et al., 2013), having multiple impacts on ecosystems, biogeophysical cycles, development patterns and resource geopolitics (Burgos Cáceres and Ear, 2012; Le Billon, 2007). Through international trade, policies, consumption patterns and socio-environmental dynamics in one place may be key drivers of land use change, biodiversity loss, poverty or conflict in distant locations (Johnstone and Mazo, 2011). These interconnections may arise from direct causal links or occur indirectly as a consequence of complex chains of apparently unrelated dynamics, such as indirect land use changes stemming from biofuel policies (Ostwald and Henders, 2014), or cascading effects of sectoral policies to other sectors within and across countries, driven by the diversity of socio-economic processes shaping globalization (Lambin and Meyfroidt, 2011). International trade patterns, which depend on the geography of natural resources, levels of producer specialization, trade costs and policies, demographics, geopolitics and political history, shape these distant dependencies (Villoria and Hertel, 2011).

The complex geographies of trade make it increasingly difficult for consumers to trace the goods they consume to the place of production. Meanwhile, ongoing environmental impacts from the unsustainable use of natural resources have raised awareness of the need to understand and mitigate the ecological and social impacts associated with consumption choices (Rautner et al., 2013). As these impacts are ultimately determined by the characteristics of the specific locations where goods are produced, precise information on the origin of a given product is an essential basis for achieving more sustainable resource supply systems, evaluate dependencies, and reduce environmental and social impacts associated with consumption. In recognition of these concerns, trade analyses have evolved greatly from simple models based on bilateral physical trade reports to more sophisticated approaches that take into account transformation of goods and services, complex trade pathways and life cycle impact assessments (Davis et al., 2011).

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However, despite improvements in tracing material flows across sectors and international markets, especially with the recent booming of environmentally extended multi-region input-output (MRIO) studies (Lenzen et al., 2012a; Peters et al., 2011), trade analyses remain highly aggregated, relying on country-to-country trade data and national production data, and assume that the socio-environmental impacts associated with production of a given commodity are homogenous within each producer country. Yet, by their nature, the socio-environmental impacts of production are spatially heterogeneous within countries, depending on the characteristics of local social–ecological and production systems.

The fact that global biophysical accounting approaches currently do not include spatially-explicit information on sourcing locations at scales matching the heterogeneity of the socio-environmental impacts they aim to asses (Erb et al., 2009), decreases their policy relevance. In this context, we argue for a spatial disaggregation down to the scale relevant to the impacts being assessed. More spatially-explicit models could also strongly contribute to an effective understanding of causal links along supply chains, revealing hidden producer-to-consumer linkages. This could improve the understanding of trade-offs and leakage effects resulting from policy interventions in one place, and increase effectiveness in governance of natural resource use and supply chains (Lambin et al., 2014).

Here we present the *Spatially Explicit Information on Production to Consumption Systems* model (SEI-PCS), which aims to overcome some of the shortcomings of current approaches by allocating the socio-environmental impacts that are embedded in the trade of commodities produced in specific regions to the country of final consumption (as well as spatially disaggregated domestic consumption). The objective of the model is to identify the actual locations where the traded goods consumed in any nation are produced. Our main advance is to link data on location and supply chains of domestic production at sub-national scales to data on international trade flows, thereby downscaling and refining country-to-country trade analyses. Subsequently, any socio-economic or environmental impact indicator related to the place of production can be linked to the volume produced, traded and consumed. The scale of what constitutes the "place" of production depends only on the availability of sub-national data. We provide an example based on the trade in agricultural commodities, but the model can be applied to any form of material production and flows from other industrial sectors.

The remainder of the paper is organized into four sections. Section 2 further discusses the shortcomings of current non-spatially explicit (i.e., country-to-country) approaches to mapping trade relations and associated socio-environmental impacts. Section 3 describes the SEI-PCS model, and employs a simple conceptual example to facilitate its comprehension (see also SI 1 for a fuller description, and SI 2 for step-by-step calculations in an Excel workbook). Section 4 showcases the results of a real example — tracing back global and national consumption of Brazilian soy to the individual municipalities where soy is produced—and the advantages of this method versus non-spatially explicit models. Section 5 reflects in more depth on the potential applications and limitations of the SEI-PCS model and discusses how the model can be used to generate crucial insights for impact assessments, the governance of socio-ecological systems and an improved theoretical understanding of international trade and supply chains.

2. Limitations of non-spatially explicit footprint accounting and ways forward

Current country-to-country assessments of social and environmental impacts embedded in trade do not constrain footprints or impact calculations of a specific consumed unit to the actual location of its production, but instead assume an average impact per unit of primary product at national or even global scales (e.g. national yields for land and water footprints (Hoekstra and Chapagain, 2006; Erb et al., 2009; Saikku et al., 2012; Weinzettel et al., 2013)).

This lack of spatial explicitness across the production-to-consumption system (PCS) can lead to misleading generalizations and unreliable biophysical accounting, especially in countries with high levels of heterogeneity in social and/or environmental conditions, including in ecosystem services provision, resilience and adaptive capacity of local ecosystems. Impacts of production typically depend on region-specific factors such as soil, climate, technological knowledge, infrastructure and the characteristics of production systems, and may thus vary markedly across space. For instance, a country importing Argentinean soy primarily from the Pampa region (almost fully converted to farmland decades ago (Carreño et al., 2012)) will have a much lower land footprint and land use change impacts than a country importing the same amount of soy produced in the Chaco region (where average soybean yields are about half those in the Pampa (SIIA, 2014) and deforestation rates associated with soy expansion are high). On the other hand, because agriculture in the Pampa, where soil P-stocks are almost depleted (Viglizzo et al., 2011), is more input dependent, the impacts of soy consumption on nutrient runoff may be higher there than in the Chaco. These distinctions would be masked by conventional country-to-country trade footprint analyses. Similarly, with country-level analyses, biodiversity losses in a biodiversity-rich and ecologically diverse country such as Brazil are attributed equally to all traded products in one sector and/or to all the consumed units of a given product (Lenzen et al., 2012b) even though the production of certain commodities may actually be concentrated in regions with relatively high or low biodiversity values. Dynamics and modes of production also vary spatio-temporally. For the same amount of new cropland destined to a certain commodity, local pathways of agricultural expansion in different forested areas may imply strikingly different deforestation and environmental impacts (Meyfroidt et al., 2014).

This within-country spatial variability in historical agricultural expansion, modes of production and social and environmental impacts is not considered in global trade data and models, value chain analyses, and biophysical and socio-economic accounting. Thus, causal attribution of socio-environmental consequences to global material and financial flows and to consumers' choices remains poor (Meyfroidt et al., 2013). This misrepresentation of spatial heterogeneity means that such analyses are unable to discriminate the effect of policies in countries, especially where such policies also vary across regions. Understanding the indirect effects of production of a given commodity for a given consumer also requires information on the specific locations of production. For example, although intensification of production in highly suitable areas could theoretically lead to global land sparing, the actual outcome depends on trade geographies. Land intensification in highly suitable areas could produce, by competition, a reduction in the adoption of technological innovations, thus hindering intensification in marginal areas with lower yields (Schmitz et al., 2012). If agricultural expansion in the latter areas would induce high socio-environmental costs, the net effect could counteract the positive effects of intensification in other regions.

