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Surveys

# Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods

Martin Bruckner [a,b,*], Günther Fischer [c], Sylvia Tramberend [c], Stefan Giljum [a]

[a] Vienna University of Economics and Business, Vienna, Austria
[b] University of Natural Resources and Life Sciences, Vienna, Austria
[c] International Institute of Applied Systems Analysis, Laxenburg, Austria

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ABSTRACT

In an increasingly globalized world with more and more distributed international supply chains, sustainability studies and policies need to consider socioeconomic and environmental interactions between distant places. Studies of the global biomass metabolism investigate physical flows between and within nature and human systems, thus providing a useful basis for understanding the interrelatedness of changes in one place with impacts elsewhere. Various methodological approaches exist for studying the human–nature metabolism and estimating the land embodied in international trade flows, a core element of assessing telecouplings in the global land system. The results of recent studies vary widely, lacking robustness and thus hampering their application in policy making. This article provides a structured overview and comparative evaluation of existing accounting methods and models for calculating land footprints. We identify differences in available accounting methods and indicate their shortcomings, which are mainly attributable to the product and supply chain coverage and detail, and biases introduced by the use of monetary flows as a proxy for actual physical flows. We suggest options for further development of global land footprint accounting methods, particularly highlighting the advantages of hybrid accounting approaches as a framework for robust and transparent assessments of the global displacement of land use.



## 1. Introduction

In an increasingly globalized world with complex supply chains and trade relations, changes in consumption patterns or the implementation of land-related policies in one country may cause production displacement or leakage effects and thus trigger changes in land use and management elsewhere (Lambin and Meyfroidt, 2011; Meyfroidt et al., 2013). Consumers may not be aware of all direct and indirect environmental and social impacts of their consumption. For example, cumulative from 1990 to 2008, goods consumed in the European Union contributed to approximately 90,000 km$^2$ of deforestation elsewhere (EC, 2013). The sustainability of the global food, agriculture and forestry system depends both on the scale and preferences of consumer demand as well as the scale and management practices applied for the production of primary commodities, and their inter-linkages.

Trends and patterns of global biomass consumption and land use are key determinants of global sustainable development. This is particularly true for the land-intensive agriculture and forestry sector. Management and conversion of land uses affect sources and sinks of greenhouse gas emissions. The conversion of natural ecosystems for biomass production is the single most important driver of species extinction (Strassburg et al., 2010). Emerging competition for land and water from increasing global demand for food, feed and bioenergy (Smith et al., 2010) and climate change impacts challenge global food security for an expected global population of 8 to 10 billion by 2050. To meet the world's future food security and sustainability needs, food production must increase substantially while, at the same time, agriculture's environmental footprint must shrink dramatically (Foley et al., 2011). Agricultural expansion is by far the leading proximate cause of tropical deforestation (EC, 2013; Geist and Lambin, 2002; Gibbs et al., 2010; Rudel et al., 2009) endangering some of the most precious ecosystems around the globe. Against this background it becomes increasingly important to measure and monitor global land use implications of consumption patterns and associated policies.

The concepts of telecouplings (Liu et al., 2013; Liu and Yang, 2013) and land teleconnections (Güneralp et al., 2013; Haberl et al., 2009; Seto et al., 2012; Yu et al., 2013) provide an analytical framework to investigate socio-economic and environmental interactions over distances, to measure their extent, drivers and impacts and to formulate adequate responses. Measuring telecouplings challenges research and governance due to their complexity involving multiple agents acting across multiple systems at different scales and interacting via physical, monetary and information flows. Studies of the global biomass

* Corresponding author at: Welthandelsplatz 1/D4, 1020 Vienna, Austria.
*E-mail address:* martin.bruckner@wu.ac.at (M. Bruckner).

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metabolism investigate the physical flows between and within nature and human systems, tracking flows between distant places and along complex supply chains and considering environmental implications of trade-related teleconnections (Fischer-Kowalski, 1998; Haberl et al., 2009). Human–nature metabolism studies provide a useful basis for understanding the interrelatedness of changes in one place with ecological, economic, and social impacts elsewhere.

Various methodological approaches exist for studying the human–nature metabolism and estimating the land embodied in international trade flows, a core element for assessing telecouplings in the global land system. Land footprint indicators characterize land-based commodity supply chains and related land use systems from a consumer-perspective. The aim is to connect prevailing national consumption patterns with observed global land use and in further consequence to attribute associated resource uses and environmental impacts to final consumption. Area-based land footprints are currently applied in delineating the safe operating space for humanity (Rockström et al., 2009), a key component for achieving sustainable land use systems. A rapidly expanding body of literature reports area-based land footprints and virtual land embodied in trade, with varying results. Table 1 presents a selection of results from recent studies on the land footprint and virtual land import and export flows for the European Union.

Estimated cropland footprints for the European Union range between 0.25 and 0.34 ha per capita. More detailed results, for example on the cropland embodied in imports and exports, show variations by an order of magnitude. Robustness and in some cases even directionality of land footprint calculations have been contested (Kastner et al., 2014b), showing that China is alleged to be a net exporter of virtual land according to some studies while others find the country to be a major net importer of foreign land resources. In their review of accounting methods for land-related leakage and distant deforestation drivers, Henders and Ostwald (2014) conclude that all available accounting approaches involve uncertainties. Varying results and large uncertainties impede and affect decision and policy making through eroding trust in the available accounting methods.

