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Review of land flow accounting methods and recommendations for further development

by

Martin Bruckner, Stefan Giljum
Vienna University of Economics and Business

Günther Fischer, Sylvia Tramberend
International Institute of Applied Systems Analysis, Laxenburg

Vienna University of Economics and Business
Welthandelsplatz 1/D4
1020 Vienna, Austria

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Autor(en) **(Name, Vorname)**	**Bruckner, Martin** **Giljum, Stefan** **Fischer, Günther** **Tramberend, Sylvia**
Durchführende Institution **(Name, Anschrift)**	**Wirtschaftsuniversität Wien** **Welthandelsplatz 1/D4** **1020 Wien, Österreich**
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Author(s) (Family Name, First Name)	**Bruckner, Martin Giljum, Stefan Fischer, Günther Tramberend, Sylvia**
Performing Organisation (Name, Address)	**Vienna University of Economics and Business Welthandelsplatz 1/D4 1020 Vienna, Austria**
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Kurzbeschreibung

Robuste Indikatoren zur Beschreibung des Flächenfußabdrucks können eine wertvolle Ergänzung zum derzeitigen konsumbasierten Ressourcennutzungsindikator der deutschen Nachhaltigkeitsstrategie darstellen. Dieser fokussiert auf abiotische Ressourcen wie fossile Energieträger, Metalle und Bau- und Industrieminerale und schließt biotische Ressourcen dezidiert aus.

Verschiedene Ansätze und Methoden zur Quantifizierung von konsumbasierten Landnutzungsindikatoren stehen zur Verfügung. Man kann unterscheiden zwischen a) *ökonomischen Bilanzierungsansätzen*, die Input-Output-Analyse anwenden um Ressourcenflüsse entlang von Wertschöpfungsketten zu verfolgen, b) *physischen Bilanzierungsansätzen*, die produktspezifische physische Informationen über die Produktion, die Verwendung und den Handel mit land- und forstwirtschaftlichen Produkten und verarbeiteten Biomasseprodukten verwenden, und c) *hybriden Bilanzierungsansätzen*, die Elemente beider Methoden miteinander kombinieren. Die in verschiedenen Studien ermittelten Flächenfußabdrücke variieren stark, was auf mangelnde Robustheit deutet und die Anwendung solcher Berechnungen in der Politikgestaltung bisher erschwert.

Dieser Bericht bietet eine kritische Betrachtung des derzeitigen Standes der Entwicklung in der Messung von Flächenfußabdrücken. Wir identifizieren Unterschiede bei verfügbaren Bilanzierungsmethoden. Diese sind vorwiegend auf den Umfang und Detailgrad bei der Erfassung von Produkten und Wertschöpfungsketten sowie auf Verzerrungen durch die Verwendung von monetären Flüssen stellvertretend für tatsächliche physische Flüsse zurückzuführen. Wir bieten Optionen und geben klare Empfehlungen für die Weiterentwicklung von Methoden zur Bilanzierung von tatsächlichen und virtuellen globalen Biomasse- und Landflüssen. Dabei zeigen wir insbesondere die Vorteile hybrider Bilanzierungsansätze als ein robuster und transparenter Rahmen für die Berechnung von Flächenfußabdrücken auf.

Abstract

Robust land footprint indicators can potentially extend the consumption-based resource use indicator of the German sustainability strategy, which focuses on abiotic resources including fossil fuels, metals, and construction and industrial minerals and decidedly excludes biotic resources.

Various approaches exist for quantifying the land embodied in international trade flows and consumption, i.e. the land footprint. These can be classified into a) *environmental-economic accounting approaches*, applying input-output analysis and tracking supply chains in monetary values, b) *physical accounting approaches*, using an accounting framework based on data for production, trade and utilization of agricultural and forestry commodities and tracking supply chains in physical units, and c) *hybrid accounting*, combining elements from both environmental-economic and physical accounting. The results of recent studies vary widely, indicating a lack of robustness and thus hampering their application in policy making.

This report provides an in-depth review of the current state of the art in measuring 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 offer options and give clear recommendations for the further development of actual and virtual global biomass and land flow accounting methods, particularly highlighting the advantages of hybrid accounting approaches as a framework for the robust and transparent assessment of land footprints associated with global biomass flows.