There is also a need to better consider the importance of domestic consumption and local dynamics in exporting countries, departing from traditional South–North trade perspectives and reflecting the rise of less developed countries as major consumers of natural resources (Feng et al., 2013). This is especially so in emerging countries, which often are major contributors to total demand for some key products (e.g., Brazilian beef and soy production) (Kastner et al., 2012; Kearney, 2010). Domestic dynamics are often driven by differences in affluence (Weinzettel et al., 2013) and consumption patterns, which are often related to urban–rural divergences (Seto et al., 2012), and thus vary markedly across space. The lack of such domestic perspective on the impacts of globally traded commodities undermines our ability to understand global trade patterns and consumption dynamics and the policy relevance of any recommendations derived from such analyses. To this end, our model also traces production within the country of production to domestic centers of consumption within the same country.

3. Methods

The SEI-PCS model allocates production at the finest scale available in a country of interest to consumption countries and places of domestic consumption in the country of interest. In the model foreign and domestic consumers compete for the farming commodities, potentially within constrains imposed by available data detailing the origin of products exported at national trade facilities (e.g. seaports, land port customs, airports) and consumed in domestic consumption centers (e.g. cities or industries). When data on domestic origin of exported goods is regionally aggregated, a minimum cost allocation analysis is used to spatially allocate flows from production areas within the regions of aggregation to consumption centers and trade facilities.

To obtain a matrix $\boldsymbol{R}$ depicting the consumption of k countries originating from i sub-national regions of production of a given country of interest, it is sufficient to consider the following elements:

$$\boldsymbol{R}_{\boldsymbol{i}\times\boldsymbol{k}} = \boldsymbol{D}_{\boldsymbol{i}\times\boldsymbol{e}} \times \boldsymbol{L}_{\boldsymbol{e}\times\boldsymbol{k}} \times \boldsymbol{B}_{\boldsymbol{k}\times\boldsymbol{k}}. \quad (1)$$

The three components making up Eq. (1) are:

i) The domestic material flows matrix, $\boldsymbol{D}$, describing the flow of goods between i domestic producers (e.g., municipalities, provinces) and e international trade facilities within the same country (e.g., seaports). $\boldsymbol{D}$ is expressed as the share of the goods entering the international trade system at each trade facility e that is produced in each production center i.
ii) A bilateral trade matrix, $\boldsymbol{B}$, depicting trade flows between all k countries, which may be obtained through various methods, for example physical accounts that include re-exports between countries (e.g., using FAO bilateral trade data (Kastner et al., 2011)).
iii) A link between the two previous components by means of a matrix $\boldsymbol{L}$. $\boldsymbol{L}$ represents the net flows in all import countries that originate from the trade facilities of the country of interest, expressed as a share of each country's own production. By considering only domestic production, matrix $\boldsymbol{L}$ filters the exports from the country of interest that have not been produced within that country but are re-exports from third countries.

Eq. (1) follows the flows of exported products between different geographic scales sequentially, from the producer scale to the domestic consumption centers and international trade facilities, from the latter to the countries of first import, and from them to the consumer countries. Below we propose a generic method to obtain these three components, applicable to any traded good and any scale of production (e.g. household, municipality, province) or consumption (e.g. regional or country-level).

3.1. Domestic allocation of sub-national production to domestic consumption centers and trade facilities (D)

In the absence of detailed traceability data on domestic flows from the production areas to the export facilities at the desired scale, production, imports, exports, and domestic consumption for the country of interest need to be obtained to produce matrix $\boldsymbol{D}$, with total production plus imports equaling the sum of domestic consumption and exports (Eq. (2)). Domestic consumption is distributed spatially among the domestic consumption centers (Eq. (3)). This distribution is proportional to i) the share of domestic demand capacity α in each domestic consumption center (e.g. share of national population if the commodity is directly consumed, or the share of domestic transformation/industrial capacity if the product needs to be processed, such as ethanol); and ii) the consumption intensity ß (which can be the consumption per capita in different regions of domestic consumption, or the efficiency in processing the traded commodity per processing facility). Finally, domestically produced and imported goods are allocated competitively from producers and import facilities to domestic consumers and export facilities through a minimum cost flow analysis, using linear programming (Eq. (4)). Typically this analysis will account for transport cost, but other costs can also be considered. When available, information on domestic flows of produced and imported goods constrains the allocation model increasing its accuracy. We present the generic case in which domestic traceability data is presented in an aggregated form which does not match the scale of the production data, as in the Brazilian soy example in Section 4 (e.g., domestic traceability data per Brazilian state, production data per municipality). This allocation procedure is not needed when the spatial detail of the domestic origin of exported goods matches that of production.

$$\boldsymbol{C} = \sum\nolimits_n \boldsymbol{C}_{\boldsymbol{n}} = \sum\nolimits_i \boldsymbol{P}_{\boldsymbol{i}} + \sum\nolimits_q \boldsymbol{I}_{\boldsymbol{q}} - \sum\nolimits_e \boldsymbol{E}_{\boldsymbol{e}} \quad (2)$$

$$\boldsymbol{C}_{\boldsymbol{n}} = \boldsymbol{C} \times \boldsymbol{\alpha}_{\boldsymbol{n}} \times \boldsymbol{\beta}_{\boldsymbol{n}} \quad (3)$$

where

C	*total consumption*
C_n	*total consumption in domestic center n*
P_i	*production in production center i*
Iq	*imports from import facility q*
E_e	*exports from export facility e*
a_n	*Share of demand capacity of domestic center n*
β_n	*consumption intensity of domestic center n*

$$\textbf{\textit{Minimize}} \sum\nolimits_i \sum\nolimits_e \boldsymbol{w}_{\boldsymbol{i},\boldsymbol{e}} \boldsymbol{x}_{\boldsymbol{i},\boldsymbol{e}} + \sum\nolimits_i \sum\nolimits_n \boldsymbol{w}_{\boldsymbol{i},\boldsymbol{n}} \boldsymbol{y}_{\boldsymbol{i},\boldsymbol{n}} + \sum\nolimits_q \sum\nolimits_e \boldsymbol{w}_{\boldsymbol{q},\boldsymbol{e}} \boldsymbol{z}_{\boldsymbol{q},\boldsymbol{e}} + \sum\nolimits_q \sum\nolimits_n \boldsymbol{w}_{\boldsymbol{q},\boldsymbol{n}} \boldsymbol{z}_{\boldsymbol{q},\boldsymbol{n}}. \quad (4)$$

Subject to:

Supply limit at production units i :

$$\forall \boldsymbol{i}, \ \sum\nolimits_e \boldsymbol{x}_{\boldsymbol{i},\boldsymbol{e}} + \sum\nolimits_n \boldsymbol{y}_{\boldsymbol{i},\boldsymbol{n}} \le \boldsymbol{P}_{\boldsymbol{i}}$$

Supply to domestic centers :

$$\forall \boldsymbol{n}, \ \sum\nolimits_q \boldsymbol{z}_{\boldsymbol{q},\boldsymbol{n}} + \sum\nolimits_i \boldsymbol{y}_{\boldsymbol{i},\boldsymbol{n}} = \boldsymbol{C}_{\boldsymbol{n}}.$$

Supply from import facilities conditioned to region of consumer:

$$\forall \boldsymbol{q}, \sum\nolimits_{n\in r} \boldsymbol{z}_{\boldsymbol{q},\boldsymbol{n}} + \sum\nolimits_e \boldsymbol{t}_{\boldsymbol{q},\boldsymbol{e}} \le \boldsymbol{I}_{\boldsymbol{q}}^{(\boldsymbol{r})}.$$

