Trading Land

A Review of Approaches to Accounting for Upstream Land Requirements of Traded Products

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Summary

Land use is recognized as a pervasive driver of environmental impacts, including climate change and biodiversity loss. Global trade leads to “telecoupling” between the land use of production and the consumption of biomass-based goods and services. Telecoupling is captured by accounts of the upstream land requirements associated with traded products, also commonly referred to as land footprints. These accounts face challenges in two main areas: (1) the allocation of land to products traded and consumed and (2) the metrics to account for differences in land quality and land-use intensity. For two main families of accounting approaches (biophysical, factor-based and environmentally extended input-output analysis), this review discusses conceptual differences and compares results for land footprints. Biophysical approaches are able to capture a large number of products and different land uses, but suffer from a truncation problem. Economic approaches solve the truncation problem, but are hampered by the limited disaggregation of sectors and products. In light of the conceptual differences, the overall similarity of results generated by both types of approaches is remarkable. Diametrically opposed results for some of the world's largest producers and consumers of biomass-based products, however, make interpretation difficult. This review aims to provide clarity on some of the underlying conceptual issues of accounting for land footprints.

The Need to Account for Upstream Land Requirements

Researchers and policy makers alike are responding to the challenge posed by the global fragmentation of supply and use chains. In environmental accounting, the need to account for upstream resource requirements associated with traded goods has been identified. As indicators are developed for environmental pressures and impacts, no matter where they occur, associated with a given level of consumption, questions arise as to how to allocate responsibility for global resource use. As a contribution to the ongoing debate, this article provides a

review of approaches to accounting for upstream land requirements of traded products.¹ Upstream land refers to the land globally required to produce the goods and services for a given level of final demand. Upstream land consists of direct (e.g., cropland used to grow wheat for export) and indirect requirements (e.g., land used to grow oil crops for the production of lubricant for agricultural machinery used in the harvest of wheat for export). Biologically productive land is a key resource for humans as well as ecosystems. Land use is a pervasive driver of climate change, biodiversity loss, and other aspects of global environmental change (Foley et al. 2005).

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Environmental policies and accounts, such as the United Nations Framework Convention on Climate Change (UNFCCC), operate from a production-based perspective (Peters 2008), holding countries accountable for the emissions that occur on their territory. In some cases, however, policies aimed at reducing domestic emissions lead to increased emissions elsewhere. In order to curb anthropogenic global warming, it is necessary to avoid this so-called leakage of greenhouse gases (GHGs) (Munksgaard and Pedersen 2001). Owing to the high relevance of emission leakage for global climate-change policy, research is more advanced for upstream emissions than for other forms of resource use (Galli et al. 2013; Fang et al. 2014; Čuček et al. 2012). The issue of upstream land requirements, however, is closely related to that of upstream emissions, which include emissions from land-use change (Gavrilova et al. 2010; Saikku et al. 2012). Leakage has also been observed for land-use policies. Prohibiting or limiting land-use expansion, for example, for nature conservation, in one country may lead to increased imports or decreased exports of biomass products (Rudel et al. 2009) unless consumption levels decrease. Protection of forests, as envisioned in the UNFCCC REDD+ Program (FAO/UNDP/UNEP 2008), can lead to increased imports of wood and wood products, which may, in turn, be associated with deforestation or forest degradation in other countries. If lower technical efficiency or environmental standards apply in these countries, aggravated impacts may be the result (Mayer et al. 2005). Stricter environmental protection legislation in developed countries could cause displacement of production to areas of the world where it is more environmentally harmful owing to the required intensification and/or extensification of land use (West et al. 2010). The regrowth of tropic forest cover in Vietnam can be linked to (partially illegal) logging and reduction of forest cover in other countries of South East Asia and in China (Meyfroidt and Lambin 2009). In many cases, forest transitions, that is, the return of forests in area and density after periods of deforestation (Kauppi et al. 2006), coincide with considerable displacement of forest harvest or even deforestation to other countries (Kastner et al. 2011a; Meyfroidt et al. 2010).