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Glossary

EU-27	European Union (27 Member States)
EXIOBASE	A detailed global multi-regional environmentally extended input-output database
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Statistics Division of the FAO
GHG	Greenhouse gas
Gt	Giga tonne = 1 billion tonnes
GTAP	Global Trade Analysis Project
HANPP	Human appropriation of net primary production
IIASA	International Institute for Applied Systems Analysis
IO	Input-output
IOT	Input-output table
MRIO	Multi-regional input-output
OECD	Organisation for Economic Co-operation and Development
RMC	Raw Material Consumption
SEEA	System of Integrated Environmental-Economic Accounts
StBA	Statistisches Bundesamt (German Federal Bureau of Statistics)
SUA	Supply Utilization Accounts
UBA	Umweltbundesamt (German Federal Environment Agency)
WIOD	World Input-Output Database
WU	Wirtschaftsuniversität Wien (Vienna University of Economics and Business)

1 Introduction

In an increasingly globalized world with complex supply chains and trade relations, changes in consumption patterns or the implementation of land use policies in one country or region may cause displacement or leakage effects and thus trigger changes in land use and management elsewhere. For example, a conservation policy aiming at reducing pressure on domestic land and ecosystems may relocate land use and related environmental impacts to other world regions. Consumers may not be aware of all direct and indirect environmental and social impacts of their consumption patterns. Thus, the sustainability of the global food, agriculture and forestry system depends both on the consumer demand and preferences 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 for global sustainable development. This is particularly true for agriculture, which is facing multiple challenges threatening global food supplies, including: an increasing world population, changing eating habits, increasing demand for agro-energy and bio-materials and climate change impacts. Furthermore, increasing global demand for food, feed and bioenergy may cause land clearing of up to 1 billion hectares by 2050 (Tilman et al. 2011). This area corresponds to two thirds of the cropland currently under use. Such massive land use changes would result in annual GHG emissions of about 3 Gt of Carbon, equivalent to 20% of all current anthropogenic GHG emissions (ibid). The threat of a possible expansion of agricultural land is endangering some of the most precious ecosystems, particularly outside Europe. In this context it becomes increasingly important to measure and monitor global land use implications of consumption patterns and associated policies.

Land footprint indicators and their impact-oriented extensions intend to characterize from a consumer perspective the land-based commodity supply systems and their related land use intensities and changes. The aim is to relate prevailing national consumption patterns with observed global land use and to attribute associated resource uses and environmental impacts to final consumption.

The German Federal Environment Agency (Umweltbundesamt, UBA) has commissioned a research project in support of UBA and the German Federal Bureau of Statistics (Statistisches Bundesamt, StBA) to further develop and establish land footprint indicators for monitoring global implications of German consumption on land use and related environmental impacts. Such indicators can potentially extend the consumption-based resource use indicator of the German sustainability strategy, which focuses on abiotic resources including fossil fuels, metals, and construction and industrial minerals and decidedly excludes biotic resources. The UBA expects that such indicators would make an important contribution to the current discussion on land use in third countries.

The project therefore has the following objectives:

1. Elaborate recommendations for consumption-based land use indicators
2. Develop impact-oriented land footprint indicators
3. Calculate possible indicators for Germany

This report addresses the first aim of the project and for this purpose reviews and evaluates existing land footprint studies and land flow accounting methodologies and provides recommendations for the further development of robust consumption-based land use indicators.

Various approaches and models exist for quantifying environmental footprints of biomass consumption by estimating the virtual resources (e.g. land, water) or environmental pressures and impacts (e.g. deforestation, GHG emissions, biodiversity loss, HANPP) embodied in consumption. While area-based indicators, i.e. indicators using hectares as their accounting unit, have already been developed more than a decade ago, impact-oriented indicators have just recently been discussed in academia and policy contexts. In this report, we present a literature review of resource flow accounting methods, tracking the hectares of land from production to consumption considering land embodied in trade. Another report within this project will be dedicated to the recent developments and state of the art in the area of impact-oriented land use indicators from a consumption perspective.

The land demand estimates found in the rapidly expanding body of literature vary widely. Table 1 shows available results for the land footprint and virtual land import and export flows for the EU-27 and Germany.