Supply to trade facilities conditioned to region of producer:

$$\forall \boldsymbol{e}, \sum\nolimits_{i\in r} \boldsymbol{x}_{\boldsymbol{i},\boldsymbol{e}} + \sum\nolimits_q \boldsymbol{t}_{\boldsymbol{q},\boldsymbol{e}} = \boldsymbol{E}_{\boldsymbol{e}}^{(\boldsymbol{r})}$$

r	*sub-national* region of the country of interest[1]
x	*amount of exports produced domestically*
y	*amount of domestic consumption produced domestically*
z	*amount of imports consumed domestically*
t	*amount of imported goods that are re-exported from the country of interest*
w	*allocation cost,* $(i + q) \times (n + e)$ *values.*

The optimization yields a matrix $\boldsymbol{M}_{(\boldsymbol{i}+\boldsymbol{q})\times(\boldsymbol{n}+\boldsymbol{e})}$ representing the allocation from supply units (producers and import facilities) to demand units (trade facilities and domestic consumption centers) (Eq. (5)). The submatrices $\boldsymbol{Y}_{\boldsymbol{i}\times\boldsymbol{n}}$ *and* $\boldsymbol{Z}_{\boldsymbol{q}\times\boldsymbol{n}}$, representing respectively the production and imports allocated towards national consumption, are extracted because we do not assume re-exports among domestic consumption centers. The submatrix $\boldsymbol{X}_{\boldsymbol{i}\times\boldsymbol{e}}$ represents the traded goods which are domestically produced and are exported to other

[1] Regions r include i producers and q import facilities. In practice they may be administrative units such as provinces or states.

countries from the e trade facilities in the country of interest, and thus are potentially subject to subsequent re-exports that need to be accounted for. The submatrix $\boldsymbol{T_{q\times e}}$ represents the imports to the country of interest which are directly reexported to other countries.

$$\boldsymbol{M}_{(\boldsymbol{i}+\boldsymbol{q})\times(\boldsymbol{e}+\boldsymbol{n})} = \begin{bmatrix} \boldsymbol{X}_{\boldsymbol{i}\times\boldsymbol{e}} & \boldsymbol{Y}_{\boldsymbol{i}\times\boldsymbol{n}} \\ \boldsymbol{T}_{\boldsymbol{q}\times\boldsymbol{e}} & \boldsymbol{Z}_{\boldsymbol{q}\times\boldsymbol{n}} \end{bmatrix} \tag{5}$$

The matrix $\boldsymbol{D_{i\times e}}$, expressing the share of exports from any given trade facility e that originates from a given production unit i is obtained by dividing each element in the submatrix $\boldsymbol{X_{i,e}}$ by the total exports from each trade facility according to Eq. (6).

$$\boldsymbol{d_{i,e}} = {}^{\boldsymbol{x_{i,e}}}\Big/{\textstyle\sum_{i}}\boldsymbol{x_{i,e}} \tag{6}$$

Table S1 sets up a conceptual example of the basic inputs needed for obtaining matrix $\boldsymbol{D}$, in which five production units (A1–A5) situated in a country of interest A supply trade facilities E and F and domestic consumption centers G and H with a commodity. E and F not only export to countries B, C and D, but also import the same commodity from those countries. Sourcing and destination restrictions to domestic flows are known for the exports and imports from/to each trade facility. The example mirrors that provided by Kastner et al. (2011). More details are provided in SI 1.

3.2. Trade dependency — linking exports of domestically produced goods from trade facilities to countries of first import (L)

Given a matrix $\boldsymbol{N_{e,k}}$ that contains data on net exports from e trade facilities to k countries, our $\boldsymbol{L}$ matrix is constructed by dividing each of the elements in the columns of $\boldsymbol{N}$ (net imports of each country by sourcing port of the country of interest) by the total production of the importing country (Eq. (7)). The resulting ratios represent the relationship between the imports originating in a country and its own production. A negative value indicates a net flow to the country of interest through that export facility, whereas a value of zero indicates no bilateral trade of goods from a trade facility. In case the country of import lacks domestic production of the commodity in question, the value would reach infinity, which indicates complete dependency on imports. The data required to obtain this matrix for the above presented conceptual example can be found in Table S2.

$$\boldsymbol{l_{e,k}} = {}^{\boldsymbol{n_{e,k}}}\Big/{}_{\boldsymbol{P}(\boldsymbol{k})} \tag{7}$$

3.3. Allocation of country-aggregated trade flows from countries of first import to countries of consumption by accounting for re-exports between countries (B)

In a third stage the exported goods arriving in a country of first import are partly allocated to consumption in that country and partly re-enter the international market trade flows, in which they can be re-exported successively between countries and even be transformed into new products in the process. This complex path of traded goods in international markets is represented by a country-to-country $\boldsymbol{B}$ matrix tracing the consumption of traded goods in a given country that are produced in any other country. The main approaches for obtaining such a matrix are:

i) Biophysical analyses based on bilateral trade flow data (e.g. from FAOSTAT (FAO, 2014)), in which traded commodities are converted into primary equivalents and re-exports between countries are accounted for. One example to account for re-exports is to estimate a matrix of apparent consumption as described by Kastner et al. (2011). This method assumes proportionality in exports between domestically produced and imported goods, and that a country's consumption originates in proportional shares from its own production and imports; or
ii) MRIO analyses, which account for complex transformations of products along the supply chain. MRIO analyses use the Leontief inverse (Peters et al., 2011) and rely on the integration of monetary trade flow data and data on financial flows between sectors. Its complexity leads to large aggregations and necessary simplifications of the global economy, but offers a powerful multi-region life-cycle inventory of supply chains (Wiedmann et al., 2011). The use of a matrix based on a MRIO analysis requires the additional step of disentangling the traded good of interest from the sector it belongs in the particular sectorial structure defined by the MRIO approach.

For the conceptual and empirical examples presented here we use the $\boldsymbol{B}$ matrix of apparent consumption calculated using the biophysical analysis methodology presented by Kastner et al. (2011) (SI 1).

3.4. Obtaining the consumption of countries from production municipalities

By multiplying the three matrices obtained in the previous steps, the matrix $\boldsymbol{R}$ of Eq. (1) is obtained. This matrix shows the consumption of all k countries of a trade good produced in i sub-national regions and exported through e trade facilities of a given country of interest.[2] However, to obtain the full description of flows of products from places of production to places of consumption, including domestically consumed in the country of production, it is necessary to include the submatrices $\boldsymbol{Y_{i,n}}$ and $\boldsymbol{Z_{q,n}}$ from Eq. (5). Numerically, the inclusion of these two elements is equivalent to subtracting the amount of exported goods domestically originated in each sub-national production region from the total amount of exported goods of each sub-national production region (regardless if originated from imports or production). As a result we obtain a final matrix $\boldsymbol{\overline{R}_{i,k}}$ representing the amount of traded good produced in each of the production units of a given country of interest that is consumed in any country, including in the country of interest.[3] Thus, the resulting matrix $\boldsymbol{\overline{R}_{i,k}}$ also identifies the origin, within the country of interest, of the consumption in the trading country partners as well as in the country of interest itself. The total consumption for each country is the same as obtained in the similar country-to-country example of Kastner et al. (2011), Table S3. As discussed in SI 1 the increased spatial explicitness from downscaling country level analyses increases the accuracy of impact accounting substantially.

$$\boldsymbol{\overline{r}_{i,k}} = \begin{cases} \boldsymbol{r_{i,k}} \;\; \textbf{\textit{if}} \;\; \boldsymbol{k \neq country \;\; of \;\; interest} \\ \boldsymbol{r_{i,k}} + \boldsymbol{P_i} - \sum_j \boldsymbol{r_{i,j}} \;\; \textbf{\textit{if}} \;\; \boldsymbol{k = country \;\; of \;\; interest}\} \end{cases} \tag{8}$$

4. Empirical example: global consumption and land footprint associated to Brazilian soy

Here we apply the SEI-PCS model to obtain a matrix showing in which Brazilian municipality the soybeans consumed in any country

[2] The rows in this matrix represent the net trade balance per sub-national production unit, that is, the theoretical amount of the traded good that each sub-national production unit would have to produce for the country of interest to be self-sufficient in that particular traded good.