Displacement effects occur not only within, but also across land-use types. Tropical deforestation is significantly driven by the expansion of agricultural land for export-oriented production (DeFries et al. 2013; 2010; Hosonuma et al. 2012; Karstensen et al. 2013). The GHG savings achieved by substituting bioenergy for fossil fuels may be reduced or even negated through the associated indirect land-use change (Bird et al. 2013; Lapola et al. 2010) and the GHG emissions it causes (Chum et al. 2011; Haberl 2013; Searchinger et al. 2008). Land is increasingly recognized as a scarce resource and competition between the different possible uses of land is already, as expected (Haberl et al. 2014; Lambin and Meyfroidt 2011; Weinzettel et al. 2013), leading to conflicts between the different stakeholders involved (Gerber 2011; Peluso and Lund 2011).

In order to be effective, policies for sustainable governance of the earth's biologically productive land must consider the connection (or coupling) of developments across spatial distances.

Trade is one of the central mechanisms mediating these connections: Changes in the final demand of one region are often directly and/or indirectly linked to land-use change elsewhere. Within land-system science, these insights have motivated the analysis of "teleconnections" or "telecouplings" (e.g., Güneralp et al. 2013; Haberl et al. 2009; Meyfroidt et al. 2013; Seto et al. 2012). Taking into account direct and indirect land requirements along global supply and use chains is paramount to understanding issues such as land-use displacement or land-related leakage. The currently emerging indicators of upstream land requirements of traded products push hard on the frontiers of socioeconomic metabolism research. New methods must be developed for the calculation of such indicators. These approaches challenge existing system boundary definitions and allocation principles in environmental accounting. The central challenges lie in developing an accounting principle by which land use can be allocated from a consumption perspective that reflects specific natural productivity and land-use intensity. Two main families of approaches currently exist that allow for the estimation of the share of a country's production that is dedicated to trade (also see Henders and Ostwald 2014). One can be characterized as economic modeling and most commonly takes the form of environmentally extended input-output analysis (EEIOA) based on the work of Leontief (1970). The other is based on biophysical accounting. Kastner and colleagues (2014b) have pointed out that these two types of approaches may produce diametrically opposed results for the land requirements associated with one country's final demand. The reasons why different results are generated are currently being investigated (Liang and Zhang 2013; Owen et al. 2014).

This review focuses on the conceptual differences among approaches to accounting for upstream cropland requirements of traded products. An a priori political decision as to how responsibility for land use ought to be allocated globally must be made in choosing the appropriate approach to use in calculating upstream land requirements. The results of these approaches are discussed in light of their conceptual differences.

Allocating Responsibility for Land Use

Whether production- or consumption-based land-use accounts are required depends on the research or policy question. Upstream land requirements that are related to domestic final demand, but occur in another sovereign country, are subject to that country's legislation and jurisdiction. European politicians, for example, cannot pass laws to alter agricultural production in Brazil. In order to inform domestic policy, it is necessary to use production-based accounts on land use. Where land-use decisions increasingly respond to foreign, rather than domestic, final demand, the potential impact of national policies in regulating land use may be limited (Lambin and Meyfroidt 2011). In order to curb global deforestation, reducing domestic consumption associated with a high upstream land requirement may be defined as a political goal. Corresponding policies may aim for the reduction of food waste or introduce disincentives to the

import of bioenergy directly or indirectly linked to tropical deforestation. Information on imported and exported upstream land requirements may additionally be required in guiding policy.

The choice of either a production- or a consumption-based approach simultaneously reflects a political decision on the allocation of responsibility for land use. In economic terms, production is associated with added value, from capital and labor, within an economy. A country that exports land-based products receives revenues in return. France, for example, designates valuable agricultural land to the production of wine, one of the world's most expensive agricultural commodities, for export and receives significant income in return (FAO 2014). Under a production-based perspective, the argument might be made that a country is responsible for the income from its factors of production. In contrast, the two main families of consumption-based approaches (economic modeling and biophysical accounting) allocate responsibility by either economic spending or biophysical use: In simplified terms, the environmentally extended input-output approach distributes land use to monetary final demand according to the direct and indirect monetary inputs required in the production process. The biophysical approaches translate consumption in biophysical units (most commonly tonnes [t]) into the land required in production by using product-specific factors (most commonly in tonnes per hectare [t/ha]).