Table 1: Available results from recent land footprint studies for the EU-27 and Germany, in hectares per capita (LF = Land Footprint, IM = virtual land imports, EX = virtual land exports)

Source	Base year	Land types	EU-27			Germany		
			LF	IM	EX	LF	IM	EX
Lugschitz et al. (2011)	2004	Agricultural and forest areas	1.31	0.93	0.24	1.20	1.01	0.12
ibid.		Cropland		0.76	0.08			
Bruckner et al. (2014)	2007	Agricultural and forest areas	0.92	0.44	0.21	0.81	0.62	0.14
ibid.		Cropland	0.34	0.13	0.02	0.28	0.19	0.05
Yu et al. (2013)	2007	Agricultural and forest areas	1.17	1.45	0.82	0.99	1.28	0.50
ibid.		Cropland		0.31	0.18		0.26	0.11
Kastner et al. (2014a)	2007	Cropland	0.25	0.09	0.02	0.18	0.11	0.04
Mayer et al. (2014)	2005	Agricultural areas[1]				0.23	0.17	0.13
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			

When comparing land footprint studies, it is important to be aware of the land uses considered. Agricultural areas include cropland and grassland. Some studies calculate cropland footprints only, while others include grassland and forest. When comparing cropland footprints for the EU-27 and Germany, the differences between the available studies are relatively small. Yet, more detailed results, e.g. on the cropland embodied in imports and exports, show variations by an order of magnitude. Robustness, and in some cases even directionality of the results are not yet guaranteed for land footprint calculations (Kastner et al. 2014b). However, it is not always obvious which of the methods is best suited for the estimation of national land footprints. Specific pros and cons need to be evaluated, before recommendations for further development and use in the German and European policy context can be provided.

[1] The study by Mayer et al. (2014) explicitly excludes land associated with the production of biomass for non-food use, e.g. biofuels or biomaterials. Numbers thus refer to land flows associated with foodstuff only.

Against this background, this report aims at providing a structured overview of existing approaches for estimating land footprints describing their technical and structural characteristics, comparing strengths and weaknesses and drawing conclusions on their applicability to measure a country's land demand in third countries according to the requirements of UBA and StBA.

2 Literature review

This chapter introduces the general concept of land flow accounting and outlines the available methodological options for land footprint calculations. We present the studies considered by the review of land flow accounting approaches and investigate co-authorship networks. Finally, we describe the three basic accounting methods and illustrate their major advantages and shortcomings according to a set of evaluation criteria. A summary concludes the most important conclusions from the literature review.

2.1 General concept of land flow accounting

Figure 1 illustrates the general concept of the land flow accounting methodology. In a nut-shell, land flow accounting follows two overarching steps:

1. observed land use is attributed to the primary producing sectors, and
2. the land embedded in goods and services is tracked along global supply chains through to its final use.

Data used for this purpose provide information on the sources of supply (domestic production and imports) and describe utilization in terms of exports and different domestic use categories 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 is recorded in the data system). Different accounting approaches exist for tracking the land content embodied in products.

Figure 1: General concept of land footprint methodologies

An important difference between approaches is whether supply chain flows (and embedded land uses) are tracked in terms of monetary values or physical quantities. This is on one hand because many industries involve joint production processes (e.g. crushing of soybean resulting jointly in soybean oil and soybean cake) requiring rules to attribute the land embedded in the raw material to the jointly produced commodities, and on the other hand due to the fact that land embedded in a countries domestic supply (i.e. from production and imports) has to be attributed to different utilization categories, which can be done in different ways, e.g. allocating in terms of economic values describing the different consumption categories or by applying relationships based on technical coefficients and actual physical volumes. We henceforth term approaches applying monetary values as 'environmental-economic accounting', and approaches using physical volumes as 'physical accounting'. 'Hybrid accounting' uses a combination of both aiming to overcome some specific limitations or weaknesses of the individual methods.

In this study we hence classify land flow accounting methodologies as follows:

- Environmental-economic accounting: applying environmentally-extended input-output analysis and tracking supply chains in monetary values;
- Physical accounting: using an accounting framework based on data for production, trade and utilization of agricultural and forestry commodities and tracking supply chains in physical units;
- Hybrid accounting: combining elements from both environmental-economic and physical accounting.

Environmental-economic accounting is based on statistical data compiled in national economic input-output tables (IO tables) and trade (see chapter 3.2.1 for an overview of available data sets). IO tables are available only for selected years. Economic input-output tables cover the entire economy of a country but use fairly aggregate sectors to portray agriculture and forestry.