[3] It is worth noting that both the $\boldsymbol{L}$ and $\boldsymbol{B}$ matrices can be expressed as shares. Although we chose to divide $\boldsymbol{N_{e,k}}$ by the production of the importing country (Eq. (7)), it is equally correct to apply the division to the $\boldsymbol{B}$ matrix. That would let the $\boldsymbol{L}$ matrix be in absolute form (dictating the magnitude of trade flows), and expressing the $\boldsymbol{B}$ matrix in relative terms (dictating the shares of total production consumed in different countries).

Table 1
Description of data needed to run the SEI-PCS model, with examples for Brazilian soy.

Description	Comment/examples	Data source for the Brazilian soy example	Symbol (Section 3)	Importance
1—Data for domestic allocation of sub-national production shares to trade facilities ($D_{i \times e}$)				
#1—Sub-national production data of the primary product at sub-national scales for the country of interest.	Available from governmental sources or supra-national institutions such as FAO for land-based products. Different scales of information can be used, e.g. households, municipalities, provinces.	Municipal agricultural production, Brazilian Institute of Geography and Statistics (IGBE)	P_i	Required
#2—Distribution of domestic demand and relative consumption per unit, for the primary and secondary products of interest.	—For products that are directly consumed, units of consumption/demand are for example households. Spatial distribution of domestic consumption would thus be proportional to national demographics. For products that need processing, consumption units are, for example, transformation/processing facilities. —The total domestic consumption/demand in each unit is proportional to the ratio of observed consumption/processed demand vs. national average.	Location and share of national soy processing capacity (ABIOVE, 2013). Location and share of national storing capacity of grains (CONAB, 2014)	α_n, β_n	Required
#3—Domestic allocation cost.	For example, based on GIS layers describing the transportation network in the country of interest, if transport cost is the main allocation cost. Not necessary if allocation data to domestic consumers and trade facilities is available at the same scale as production data.	Brazilian National Plan of Transports and Logistics, PNLT (PNLT, 2010). Relative costs per kilometer of different transportation alternatives estimated from literature (see SI 1).	w	Required, if #5 is not exhaustive
#4—Imports and exports data on the primary and secondary products by trade facility of the country of interest.		Integrated Foreign Trade System of Brazil (SECEX, 2014)	I_q, E_e	Required
#5—Information on domestic origin/destination of traded products by trade facility of the country of interest.	It highly increases the model's accuracy by reducing or eliminating dependency on minimum cost flow analyses.	Integrated Foreign Trade System of Brazil (SECEX, 2014)	$\boldsymbol{I_q^{(r)}}$, $\boldsymbol{E_e^{(r)}}$	Optional, but required for highest accuracy.
2—Data to estimate the share of country imports from trade facilities ($\boldsymbol{I_{e,k}}$)				
Description	Comment/examples	Data source for the Brazilian soy example		
#6—Same as #4, spread by trading partner	Allows avoiding the assumption of current models that all trade facilities have the same distribution of exports to all destination countries.	Integrated Foreign Trade System of Brazil (SECEX, 2014)	$\boldsymbol{N_{e,k}}$	Required
#7—Conversion factors to convert secondary products into primary equivalents.	Each trade code of a product needs to be allocated to match the classes provided in the bilateral matrix (e.g. for soy in FAOSTAT: soybeans, soy oil, soy cake and soy sauce).	FAOSTAT http://faostat.fao.org/	–	Required
3—Data for allocation of aggregated national exports to consumer countries ($\boldsymbol{B_{k \times k}}$) (e.g. calculated using a physical trade model, (Kastner et al., 2011))				
Description	Comment/examples	Data source for the Brazilian soy example		
#8—Production data of the primary product domestically produced for all trading partners	Aggregated national production.	FAOSTAT, FAO (2014)	$\boldsymbol{P^{(k)}}$	Required
#9—Same as #7	Each of the trade codes of a product needs to be allocated to match the classes provided in the bilateral matrix (e.g. for soy in FAOSTAT: soybeans, soy oil, soy cake and soy sauce)	FAOSTAT, FAO (2014)	–	Required
#10—Bilateral trade data for the primary product and secondary products derived from it		FAOSTAT, FAO (2014)	–	Required

are produced. Table 1 summarizes the type of data required, and the data sources for the Brazilian example. Further details on data used and how the SEI-PCS method was applied can be found in SI 1.

The maps of Fig. 1 illustrate how SEI-PCS captures differential country sourcing patterns of China, the European Union (EU 28), Brazil and the Nordic countries, showing temporal and spatial dynamics of sourcing and national consumption for three selected years (2001, 2006, 2011). While China has strongly increased its consumption of Brazilian soy, from 3.87 Mt in 2001 to 24.69 Mt by 2011 (+639%), its pool of sourcing regions remained relatively stable, with an expansion in the vicinity of original sourcing areas in Southern Brazil (Atlantic Forest biome and the South of the Cerrado biome), but little expansion to the Northern and Central Amazon biome and moderate to the Northern Cerrado[4] (Figure S1). The EU, on the contrary, reduced its consumption of Brazilian soy from 2006 to 2011, although levels remained high (starting at 16.14 Mt in 2001, consumption peaked at 18.86 Mt in

[4] The Brazilian Amazon biome (4.2 million km^2) is the world's largest tropical forest and one of the main repositories of terrestrial carbon, water and biodiversity. Deforestation has mostly occurred in the Eastern and Southern fringes; The Cerrado biome (2.0 million km^2) is the most biodiverse wet savannah in the World, and since recently suffers from very high rates of deforestation. Most remaining forests are situated in its Northern half; The Atlantic forest biome (1.1 million km^2), although originally hosting a large biodiversity and endemism rates, currently hosts 70% of the Brazilian population and a vast proportion of the land has been already transformed into farming and urban areas. http://www.mma.gov.br/estruturas/chm/_arquivos/mapas_cobertura_vegetal_ingles.pdf.