The consumption-based allocation of land requirements raises issues that form part of the long-standing debate on the allocation of environmental burdens to products in the life cycle assessment (LCA) community (Reap et al. 2008; Finnveden et al. 2009). Where one production process yields more than one product, environmental burdens may either be allocated to the dominant product (see Huppes 1994) or to all of the coproducts according to their share in monetary value of production (e.g., Fargione et al. 2008) or according to their share in the total mass, energy, or exergy expended in production. The current International Organization for Standardization (ISO) standards on LCA (ISO 2006) prescribe subdivision or expansion of the system boundaries of analysis by allocating to each product of a multiproduct process those environmental burdens that would occur in the corresponding single-product process (Azapagic and Clift 1999; Kim and Dale 2002).

Comparative assessments of producer and consumer responsibility (Munksgaard and Pedersen 2001; Muradian et al. 2002) have formed the basis for distinguishing allocation of responsibility by considering (economic) benefits or (ecological) burdens (Feng 2003). It has been shown that even though a form of shared responsibility might be most appropriate, its definition is not trivial (Bastianoni et al. 2004; Jakob and Marschinski 2012). The concept of shared producer and consumer responsibility (Gallego and Lenzen 2005; Lenzen et al. 2007) is one manner of dealing with these issues. Thereby, all factor use is shared between the sectors along the supply chain, downstream sectors, and final consumers. It can either be formulated on a simple 50:50 allocation in each step through the supply chain or by using information on value added generated by production

step, allocating responsibility for factor use by profit generated. Owing to the complexity and data requirements of such an approach, it has not been widely applied.

Next to the choice between the production- and consumption-based perspective and the different possibilities of allocating responsibility under the latter, upstream land requirements could be allocated in a number of different manners (Eder and Narodoslawsky 1999), depending on whether or not indirect effects of land-use change across spatial and temporal scales are taken into account. The approaches reviewed in this article are discussed in terms of the principles according to which they allocate land use to final consumption.

Measuring Land

In addition to differences in the principles according to which responsibility for land use is allocated, approaches to accounting for upstream land requirements differ conceptually in the metrics they employ. When land is measured in units of area such as hectares or square kilometers, no information about the productivity of that land or the intensity of its use can be conveyed. Land is used for agricultural production, as cropland, grazing land, and pasture, for forestry and as built-up land for human settlements, buildings, and infrastructure. These land-use types have very different impacts on ecosystems. Further, it is not straightforward to correctly represent land used for multiple purposes (e.g., agroforestry or forest grazing) in environmental statistics and accounting. Measuring upstream land requirements in terms of area extent aggregates land of different qualities, potentially making the results of such accounts difficult to interpret (Erb 2004; Haberl et al. 2004).

In accounts of upstream land requirements, trade flows (in biophysical units such as tonnes or monetary units such as Euros) are commonly converted into an area equivalent based on assumed yields, that is, on the mass or the economic value obtained per unit of area at the point of origin of the trade flow. A particular challenge in assessing upstream land requirements across land-use types (e.g., cropland, grassland, or forestry) is that land itself is an extremely heterogeneous resource in terms of quality. Land shows a vast gradient in natural productivity (declining in general terms from the equator to the poles owing to the temperature gradient, but strongly modified by other climatic factors, in particular, precipitation), in soil fertility (depending on many parameters, such as chemical composition of subsoil, microorganisms, depth, and so on), topography, and other factors. These differences in quality are often mirrored in the way land is used in agriculture, which may be labor- and/or energy-intensive (Erb et al. 2013; Kuemmerle et al. 2013). Grazing often occurs on marginal land (Asner et al. 2004; Erb et al. 2007), whereas high-value market crops will usually concentrate on the most fertile, productive plots.