Against this background, this article aims at providing a structured overview and comparative evaluation of existing accounting methods and models for calculating land footprints describing their methodological characteristics, comparing strengths and weaknesses and drawing conclusions on the further development needs and options of consumption-based land use accounting methods.

The article proceeds as follows. In Section 2 we introduce the concept of land footprint accounting and the main methods currently applied. Section 3 provides a structured overview of the field of research and identifies active research networks and clusters. In Sections 4 and 5 we present our findings from the detailed analysis of methodological characteristics and data sources used in the reviewed studies, first for the collection and processing of global land use data, and in the second place for tracking land flows along global supply chains. The advantages and limitations of the different methodological approaches are discussed in Section 6, followed by concluding comments in Section 7.

**Table 1**
Available results from recent land footprint studies for the European Union, in hectares per capita (LF = land footprint, IM = virtual land imports, EX = virtual land exports).

| Source | Base year | Land types | European Union | | |
|---|---|---|---|---|---|
| | | | LF | IM | EX |
| Lugschitz et al. (2011) | 2004 | Agricultural and forest areas | 1.31 | 0.93 | 0.24 |
| ibid. | | Cropland | | 0.76 | 0.08 |
| Bruckner et al. (2014) | 2007 | Agricultural and forest areas | 0.92 | 0.44 | 0.21 |
| ibid. | | Cropland | 0.34 | 0.13 | 0.02 |
| Yu et al. (2013) | 2007 | Agricultural and forest areas | 1.17 | 1.45 | 0.82 |
| ibid. | | Cropland | | 0.31 | 0.18 |
| Kastner et al. (2014a) | 2007 | Cropland | 0.25 | 0.09 | 0.02 |
| Prieler et al. (2013) | 2007 | Cropland | 0.31 | 0.14 | 0.08 |
| Bringezu et al. (2012) | 2007 | Cropland | 0.31 | | |
| van der Sleen (2009) | 2005 | Cropland | | 0.04 | 0.01 |
| von Witzke and Noleppa (2010) | 2007 | Cropland | | 0.10 | 0.03 |

## 2. General Concept and Main Methods of Land Footprint Accounting

Land footprint accounting, sometimes also referred to as global or consumption-based land use accounting follows two overarching steps: 1) observed land use is attributed to the primary producing sectors or to primary commodities, and 2) the land embodied in goods and services is tracked along global supply chains from primary production to its final use. Data used for this purpose provide information on the sources of supply (domestic production and imports) and describe the utilization of commodities in terms of exports and different domestic uses including intermediate consumption (e.g., feeding livestock) and further processing. Supply chains are either tracked up to final demand or end at a point of apparent final consumption, i.e., no further processing or utilization is specified in the data system.

An important difference between approaches is whether supply chain flows and embodied land use are tracked in terms of monetary values or physical quantities. We henceforth term approaches tracking land along monetary value chains as *environmental-economic accounting*, and approaches using physical volumes as *physical accounting*. *Hybrid accounting* uses a combination of both. An alternative nomenclature used in a review by Henders and Ostwald (2014) denotes monetary approaches as input–output analysis and physical methods as material flow analysis.

### 2.1. Environmental-Economic Accounting

Environmental-economic accounting models apply input–output (IO) analysis to track monetary transactions and embodied land flows through the economy. Input–output economics was founded by Wassily Leontief, who investigated the structure and interdependencies of an economy and its industries (Leontief, 1936, 1986). For this purpose, an economy is represented by an input–output table (IOT) comprehensively depicting all inter-industry flows (supply chains) in a specific year (see Fig. 2a). When IOTs are extended by environmental data, embodied environmental resources can be tracked from the first stage of supply chains (for example, the harvest of an agricultural product) to the stage of final consumption. This technique is called environmentally extended input–output analysis and has become an increasingly popular tool for national and international environmental assessments, driven by continuous development of data availability and computational power during the past 15 years.

Multi-regional input–output (MRIO) models link IOTs of several countries or regions via bilateral trade flows and are capable of tracking global supply chains using country specific information on production technologies and economic structures (Wiedmann, 2009; Wiedmann et al., 2011). Thus, MRIO analysis allows considering specific resource intensities across countries (Tukker et al., 2013).

### 2.2. Physical Accounting

While footprint models based on environmental-economic accounting use monetary data on economic structures and international trade for tracking natural resource inputs (such as land areas) to final use, physical accounting models represent global production chains and trade structures in physical units, e.g., tonnes of biomass, in order to track embodied land areas through international supply chains (Kastner et al., 2014a).

Physical accounting models use information on the production, imports, exports and domestic utilization of primary and processed commodities from agricultural and forestry statistics and combine this with technical knowledge on conversion efficiencies for building a consistent commodity tree structure (for a more detailed explanation, see Section 5 and Fig. 2b). Existing data sources allow tracking global supply