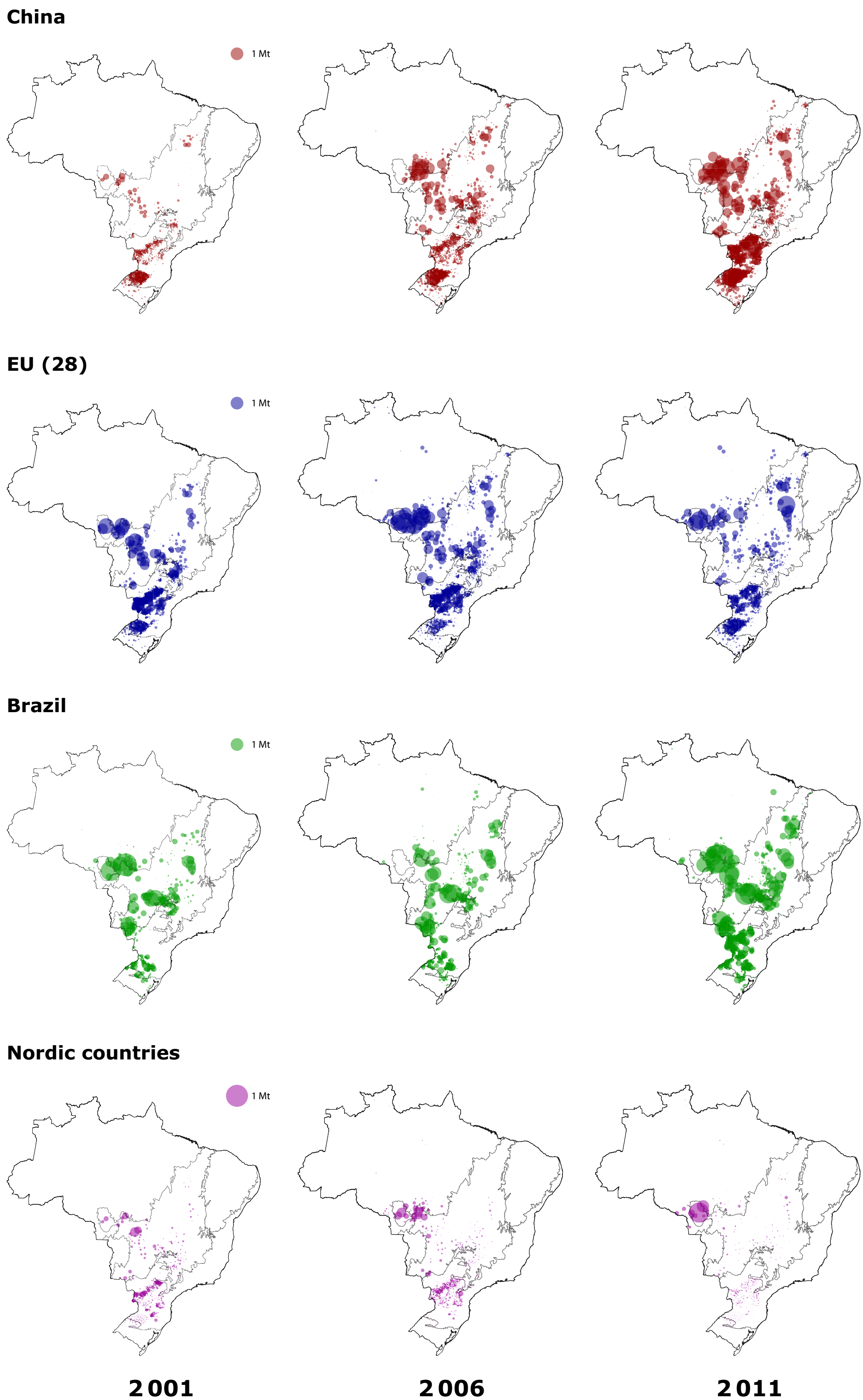

Fig. 1. Estimated municipal origin of the soy consumed in China, the European Union (28), Brazil and the Nordic countries (Sweden, Finland, Norway, Denmark and Iceland) in the years 2001, 2006 and 2011. Each circle represents a production municipality, with circle areas proportional to quantity consumed. In 2011, 1832 municipalities reported soy production, out of 5565 in Brazil. The 6 Brazilian biomes are delineated to illustrate the differential sourcing of consumer countries from areas with marked environmental differences (see also Figure S1 to compare with land cover in the same biomes).

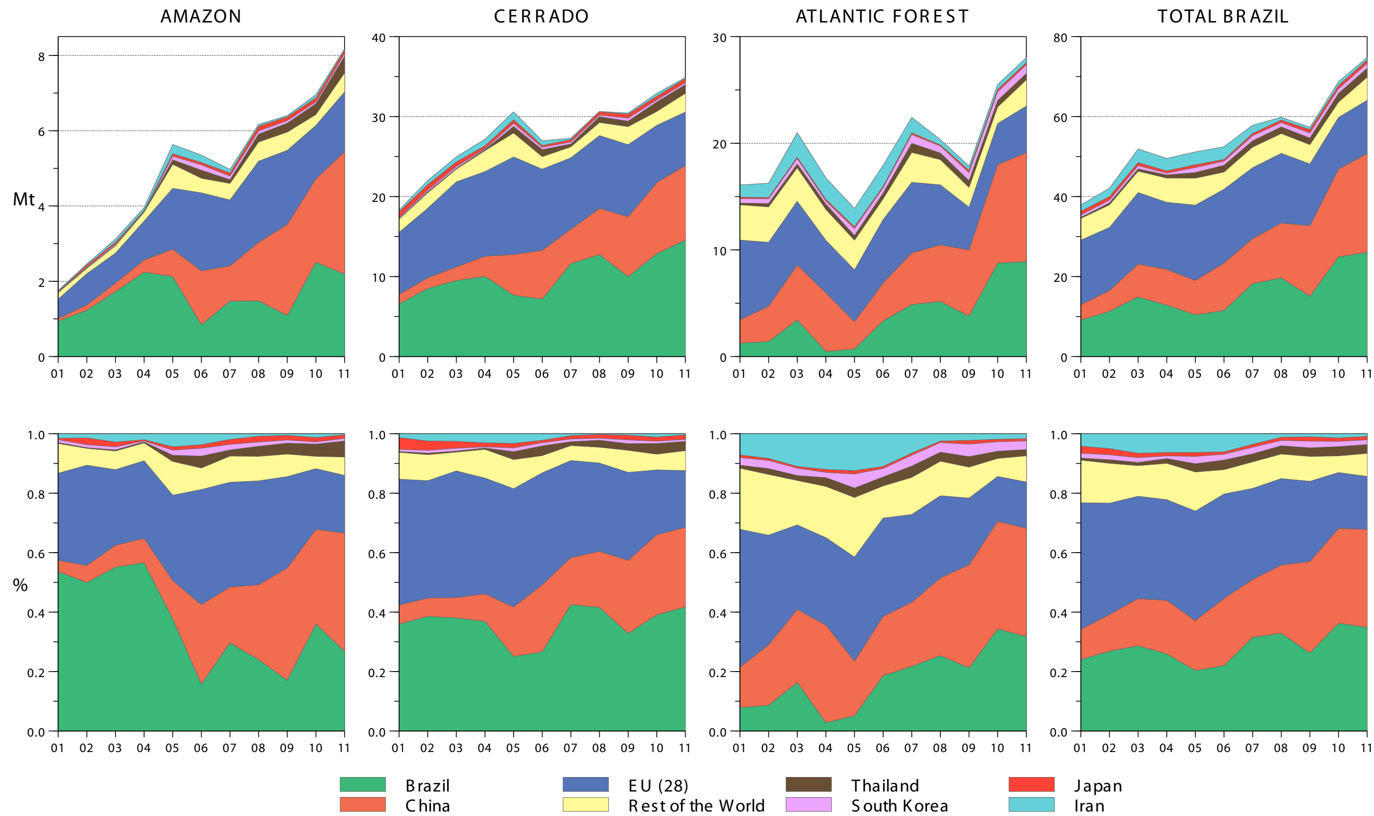

Fig. 2. Time series of global soy consumption from different Brazilian biomes and Brazil 2001–2011, representing the amount of soy consumed in million tons (Mt) and the respective percentage of consumption.