Even within the same land-use type, productivity differences can be substantial owing to differences in land quality and/or management intensity. For upstream land accounts, this also raises the question of how multicropping (i.e., multiple annual

Figure 1 Yields in tonnes per hectare and harvest event in 2007 (t/ha/harvest event) for maize, rice, and wheat by country quintiles and world average in 2007, based on FAOSTAT data (FAO 2014). Quintiles each represent approximately 20% of global area harvested for the respective crops (as closely as possible using data at the national level), ordered by average country-level yields. Quintile yields are averages calculated from total production of the crop on the area. t/ha = tonnes per hectare.

harvests on the same plot of land) are translated into units of area. Between the quintile of countries with the highest maize yield and those with the lowest, for example, yields (in t/ha/harvest event) differ by a factor of approximately 9 (approximately 3 for rice and 4 for wheat; see figure 1) in 2007.² Yields on, in this case, cropland differ not only between, but also within countries (Monfreda et al. 2008). In terms of estimating upstream land requirements associated with traded products, this can become relevant if, for example, crops for export are produced on high-yielding productive areas whereas crops for domestic consumption are harvested from less-productive land. In this case, the use of the national average yield would lead to an overestimation of the land dedicated to production for export and an underestimation of the land required to satisfy domestic final demand.

The ecological footprint (EF) (Wackernagel and Rees 1998) is an approach to estimating upstream land requirements, which addresses different productivity levels of land by distinguishing types of land use. Land in ha of varying productivity is converted to global hectares (gha). This measure reflects the area that would be needed to produce a given harvest on land of global average productivity in a specific reference year (Kitzes et al. 2009; Wackernagel et al. 2002). The transformation from ha to gha allows for comparison of the results with the

threshold of global biocapacity. The global or national “overshoot,” that is, the extent to which resource demand exceeds potential resource supply (biocapacity), provides a strong indication of unsustainability. In order to account for the vast differences in average productivity of different land-use types, the footprint approach applies equivalence factors. These factors reflect the variation of the productivity of a given land-use type (at the global scale) from the global average productivity. Once they have been transformed to gha as a standardized measure of productivity, land areas of different quality and under different use can be aggregated (Kitzes et al. 2009). However, in expressing upstream land requirements in gha, the relationship to the land area actually available or used within each country is lost (Erb 2004; van den Bergh and Grazi 2014; van den Bergh and Verbruggen 1999). In particular, the global average productivity estimates for each land-use type cannot distinguish between the impact of natural fertility and agricultural management on yields (Wackernagel et al. 2004).

An approach that takes a different route in tackling these intricacies is the embodied human appropriation of net primary production (eHANPP) approach (Erb et al. 2009). The eHANPP concept is an extension of the human appropriation of net primary production (HANPP), an indicator of the changes in ecological energy flows associated with land use. HANPP is defined as the difference between the potential net primary production (NPP; i.e., the biomass production of green plants) of a defined land area and the amount of NPP remaining in the ecosystem after harvest. HANPP includes two separate processes: (1) alterations of NPP resulting from land use ($\text{HANPP}_{\text{luc}}$) and (2) harvest ($\text{HANPP}_{\text{harv}}$) (Haberl et al. 2007). eHANPP considers the differences in productivity potentials of land in trading countries, as well as the differences in land-use intensity across all types of land use (cropland, grazing, forestry, and built-up land) and between countries (also see the Supporting Information on the Web). eHANPP refers to the NPP of ecosystems and assesses the amount of ecological energy (or carbon) flows appropriated in providing biomass products. In contrast to land-use or footprint accounts, which are measured in area units, eHANPP is measured in t of carbon or dry-matter biomass.

A central advantage of this approach is that, whereas land can be used multiple times within a time frame for different purposes, the flow of NPP can only be used once. Further, it allows one to take differences in productivity as caused by, for example, soil quality or climate, into account. The embodied HANPP approach allocates NPP from land use to biomass products ($\text{HANPP}_{\text{harv}}$), the amount of unused extraction, as well as the productivity foregone owing to land conversions ($\text{HANPP}_{\text{luc}}$). This allows one to calculate the global HANPP associated with the consumption of biomass products in a country and contrast it with the HANPP that is associated with domestic land use (Erb et al. 2009; Haberl et al. 2012, 2009; see Kastner et al., this issue).

Upstream Land Requirements: What Do the Results Mean?