Time-series of agricultural production data, bilateral trade statistics and overall commodity balances (Supply Utilization Accounts) compiled by the UN Food and Agriculture Organization (FAO) provide fairly detailed and comprehensive national data for physical accounting methods of the most land-intensive sectors, i.e. crop agriculture, livestock production and forestry. These global databases commonly used for respectively environmental-economic and physical accounting approaches differ in their levels of commodity detail as well as the detail and depth at which they cover the supply chains and consumption of agricultural and forestry products. FAO provide very detailed data at commodity level (both physical volumes and value estimates) but are not able to track the entire supply chains of all commodities, especially of highly processed non-food uses of agricultural raw materials.

2.2 Literature selection and researcher networks

The review of existing accounting methods covers 50 publications in the thematic area of virtual land flows and tele-connecting production and consumption. Moreover, some of the most influential papers and reports presenting recent developments in material flow accounting (material footprint / raw material equivalents) were considered. The review identified more than 20 organizations / teams working and publishing in the field of land flow accounting. Table 2 provides a detailed list of publications structured according to authors, research institutions and the applied models / methodologies (see Table 2). Descriptions of all reviewed studies and models can be found in Annex 5.1.

Please note that publications in the areas of virtual water flows, material flows, Ecological Footprint and eHANPP (embodied Human Appropriation of Net Primary Productivity), although methodologically related, have not been included in the review of physical accounting techniques. Input-output analysis (environmental-economic accounting) and hybrid methods were used only lately for the calculation of land footprints, with most publications dating to years after 2010. We therefore also reviewed a number of studies applying these methods on consumption-based indicators for biodiversity loss, deforestation, biocapacity, materials and emissions.

Table 2: Structured list of existing methods for the quantification of land footprints and related publications

Method	IO-data set[2]	Research institution(s) / model name[3]	Publications
Environ-mental-economic accounting	GTAP	Netherlands Environmental Assessment Agency (PBL)	Wilting and Vringer (2009)
		Sustainable Europe Research Institute (SERI)	Lugschitz et al. (2011), Bruckner et al. (2012a)
		Center for International Climate and Environmental Research (CICERO)‡	Karstensen et al. (2013)
		University of Maryland (UMD)	Yu et al. (2013)
		Vienna University of Economics and Business (WU)	Bruckner et al. (2014)
	WIOD	Joint Research Centre (JRC) and others[4]	Arto et al. (2012)
	OECD	Global Resource Accounting Model (GRAM)†,[5]	Bruckner et al. (2012b), Wiebe et al. (2012)
	EXIO-BASE	Netherlands Organisation for Applied Scientific Research (TNO) and others[6]	Tukker et al. (2013), Tukker et al. (2014)
	Eora	University of Sydney (USyd)‡	Lenzen et al. (2012)
Physical accounting	University of Groningen (RUG)		Gerbens-Leenes et al. (2002), Gerbens-Leenes and Nonhebel (2005), van der Sleen (2009) , Kastner et al. (2011a), Kastner et al. (2011b), Kastner et al. (2012)
	Institute of Social Ecology (SEC)		Erb (2004), Kastner et al. (2011a), Kastner et al. (2012), Kastner et al. (2014a)
	Chinese Academy of Sciences (CAS)		Qiang et al. (2013)
	Swiss Federal Institute of Technology (ETH)		Würtenberger et al. (2006)
	University of Bayreuth (UBT)		Koellner and van der Sleen (2011)

[2] We specify the used source of input-output tables and trade data for studies applying multi-regional input-output (MRIO) analysis. Please find further details on the different available data sets for the construction of MRIO models in chapter 3.2.1.

[3] Many studies have been conducted in co-operation of researchers from more than one organisation. For simplicity, we assigned each reviewed publication only to the organisation where the first author was affiliated at the time of publication. In a few cases, where the first authors were affiliated to more than one university, we list publications twice. Where available, we give the model name instead of the name of the involved research institution(s).

[4] See **http://www.wiod.org/new_site/project/participants.htm**.

[5] Developed by GWS and SERI within the petrE project, see **http://www.petre.org.uk/**.

[6] See **http://exiobase.eu/about-us/partners**.