2006, declining to 13.34 Mt in 2011). More importantly in terms of environmental impacts, EU consumption has shifted geographically from an initial focus in the long-settled agricultural regions of the South of Brazil in 2001, towards the Southern and Western Cerrado, and then also towards the forested agricultural frontiers in the Northern Cerrado and Eastern Amazon (year 2011). In fact the EU dominates the soy consumption from the states entirely situated in the Amazon biome (65.4% of exported soy produced in Pará, 81.3% in Rondonia and 50.4% in Roraima), as suggested by Elferink et al. (2007) and Garrett et al. (2013a). However, given the large share (90.8%) of soy production in the Amazon biome that originates from the state of Mato Grosso (divided in halves between the Amazon and Cerrado biomes, and comparatively highly deforested), consumption of soy produced in 2011 in the Amazon biome as a whole is dominated by China (39.8%), almost as high as Brazilian and EU consumption together (26.8 and 19.4%, respectively, Fig. 2). Brazil has strongly increased its share of soy consumption in all biomes, with special focus on the Cerrado and the South of the Atlantic Forest. Brazil was the largest consumer of Brazilian soy in 2011.[5] In turn, the Nordic countries have transitioned from a diversified sourcing in 2001, to concentrating consumption in 2006 in the limit between the Amazon and Cerrado biomes, and to sourcing almost exclusively from providers of certified soy from Mato Grosso by 2011 (see Section 5.1).

A time series of global consumption of soy from the Brazilian biomes illustrates marked changes in short periods of time (Fig. 2). For example, between 2001 and 2004, 54.3% of the soy produced in the Amazon biome was consumed in Brazil, while 90.7% of the soy from the Atlantic Forest biome was destined to exports, mostly to the EU (34.8%), China (23.0%) and Iran (9.7%). Seven years later, in 2011, the amount of soy from the Amazon biome consumed by Brazil was roughly unchanged (2.2 Mt), but it accounted for just 26.8% of the total. In the same year the percentage of exports from the Atlantic Forest biome decreased to just 68.2%, and Iran consumed only 1.7% of the biome's production. Almost all consumer countries increased their consumption from the Cerrado biome in absolute terms (with the notable exception of the EU), clearly indicating that growing domestic and international demand for soybeans has been satisfied largely through farming expansion in the Cerrado. Although in absolute terms China's increased demand has been mainly met through the Cerrado and Atlantic Forest biomes, in relative terms, the Amazon is the biome where Chinese supply has had the largest rate of increase. This demand is focused on the Southern edge of the Amazon biome in the limit with the Cerrado. In the same region EU's consumption has decreased significantly between 2006 and 2011, coincidental with the 2007 soy moratorium in the Amazon (Nepstad et al., 2014), while most of the comparatively small soy production in the rest of the Amazon is mostly consumed in the EU.

These and other examples of intensified demand from certain regions by different consumer countries, produce indirect effects and displacement in the impacts associated with consumption of nations. For example the land footprint per consumed unit (ha per ton) associated with Brazilian soy consumption changed considerably through time (Fig. 3). While in 2001–2002 China had a considerably higher land footprint per consumed ton than the EU, by 2003 it was similar. This coincided with declining share of consumption from the Cerrado biome, where yields were at the time generally lower than in the Atlantic Forest biome, in China and an increase in the EU (Fig. 4). The abrupt increase in consumption from the Cerrado biome in the period 2003–2005 produced a marked increase in the land footprint of China, but consumption from the three sourcing biomes progressively converged to similar land footprints per ton of soy, approaching national average yields of

[5] Here we included exclusively the soy traded as soybeans or one of its primary processed products (soy oil, soy meal and soy sauce). The inclusion of embedded soy in third products that are heavily exported (Kastner et al., 2014) would certainly decrease total Brazilian consumption, for example considering that feedstuff estimates for broilers in 2013 amount to 7.4 million tons of soybean meal (Sindiraçoes, 2014). Brazil is the biggest exporter of chicken meat, and its exports accounted for about 31% of the total production in 2011 (about 4 million tons) http://www.brazilianchicken.com.br/home/ofrangonomundo?lang=en.

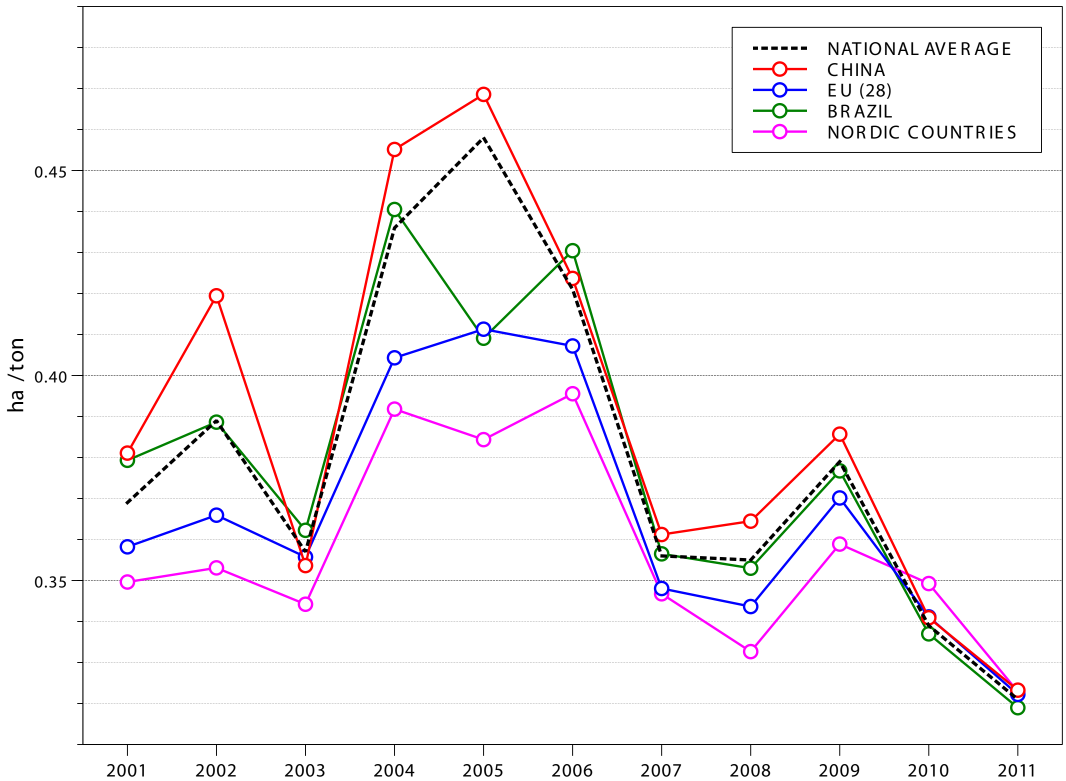

Fig. 3. Time series of land footprint (hectares) per consumed ton of Brazilian soy of China, the EU (28) and the Nordic countries, 2001–2011. The Brazilian national average land footprint per produced ton (as used in country-to-country assessments) is included for comparison (dotted line). Municipal yields obtained from IBGE (2014).