In contrast to accounts for upstream energy (e.g., Bullard and Herendeen 1975; Lenzen 1998) or emissions (see Peters et al. 2009), accounting for land requirements is a young field. A small, but growing, number of global studies has been conducted. Following up on the comparison conducted by Kastner and colleagues (2014b), examples of upstream land accounts were chosen for this review that represent biophysical accounting as well as economic modeling approaches.³ Owing to coverage by studies based on the same land-use and harvest statistics provided by the United Nations' Food and Agricultural Organization (FAO), the focus is on results for upstream requirements for cropland. In order to ensure a certain degree of comparability, neither eHANPP nor the EF were included in this review.

Biophysical Accounting Approaches

The reviewed studies based on biophysical accounting are *factor approaches*: Import and export flows (commonly in tonnes per year) are multiplied by a factor (e.g., hectare per tonne) in order to translate them into units of "embodied resource." In the case of land, the factor reflecting the (national) average land requirement per unit of product (total harvested area of product divided by total production of product) is commonly multiplied with the quantity of the product exported (e.g., Saikku et al. 2012; Würtenberger et al. 2006). Land requirements can thus be estimated based entirely on data in biophysical units. In expressing biomass trade flows in terms of their upstream land requirements, the biophysical approach allows for consideration of spatially explicit yield factors, so long as the trade data are available at a corresponding level of detail. As a prerequisite thereto, trade flows must be traced to their point of origin by correcting for re-exports: For example, to assess the land requirement of soybeans produced in Mato Grosso, shipped to Rotterdam, and imported by Austria, Brazilian, rather than Dutch, yields should be used (Kastner et al. 2011b).

The point of departure in factor approaches is that the individual traded product and total domestic land use theoretically corresponds to the summation of the land requirements of domestic production. In practice, this type of bottom-up approach faces issues of double-counting and allocation: Where one production process yields more than one product, the associated land requirements must be allocated to the co-products. This allocation can be based on the relative biophysical or economic properties of the coproducts with significant impacts on the results (see Haberl et al. 2009). For example, if both vegetable oil and cake are derived from one crop, the land requirements of that crop could be allocated to oil and cake according to their respective share in total mass, energy content, or economic value of the crop. Multiproduct production does not have to occur simultaneously: Current production may be partially based on past resource use, which must also be allocated (and depreciated). In the oil crop example, the original deforestation and conversion into cropland enabled not only the

production of crops in the first, but also in all following years. The factor approaches additionally face the challenge of system boundary definition. Points of truncation must be chosen in the supply chains for each product, whereby the analysis is limited to specific time periods, sectors, and production processes (Lenzen and Dey 2000; Suh 2004; Wiedmann 2009). For example, cropland is required in the production of vegetable oil used as industrial lubricant in agricultural machinery with which wheat for export is harvested. Truncation occurs if the oil cropland is not included in the upstream land requirements of the exported wheat. Biophysical accounts of upstream land requirements commonly allocate responsibility for land use according to relative volumes of final consumption by mass or energy content: The largest share of upstream land associated with the production of an oil crop would be allocated to that country that imports the largest share of the oil crop products for final consumption.

Economic Modeling Approaches

EEIOA is widely used in accounting for upstream resource requirements. EEIOA is a top-down approach that provides a mathematical solution to the allocation and truncation issues. Input-output tables (IOTs) of monetary flows⁴ per year are used to represent production and final demand in one economy (single-region input-output model) or in several economies or regions (multiregion input-output [MRIO] model). The IOTs are extended by data on biomass harvest or land requirements of each economic sector. Based on the IOTs, the Leontief (1970) inverse is calculated: a matrix of multipliers, which reflect the direct and indirect inputs from all other sectors required by one sector in order to produce one unit of output to final demand. By multiplying the Leontief inverse with the matrix of land requirements of each sector or product, the land use associated with monetary domestic and foreign final demand can be estimated (Bicknell et al. 1998). The upstream land requirements calculated by the EEIOA approach cover all direct and indirect inputs without truncation, so long as they occurred during the year under investigation.