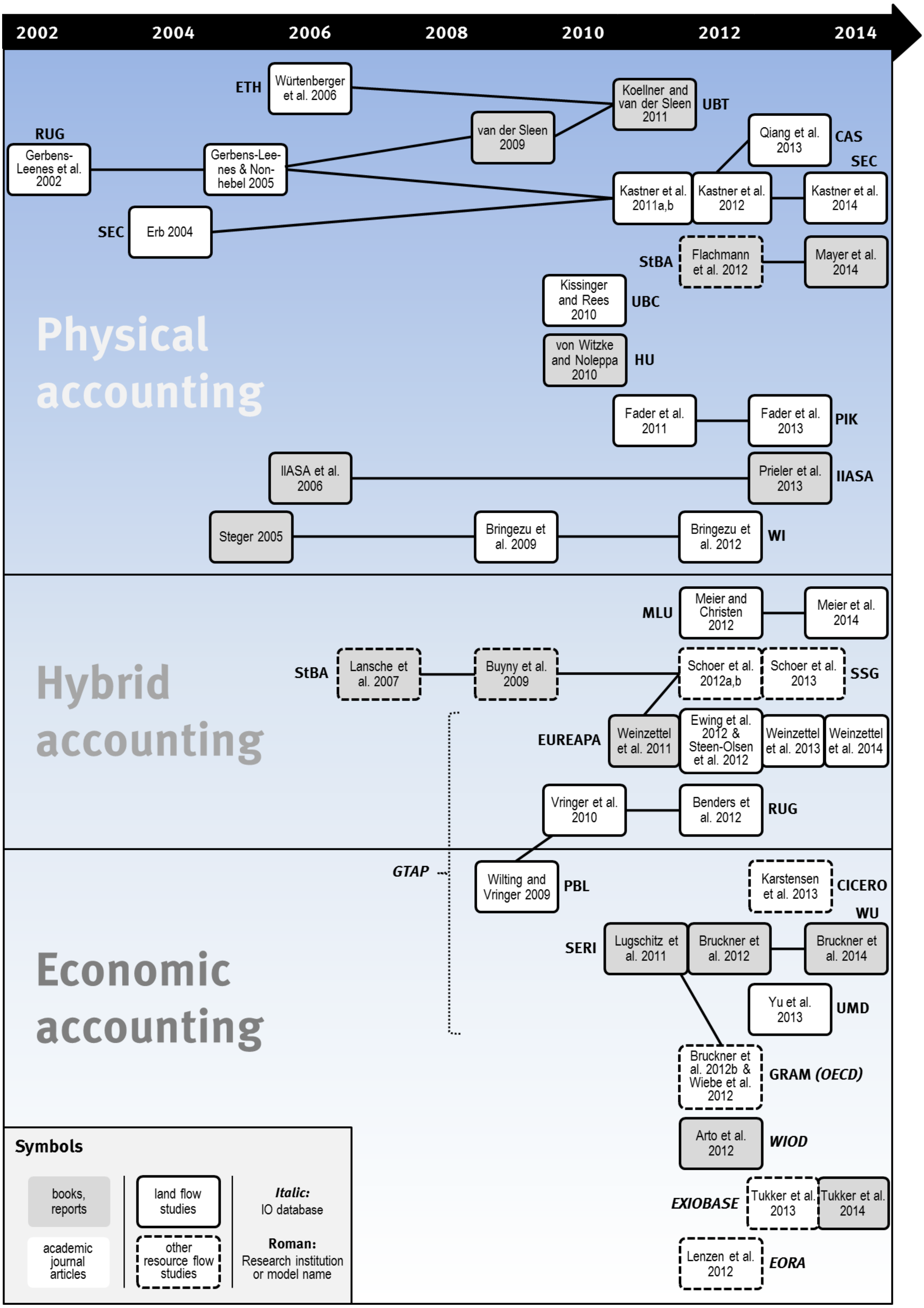
	Potsdam Institute for Climate Impact Research (PIK)		Fader et al. (2011), Fader et al. (2013)
	Humboldt University Berlin (HU)		von Witzke and Noleppa (2010)
	International Institute for Applied Systems Analysis (IIASA)		IIASA et al. (2006), Prieler et al. (2013)
	Statistisches Bundesamt (StBA)		Flachmann et al. (2012), Mayer et al. (2014)
	University of British Columbia (UBC)		Kissinger and Rees (2010)
	Wuppertal Institut (WI)		Steger (2005), Bringezu et al. (2009), Bringezu et al. (2012)
Hybrid accounting	GTAP	Netherlands Environmental Assessment Agency (PBL) / University of Groningen (RUG)	Vringer et al. (2010), Benders et al. (2012)
		EUREAPA model[7]	Weinzettel et al. (2011), Ewing et al. (2012), Steen-Olsen et al. (2012), Weinzettel et al. (2013), Weinzettel et al. (2014)
	Martin Luther University of Halle-Wittenberg (MLU)		Meier and Christen (2012), Meier et al. (2014)
	Statistisches Bundesamt (StBA)[†]		Lansche et al. (2007), Buyny et al. (2009)
	Sustainable Solutions Germany (SSG)[†]		Schoer et al. (2012a), Schoer et al. (2012b), Schoer et al. (2013)