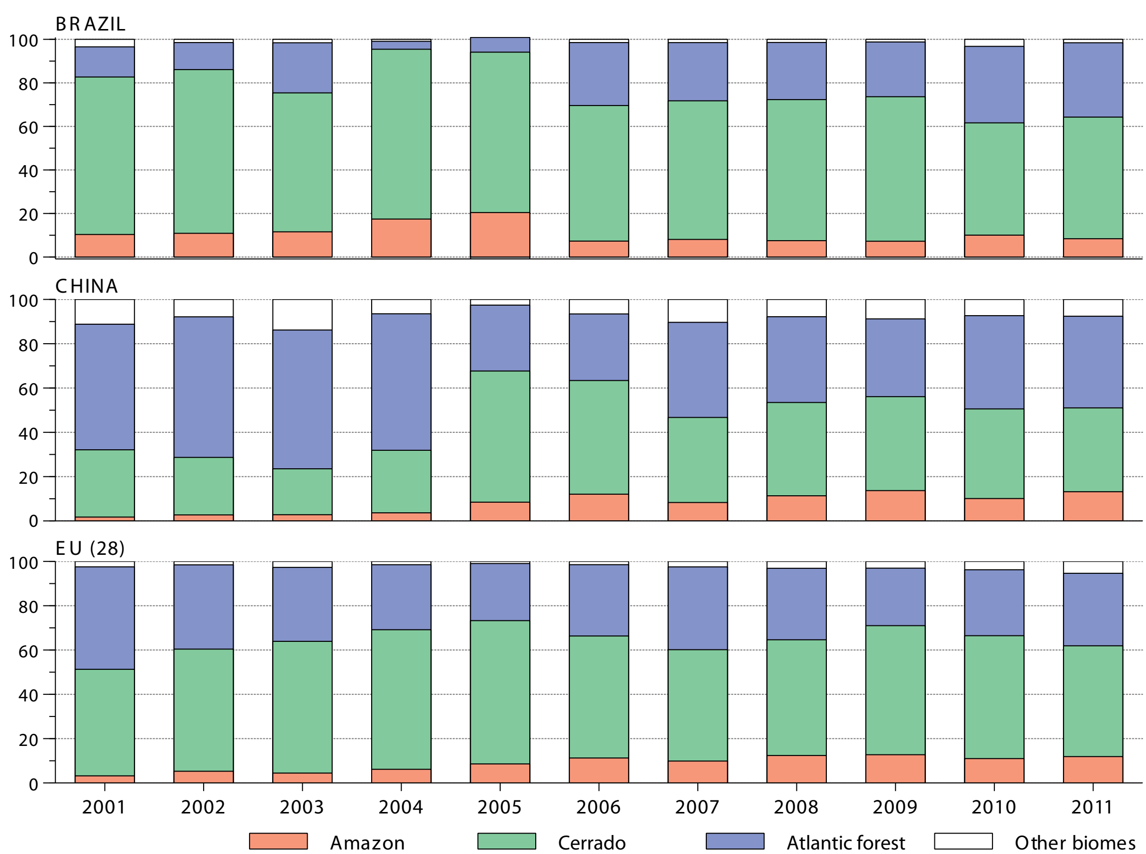

Fig. 4. Time series of the proportion of the Brazilian soy consumption of China, the EU (28) and Brazil that comes from the three main Brazilian biomes, 2001–2011.

about 3.1 ton/ha in 2011. This could be explained by the progressive homogenization of soy productivity across regions in Brazil, linked to the implementation of new input-intensive agronomic techniques adapted to areas such as the Cerrado, previously considered to have a small agricultural potential (Rada, 2013). Discrepancies in land footprint calculations compared to methods using coarser resolution, and consequently average national yields (dotted line), arise from fine-grained spatio-temporal heterogeneity in municipal soy yields (IBGE, 2014).

The impacts in terms of biodiversity, carbon stocks, land use dynamics, forest conservation and socio-cultural values per ton of consumed soy are expected to vary even more than the land footprint, due to the larger differences and heterogeneity across municipalities, states and biomes. For instance, EU's prominence in sourcing soybeans from some of the best preserved forested regions of Brazil, such as the Central and Northern Amazon and Northern Cerrado (compare Fig. 1 and Fig S1), is expected to imply a higher biodiversity and deforestation impacts per consumed ton than that of China, whose supply is much more dependent on soy from the Atlantic Forest biome and the Southern Cerrado. However current country-to-country analyses would attribute impacts caused by soy production proportionally to the consumption share of total Brazilian soy, regardless of variations in the pools of sourcing biomes, with identical environmental impact per unit of primary product for all consumption countries.

Although explaining these varying dynamics and assessing their socio-environmental implications are out of the scope of this paper, the example illustrates the potential of SEI-PCS to inform studies ranging for example from the optimization of sourcing of commodities, supply chain tracing, the better understanding of drivers of land use change or more accurate calculations of carbon emissions associated with consumption in different countries.

5. Potential and Limitations of the SEI-PCS model

In this section we first discuss the availability of data required to apply the proposed method, and the validation of the model. Then we discuss potential applications, integration with existing methods and implications for future research, in particular for trade analysis and consumption accounting.

5.1. Data availability, model validation and applicability

For many countries and products, the data required for applying SEI-PCS (Table 1) are available. Crop production data at sub-national scales is usually available in most countries from ministries of agriculture, but the spatial level of detail may vary across countries. Aggregated national production for all countries and bilateral trade matrices are made available from FAOSTAT and UN's Comtrade standardized databases, covering a large number of farming and non-farming products. Information needed to reconstruct domestic consumption and allocation of the traded goods is generally available, including GIS layers of national transportation networks, national demographics and sub-national food baskets.

The results are strongly constrained by data on the amount of traded goods at import and export facilities. Thus the bottleneck and key data requirement are information on trade amounts from each trade facility in the country of interest, detailing the country of destination. Data on sub-national origin of goods exported per trade facility (as in the Brazilian example here, where customs data links trade facilities with State of origin of the commodity) highly increases the accuracy of the model. Further implementation in other South American countries is under way (e.g. Argentina, Uruguay, Paraguay), as well as in other global leading producers of farming commodities. Apart perhaps for most least-developed countries, the necessary data generally exist for most major exporters of agricultural commodities.

With detailed data available, e.g. as in Brazil, the main potential sources of errors in the SEI-PCS approach are (1) the method chosen to obtain the matrix B depicting country-to-country consumption, and (2) the assumption of a minimum allocation cost used to allocate production to trade facilities and domestic consumption in cases where there is no direct data on these material flows. For instance in our Brazilian example the main errors likely arise from i) the assumption of Kastner et al. (2011) that the origin of exported goods — including re-exports — is proportional to imports and domestic production, which affects international re-exports determining the amounts finally consumed by countries; ii) the assumption that transportation costs are key in determining allocation of production to processing and export facilities, and the information used to calculate those costs. However errors of spatial allocation would occur only within Brazilian states, a major improvement compared to country-to-country trade models.

To validate the model implementation for Brazilian soy we compared our results with actual sourcing data, and with fieldwork detailing the allocation of soy from producers to specific Brazilian ports. The largest importers of soybeans in the Nordic countries report a strong dependency on soy supplied by Brazilian conglomerate Amaggi,[6] which is one of world's single largest soy producers and holds the largest area of certified soy (RTRS and PROTERRA), mostly produced in Mato Grosso. Particularly, the largest certified farms of Amaggi are located in the municipality of Sapezal.[7] Remarkably our model estimated that 42.7% and 49.2% of the Brazilian soy consumed by, respectively, the Swedish and Norwegian markets were produced precisely in Sapezal, which is just one of 95 soy producing municipalities in Mato Grosso and accounts for only 5.2% of the state's soy production and a tiny proportion of Brazil's overall production.

Also, our model describes the same trade paths and transportation modalities as fieldwork from Garrett et al. (2013b), which revealed that in 2010 soy produced in the Santarem area was mostly exported to Europe directly through the Santarem port, while soy produced in Sorriso (Mato Grosso) was transported by truck to the ports of Santos and Paranaguá. SEI-PCS reveals that 92.6% of the soy produced in Santarem was consumed in Europe (49.3% in the UK and 11.5% in Germany alone), and all the soy of Sorriso was transported to precisely the same two ports (99.0% to Santos and 1.0% to Paranaguá). Further validation is hindered by the limited availability of detailed public information on the supply chains of large companies.