In MRIO models, the country-level IOTs are linked by bilateral monetary trade data. By considering only imports for final demand, the EEIOA approach does not require additional correction for re-exports. The transformation of biomass harvest data into units of area is technically possible at the same level of detail as under biophysical accounting. The distribution of land use to final demand, however, occurs at the level of detail prescribed by the resolution of the IOTs. If only one sector is reported for all biomass extraction, as was the case in Austria until 2000 (Schaffartzik et al. 2014), then upstream requirements for all land-use types will be distributed to other sectors and final demand without distinction. Even in less highly aggregated IOTs, the allocation of upstream land requirements to traded products based on average prices may be unsuitable for product categories with very different unit prices (Weinzettel et al. 2014). Under the structure of the Global Trade Analysis Project (GTAP; see www.gtap.agecon.purdue.edu/), for example, the

Figure 2 Overview of common characteristics (reference year; land-use type, and countries) of five studies on upstream land requirements, x-y plot of results, test for positive linear correlation (R^2) of net imports in hectares per capita.

same resource intensity per unit of monetary export would be assigned to Malaysia's exports of palm oil (705 US\$/t in 2007) and cocoa butter (4,385 US\$/t in 2007) because both belong to the category of vegetable fats. Factoring in the different yields for oil palm fruit and cocoa beans and the respective commodity trees of these products, the prices can roughly be translated into 2,981 US\$/ha for palm oil and 2,056 US\$/ha for cocoa butter. Whereas it would take only 1.4 ha of cocoa bean production to obtain the same economic value as from 1 ha of palm fruit production, almost 10 ha are required to produce the same physical amount of final product (all calculations based on data from FAO [2014]; on the issue of prices, also see Liang and Zhang [2013]). This example shows that unambiguous distribution of land requirements requires a greater degree of detail in the underlying economic data than is usually available.

The allocation by monetary value under the EEIOA approach differs fundamentally from the allocation by mass in biophysical accounting. For example, in 2010, the average price of palm oil consumed domestically in Indonesia was slightly lower (by approximately 77 US\$/t) than the average price of palm oil exports (FAO 2014). Whereas the EEIOA approach would allocate the same upstream land requirement to each dollar spent on palm oil (if the IOT data were available at such a level of detail), biophysical accounting would allocate the same amount of upstream land to each t of palm oil exported. In this example, the upstream land requirements associated with

Indonesian palm oil exports would be slightly lower under a biophysical than an EEIOA approach.

Finally, the EEIOA approach is highly dependent on the quality of the monetary IOTs; flows which are misrepresented in these tables will impact the results for upstream resource requirements.

Results for Upstream Land Requirements

Of the currently available EEIOA-based studies of upstream land requirements, three were selected (Lugschitz et al. 2011; Weinzettel et al. 2013; Yu et al. 2013), which coincide in at least one land-use category (cropland or total land) with one of the biophysical accounts (Kastner et al. 2014a; Meyfroidt et al. 2010). The EEIOA studies' IOTs were all constructed using GTAP data and their land-use data stemmed from the database of the United Nations' Food and Agricultural Organization (FAO). More information on the underlying data and methods is available in the Supporting Information on the Web.

As examples for the biophysical accounting approach, the global study by Kastner and colleagues (2014a) and the 12-country study by Meyfroidt and colleagues (2010) on upstream cropland requirements were used. Additionally, a number of national or regional case studies based on the factor approach are compared in the Supporting Information on the Web. As with the EEIOA-based studies, the study by Kastner

Figure 3 Net imports of upstream cropland in hectares per capita and year (ha/cap/a) in 2004 from three different studies for a selection of countries. Negative net-import values indicate that exports are greater than imports, that the country is a net exporter of upstream cropland. Please note the difference in scaling of the y-axes.

and colleagues (2014a) corrects for re-exports by tracing trade flows to their point of origin (Kastner et al. 2014a, 2014b).