[†] studies calculating the material footprint; [‡] studies calculating the deforestation or biodiversity footprint

The development of land flow accounting methodologies is a very dynamic and rapidly expanding field. Figure 2 shows the genesis of the field of research on global land flows using physical accounting, environmental-economic accounting, and hybrid accounting. The boxes represent publications (white boxes for peer-reviewed journal papers; grey boxes for project reports and non-scientific publications) arranged along a time line and connected via solid lines representing personal or institutional relations, indicating that one or more co-authors and / or research institutions were involved in both studies. Publications from fields other than land flow accounting (e.g. deforestation, biodiversity or material flow accounting) are framed in dashed lines. The applied IO databases are mentioned in italic letters, where applicable, while institution or model names are written in roman letters.

[7] The model was originally developed within the OPEN: EU project, see http://eureapa.org/, and is being further developed since then at Charles University in Prague (CU) in collaboration with the Norwegian University of Science and Technology (NTNU) and the Global Footprint Network (GFN).

Figure 2: Genesis of the various research strands in land flow accounting



This illustration, although not claiming to cover all available publications concerned with land flow accounting, shows that some of the first studies applying physical accounting for the calculation of land flows and land footprints were developed in the early 2000s. Pioneering Universities and research organisations were the University of Groningen (RUG), the Institute of Social Ecology (SEC), the International Institute for Applied Systems Analysis (IIASA), the Wuppertal Institute for Energy, Climate, Environment (WI), and the Swiss Federal Institute of Technology (ETH). Some years before that, Ecological Footprint studies addressed a similar research question, quantifying the biocapacity embodied in trade (Wackernagel and Rees 1996). In the last few years, the field became more diverse and vivid. Three quarter of the reviewed studies were published as from 2010. Physical accounting studies addressing land flows were published by academic and governmental organisations from the German-speaking area with only few exceptions. However, especially the field of environmental-economic accounting is more diverse in terms of nationalities.

2.3 List of evaluation criteria

A list of criteria was set up in cooperation with Umweltbundesamt and with StBA. The evaluation of existing methods and approaches for the analysis of global land flows embodied in trade was conducted in two steps.

- Step (A) comprises an evaluation regarding general methodological criteria such as scope and level of detail, as well as the transparency of the used data sources and assumptions.
- Step (B) reviews methodological details and their potential relevance for the calculation of the land footprint. This includes issues such as the consideration of multi-cropping and re-exports or the allocation procedures and assumptions applied for the modelling of global supply chains.

2.3.1 General evaluation of existing approaches

In a first evaluation step we conducted a detailed comparative analysis of the advantages and limitations of the various approaches presented in the above listed literature. The analysis is based on a set of criteria listed in Table 3.

Table 3: List of criteria considered for the general evaluation of existing land footprint approaches

Issue	Criteria
A.1) Coverage and detail	A.1.1. Level of regional coverage and detail
	A.1.2. Level of product coverage
	A.1.3. Level of product detail
	A.1.4. Land use types considered separately
	A.1.5. Categories of designated end use (food, feed, fuel, etc.)
	A.1.6. Final industrial utilization before final consumption
	A.1.7. Categories of final demand
	A.1.8. Currency
	A.1.9. Availability of time series
A.2) Compatibility with existing statistics and indicators	A.2.1. Compatibility with indicators of domestic land use
	A.2.2. Compatibility of the trade data with the system of economic accounts (special trade system)

	A.2.3. Compatibility of the agricultural statistics with the system of economic accounts
A.3) Transparency	**A.3.1. Transparency and comprehensiveness of the technical model documentation**
	A.3.2. Source, credibility and transparency of base data

B) Detailed analysis of the technical implementation

In a second step the evaluation focuses on specific technical aspects such as data sources, generation and compilation, assumptions, system boundaries, etc. that strongly affect the results gained and thus are decisive for the robustness of the results and the conclusions that can be drawn from them. The aspects considered, clustered according to the related stage of land flows (from primary production to end use), are shown in Table 4.