5.2. Applications of the model and further perspectives

The SEI-PCS model can greatly improve the accounting of socio-environmental impacts of consumption and the understanding of the linkages between dynamics of consumption, trade and production systems, and thereby contribute to improve governance and policies for sustainable supply-chain management.

5.2.1. Accounting of socio-environmental impacts of production embodied in consumption

Multiple indicators of socio-environmental performance (e.g., greenhouse gas emissions, biodiversity, water, land and deforestation footprints, nutrient fluxes, air quality, or social indicators such as equity, income, health impacts, child labor) in each sub-national production region can be developed and attached to assess the socio-environmental externalities associated with the consumption of a given product. Our model can also be used for traceability purposes, both as a secondary source of information to verify the plausibility of ethical or environmental standards when the information on the supply chain of a given product is made available to consumers, or as a primary source where information is absent.

[6] The largest importer is Denofa which is 100% owned by the Brazilian soy producer Amaggi. Other major Nordic importers also obtain a large part of their soy from Amaggi because of high Nordic demand for certified soy (Bartholdsson et al., 2010; Wåhlin, 2012).

[7] Two Amaggi farms located in Sapezal were the first certified by RTRS in the world http://www.responsiblesoy.org/productores/amaggi-agro/?lang=en and http://amaggi.com.br/?p=3879&lang=en.

When consuming countries differ in their patterns of consumption of different processed products derived from a single original commodity (e.g., some countries consume mainly soy oil and others consume unprocessed soybean), SEI-PCS can be applied to separate processed products to analyze their trade pattern in detail. Where uses of the primary product for feedstock exist, such as for biofuels or animal production, the SEI-PCS approach can be used to trace the transformed products in an identical way as the raw product. This may be a more robust approach for certain relatively short supply chains, for which the assumptions of MRIO approaches are generally not justified (Kastner et al., 2014). Such an approach would be particularly suited to assess the full impacts of consumption of livestock products.

The SEI-PCS can inform a number of relevant analyses related to the distribution of production benefits. For example export-driven production brings much needed income for producers, but the distribution of benefits, in terms of both local consumption needs, and revenue generation, varies significantly depending on the type of landowner/actor (e.g. smallholders and agro-industries), the type of market connection and the extent to which the traded product is processed.

5.2.2. Understanding the linkages between dynamics of consumption, trade and production systems

The SEI-PCS is especially suited to analyze impacts linked to temporal dynamics of production and consumption, including changes in sourcing related to logistics, technological changes, inter-regional competition, clusters and agglomeration economies, functional upgrading, and price variations. By untangling fine-scale geographic linkages along supply chains, indirect land use changes or leakage in specific locations may be shown to be linked to changes in policies or consumption patterns in distant places through changing trade patterns (Ostwald and Henders, 2014). This can contribute to inform the contentious debate on the full impacts of biofuel policies.

Establishing spatially-explicit links between producers and consumers is very relevant also to analyze the interface between domestic consumption dynamics and international demand. This has potential implications for poverty alleviation and food security, for studying uncertainties and security in global supply chains, price formation and future trade trends. The dramatic improvement in spatial-explicitness versus country-to-country assessments allows for studying intraregional consumption dynamics and dependencies at country level. Furthermore it also allows to analyze the integration of markets of products originating from different sub-national regions, i.e., whether, when relative prices charged by different supply regions change, a consuming country fully substitutes production from different regions (fully integrated markets), or there is a certain degree of inertia in trade patterns (Villoria and Hertel, 2011). Thus, tests of market integration could be applied to trade bans for specific production regions due to socio-environmental concerns, analyzing if such measures implemented only by certain countries merely relocate production impacts or if they have a net positive effect.

Sub-country assessments of PCSs allow for better understanding linkages between different supply chains of the same commodity as well. For example, Garrett et al. (2013a) argue that Brazil's engagement in non-GM soy, by contributing to create stronger trade linkages with Europe and supply chains allowing segregation of products based on their quality, facilitated upgrading of these supply chains by overlaying environmental certification upon the already-segregated chain. The SEI-PCS model could allow the verification of linkages between flows of soy with non-GM and environmental certifications. Similarly, studies investigating the horizontal integration between different commodity supply chains, e.g. soy and beef in South America (Gasparri and le Polain de Waroux, 2014), could benefit from more spatially-explicit tracing of trade flows. This could also contribute to refining and testing theories of land use displacement, based for example on comparative advantage (Meyfroidt et al., 2013). As comparative advantages vary from one producing region to another as well as from one consuming country to another, it should be possible to analyze if different consuming countries source their products from different regions which have specific comparative advantages compared to these countries.

5.2.3. Governance of supply chains and production systems

Overall the model and analysis approach proposed here may help raise awareness of consumption impacts by unveiling concrete real-world links with the regions of production, stimulating discussions on accountability, outsourcing, labeling of products, inclusion of externalities in the price of imported goods and policy coherence. More specific information on sourcing location and socio-environmental impacts provides the consumer with much more discriminatory power, either through commodity substitution and/or shifting purchasing choices to source from areas with improved social and/or environmental standards, potentially leading to the adoption of improved standards in other regions (Lambin et al., 2014). For some policy measures, traceability needs to be realized down to the farm or individual producer level. But other policy levers can function for example at the municipal level, as exemplified by Brazil's credit restrictions program to reduce deforestation (Nepstad et al., 2014).

Furthermore, increased spatial resolution of linkages between the producer and consumer regions may also shine a spotlight on impacts in less-known areas with high socio-environmental values, which may be shadowed by other regions or embedded in national dynamics. Recently, consumer-awareness campaigns have linked consumers in specific countries to actual producer areas through “direct targeting”, rather than relying on associations between commodities and generic impacts (Sasser et al., 2006). The SEI-PCS model can improve targeting by identifying consumers linked with specific production areas for which a concern is identified. Nevertheless as currently defined, our model cannot discriminate consumption patterns at sub-national levels other than in the country of interest. Coupling the SEI-PCS with sub-national accounts of consumption patterns is therefore a logical extension of our model.

6. Conclusion

Current trade flow analyses and trade accounting methods are strongly limited by their lack of spatial explicitness, leading to imprecise causal links between consumption patterns and socio-environmental impacts in production regions. The SEI-PCS model presented here overcomes this issue and allows for more accurate location and assessment of distant impacts of consumption. The full method relies on large datasets, but it is flexible enough to be used for simplified analyses in contexts with lower data availability, with still improved accuracy compared to country-to-country analyses. Although the method was developed for farming commodities, it can be adapted to various scales and any traded good for which information is available. Furthermore, it allows for downscaling any assessment representing country-to-country bilateral consumption dependencies to production origins, potentially including those obtained from input–output analyses. The future development of this capability is central to get the most out of current input–output methods and test their suitability to accurately reflect real trade dynamics and impacts of distant consumption patterns.

The SEI-PCS model advances trade analyses by tying together detailed sub-national production, domestic material flows, and customs data. This information opens new avenues for improved analyses in various fronts. We foresee clear potential for improvements in accounting of consumption impacts for a large number of social and environmental indicators, assessment of policy effectiveness, traceability, optimization of sustainable resource supply and in the quantification of trade-related leakage. The SEI-PCS and possibly other approaches for linking detailed sub-national information with international trade data constitute crucial tools to link local-scale issues of sustainable development with global-scale dynamics, and to reveal the links production and consumption systems which have been obscured by globalization and more complex supply chains. This opens new opportunities for governance of social–ecological systems at multiple scales.

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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.2015.02.003.

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