Given the fundamental conceptual differences between biophysical and economic approaches and the large differences in results for China's cropland requirements described by Kastner and colleagues (2014b), a systematic divergence in the global studies' results might have been expected. This was not confirmed by a batch comparison (see figure 2). For the year 2004, a good overall fit ($R^2 = 0.88$) was found for net cropland imports as calculated by Weinzettel and colleagues (2013) using an EEIOA approach and the biophysical account of Kastner and colleagues (2014a). The initial biophysical modelling performed by Weinzettel and colleagues (2013) prior to the allocation via the IOTs partially explains this good fit of results. For 2007, the EEIOA-based results by Yu and colleagues (2013) did not match the biophysical results well ($R^2 = 0.51$). The x-y plots included in figure 2 show that the goodness of fit was strongly influenced by a small number of outliers. For the major net exporters of cropland, for example, the results as estimated by Yu and colleagues are generally slightly higher than those presented by Weinzettel and colleagues (2013), with the exception of Australia: Here, net exports are almost twice as large under the approach by Weinzettel and colleagues. In comparing the results generated by Kastner and colleagues (2014a) with those calculated by Yu and colleagues (2013), three outliers are highly visible in the x-y plot: The net cropland imports of the United Arab Emirates are more than twice as large under the approach used by Yu and colleagues (0.8 hectares per capita [ha/cap]) than under the approach of Kastner and colleagues (0.3 ha/cap). Namibia is a strong net exporter according to Yu and colleagues (−1.4 ha/cap of net imports) and a net importer in the study by Kastner and

colleagues (0.1 ha/cap). The assessment of Australia differs again: −0.4 ha/cap of net imports (Yu et al. 2013) and −0.9 ha/cap (Kastner et al. 2014a). The results for the biophysical accounting approach applied by Meyfroidt and colleagues (2010) are similar to those generated for this small selection of 12 countries by all other approaches.

In the analysis presented in figure 2, high values of R^2 indicate strong positive linear correlation between the results, but not necessarily that the results themselves are identical. Whereas results are similar for many important biomass producers and consumers, they are diametrically opposed for China and the United States in some cases (see figures 3 and 4).

Both the biophysical and the EEIOA-based approach identify the large, biomass-extracting economies of Australia, Canada, and Brazil as net exporters of upstream cropland (represented by negative net imports in figures 3 and 4). The small, densely populated countries of the Netherlands and Singapore are net importers of cropland. Under the biophysical accounts (Kastner et al. 2014a; Meyfroidt et al. 2010), China is one of the most dominant global importers of upstream cropland. Owing to the large Chinese population, this translates into comparatively small per capita net imports. The EEIOA approaches (Weinzettel et al. 2013; Yu et al. 2013) characterize China as a net exporter of cropland (also see Kastner et al. 2014b). In theory, EEIOA applications are built on the assumption that the same price is paid for one unit of the same good or service throughout the economy (homogenous price assumption; Weisz and Duchin [2006]). In practice, this is often not the case. Chinese economic data reveal, for example, that "services of hotels and restaurants" are associated with high indirect land requirements (through monetary inputs from land-using sectors) and constitute a relevant export category (over one third

Figure 4 Net imports of upstream cropland in hectares per capita and year (ha/cap/a) in 2007 from two different studies for a selection of countries. Negative net-import values indicate that exports are greater than imports, that the country is a net exporter of upstream cropland. Please note the difference in scaling of the y-axes.

of the total monetary output generated in this sector). The latter is mainly composed of the expenditures of residents of other countries (i.e., of tourists).⁵ If tourists were to pay a higher average price for a meal (in a hotel or restaurant) than a Chinese resident, then the calculated upstream land requirement associated with that meal would be higher, regardless of the amount of resources used in its production. This example illustrates a difference in allocation logic, compared to the biophysical approach, which does not consider exports of services. Though conceptual differences between biophysical and economic approaches in the accounting for indirect land requirements may have an impact in this case, the other country results suggest that it is not systematic.

The allocation of upstream land requirements by shares in biophysical consumption produces results that are comparable to those of the allocation by shares in monetary final demand (e.g., for Brazil), results that differ but reflect a comparable tendency (e.g., for Australia), and results that reflect opposing tendencies (e.g., for China). There are also cases in which the allocation according to an economic principle produces results that are comparable to biophysical allocation, but not to another application of the economic principle: The United States, another example of a large global producer and consumer of biomass, appears as a net exporter under the biophysical account and the EEIOA approach of Yu and colleagues (2013) (see figure 4) but are a net importer according to Weinzettel and colleagues (2013) (see figure 3).