Table 4: List of criteria considered for the analysis of the technical implementation of existing land footprint approaches

Issue	Criteria
B.1) Land use data	**B.1.1. Consideration of multi-cropping and crop rotation practices**
	B.1.2. Source, credibility and transparency of land use data
	B.1.3. Weighting procedures deriving impact-oriented indicators
B.2) Supply chains	**B.2.1. Compilation of land use factors / coefficients for animal products**
	B.2.2. Compilation of equivalence factors / coefficients for processed products
	B.2.3. Consideration of joint products
	B.2.4. System boundaries / cut-off level
	B.2.5. Regional and temporal detail and specificity
	B.2.6. Source, credibility and transparency of base data
	B.2.7. Unit (quantities or values)
B.3) Trade flows	**B.3.1. Handling of re-exports**
	B.3.2. Source, credibility and transparency of base data
	B.3.3. Unit (quantities or values)
B.4) End use	**B.4.1. Allocation entity**

These aspects decisively determine the results gained with a specific accounting approach and thus urgently need to be considered at the interpretation and application of the derived indicators in a policy context.

2.4 Review of land flow accounting methods

In the following, we provide an overview of the three basic methodological approaches used for the calculation of land footprints: (1) environmental-economic accounting, (2) physical accounting, and (3) hybrid accounting (methods combining elements from 1 and 2). We describe the key properties, advantages and shortcomings of each of the basic methods. Detailed descriptions of all reviewed methodologies and related publications can be found in Annex 6.1.

2.4.1 Environmental-economic accounting

Environmental-economic accounting models are based on ideas defined by international organisations in the System of Integrated Environmental and Economic Accounting (SEEA; United Nations et al. 2003; United Nations et al. 2014) and apply the technique of input-output analysis to trace monetary flows through the economy. Input-output economics was founded by the Russian-American economist Wassily Leontief, who investigated how changes in one economic sector affect other sectors (Leontief 1936; Leontief 1986). Leontief was the first to use a matrix representation of a national economy, disaggregating the economic system by sectors. These so-called input-output tables represent the structure and interdependencies between different sectors of a national economy, thus comprehensively depicting all supply chains in a specific year.

Input-output models allow integrating environmental data such as land use as a production factor equal to e.g. labour or capital and tracing land flows along the monetary inter-industry flows (supply chains) represented in the IO table. This technique is called environmentally extended input-output analysis (EE-IOA) and has become an increasingly popular tool for national and international environmental assessments, driven by constantly improving data availability and computational power in the past 15 years.

A review undertaken in 2010 (Hoekstra 2010), provided a comprehensive historical analysis in the field of environmental input-output analysis. Close to 360 papers were tracked in the refereed literature between 1969 and 2010. Some important conclusions from this meta-review include the following:

- The main scientific production in the EE-IOA field occurred after 1995; just 50 out of the 360 papers were published before that date.
- Papers published before 1995 focused almost exclusively on energy use, whereas more recent studies take into account a large variety of environmental issues, including GHG emissions, water, raw materials, and land.
- About 90% of the papers focused on single countries.
- Issues related to environmental factors embodied in trade have been discussed in only a few papers before 1995, whereas the number of papers increased significantly between 2005 and 2010.

2.4.1.1 How to calculate land footprint indicators with environmental-economic accounting approaches

Input-output analysis allows tracing monetary flows and embodied environmental factors from the first stage of the supply-chain (e.g. the origin of an agricultural product) to the stage of final consumption. The Leontief Inverse, a matrix generated from the input-output table, shows for each commodity or industry represented in the model all inputs required along the whole supply chain. These inputs either stem from direct input requirements of the sector itself or indirect inputs from other sectors located upstream the supply chain. When such an input-output model is extended by environmental data, e.g. on land use, the total upstream requirements of land to satisfy final consumption of a country can be determined.