Conclusions

It cannot be expected that the distribution of monetary inputs and the composition of monetary outputs in an economy correspond to the patterns of biophysical flows and land

requirements (Hubacek and Giljum 2003). Considering the fundamental conceptual differences between the economic and the biophysical accounting approach, the degree to which results are comparable is remarkable. In their review of methods to quantify land-related leakage, Henders and Ostwald (2014) concluded that owing to limitations in the underlying data or assumptions required in the modeling process, all approaches are subject to fundamental uncertainties. All approaches additionally differ at the underlying conceptual level, especially in the principles by which they allocate responsibility for land use. Although results are often described using the same terminology and are directly compared, they must be interpreted as providing different types of information.

The two main groups of approaches that have been the object of this review, the economic and biophysical accounts, both produce results that are referred to as upstream land requirements or possibly as land footprints, embodied or virtual land. Even though they go by the same names, different studies have produced noticeably different results for these indicators (see Kastner et al. 2014b). Based on the assumption that China in 2007 could not simultaneously be a net exporter of 16.6 million hectares (Mha) of cropland (Yu et al. 2013) and a net importer of 16.5 Mha of cropland (Kastner et al. 2014a), uncertainties and errors in data and methods are being investigated. As with any new indicator (and with more established indicators, too, as the corrections to gross domestic product [GDP] show), these are necessary steps. Taking into account the conceptual differences between the approaches to calculating upstream land, it could also be beneficial to make slightly more precise statements about China's net imports of cropland:

- Assuming that each economic activity in China and in all of its trade partners produces only one specific

product that is sold at the same price throughout the production system and to different types of final demand, the monetary imports to final domestic demand in China in 2007 corresponded to monetary flows in the global production system to which a total of 25.9 Mha of cropland had been allocated. The monetary exports from China to final domestic demand in other countries in 2007 corresponded to monetary flows in the global production system to which a total of 42.5 Mha of cropland had been allocated.

- b) After correcting biophysical trade flows for re-exports by assuming no consumer preference for domestically produced or imported goods, converting traded biomass-based products into primary crop equivalents and converting the latter into associated cropland requirements, biomass-based imports for Chinese consumption in 2007 corresponded to 22.4 Mha of cropland. Biomass-based exports from Chinese cropland in 2007 corresponded to 5.9 Mha of cropland.

In thus describing the results for upstream land requirements generated by Yu and colleagues (a) and Kastner and colleagues (b), it no longer seems that the characterization of China as a net exporter by one and a net importer by the other is necessarily a contradiction.

Accounting for upstream land requirements remains a highly important, but still insufficiently understood, research challenge, perhaps even the wildest frontier of sociometabolic research that currently exists. How upstream land requirements and thus responsibility for global land use are allocated is not only a choice of method, but also a political decision with significant impacts on the results. In translating trade flows into land requirements, product-specific differences in land productivity and land-use intensity must additionally be taken into account. By considering these underlying conceptual issues, a differentiated interpretation of upstream land requirements becomes possible.

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Notes

1. In the scientific literature, upstream land requirements have also been denoted as “land footprints,” “embodied land,” and “virtual land.”

2. The year 2007 is chosen here because it is the most recent year for which the upstream land accounts presented in the following section provide results.
3. One of the economic modelling approaches contained in this review (Weinzettel et al. 2013) includes an initial biophysical accounting step, the results of which are then further allocated by means of monetary input-output tables.
4. Owing to lack of physical IOTs (Weisz and Duchin 2006), all current EEIOA approaches use monetary IOTs (Turner et al. 2007).
5. In order to ensure consistency with the system of national accounts, the system of environmental-economic accounting also applies the residence principle (also see UNSTATS 2014).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides an overview of methods to measure upstream land requirements, background information on EEIOA-based global studies, a comparison of the results of global studies, and a comparison of the results of regional and national studies.