Multi-regional input-output (MRIO) models link together input-output tables of several countries or regions via bilateral trade flows. These models have the major advantage that they trace global supply chains using country specific information on production technologies and economic structures (Feng et al. 2011) and thus allow taking into account the different resource intensities (e.g. yields) in different countries (Tukker et al. 2013). The disadvantage is that MRIO systems are highly data intensive and require specific technical skills to calculate footprint-type indicators.

2.4.1.2 Key advantages of environmental-economic accounting

Input-output analysis, in particular in a multi-regional form, brings along a number of key advantages over other methodological approaches (Wiedmann et al. 2011). The main advantage of input-output models is that they allow to trace flows along increasingly complex international supply chains, as the whole global economy is included in the calculation system (Chen and Chen 2013). Input-output analysis thus avoids truncation errors often occurring in physical accounting (see below), i.e. errors resulting from the fact that the whole complexity of production chains cannot be fully analysed and certain up-stream chains have to be cut off.

Input-output models follow a top-down logic which avoids double counting. A specific land input can only be allocated once to final consumption, as all supply and use chains are completely represented (Daniels et al. 2011).

Another advantage of the input-output approach is that the accounting framework is closely linked to the internationally standardized System of Integrated Environmental and Economic Accounts (United Nations et al. 2003; United Nations et al. 2014), which ensures that, at least at the national level, a continuous process of data compilation and quality check takes place.

2.4.1.3 Key disadvantages of environmental-economic accounting

The major disadvantage of input-output analysis is the fact that most input-output models work on the level of economic sectors and product groups, assuming that each sector produces a homogenous product output (Bruckner et al. 2012b; Wiedmann et al. 2011). For the application on land footprints this implies that in one sector, a number of different products with potentially very different land use intensities are mixed together. This assumption limits the level of disaggregation that can be achieved with that approach and leads to distortions of results, for example, when crops with widely diverging mass-value-ratios are aggregated into one sector. This is the case even for the most detailed IO data sets available, where e.g. spices and fodder crops are mingled into one aggregate product group. But even for apparently homogenous products like rice, price differences by a factor of ten and more can be observed.

However, a number of recent EU research projects have been devoted to the consistent integration and / or the refinement of input-output tables and multi-regional input-output systems to calculate footprint-type indicators (Tukker and Dietzenbacher 2013; Dietzenbacher et al. 2013).[8] The intention is to create consistent systems with a higher level of disaggregation, in particular in environmentally-sensitive primary sectors, thus avoiding mistakes resulting from the high level of aggregation of the input-output tables. Also input-output systems developed outside Europe such as the Eora database (Lenzen et al. 2012; Lenzen et al. 2013) point in the same direction.

Other disadvantages that are emphasised in the literature related to footprint-type calculations based on input-output analysis are

- the large time-lag for the publication of input-output tables, in particular those harmonised for MRIO models and those tables with a high level of disaggregation: input-output tables are often published with a delay of several years, sometimes even a delay of 6-10 years;
- the high sensitivity of input-output models to relatively small errors in the trade data, in cases where imports and exports of a country are large relative to its domestic production. Relatively small errors in the estimates of imports and exports can then suddenly translate into relatively large errors in the footprint estimate (Mekonnen and Hoekstra 2011);

[8] Examples of European research projects include the 6th Framework Programme projects EXIOPOL, FORWAST and OPEN-EU, and the 7th Framework Programme projects CREEA, DESIRE and WIOD.

- the uncertainties and discussions arising from the differences between agricultural statistics and input-output statistics, with the latter reporting bigger shares of agricultural production going into manufacturing industries than the former (Kastner et al. 2014b);
- the use of monetary economic structures for the allocation of physical flows and the applied proportionality assumption, i.e. that a flow from a specific sector has the same land use intensity disregarding the receiving country and sector, may cause high discrepancies (Bruckner et al. 2012b) – it is likely that trade of western countries with high value-to-weight ratios is overestimated by such a model;
- the high sensitivity of results to potential incompatibilities of the environmental data with the economic accounts (e.g. differing system boundaries). Sector classifications often vary between countries, which cannot be fully considered in the available IO databases. Therefore, some countries for example include non-market fodder crops by estimating their economic value, while other countries do not. These inconsistencies pose problems when allocating physical flows to the monetary IO framework.

Including physical information on the detailed product level into land flow input–output models, in particular for the first steps of processing, could significantly improve the robustness of the results (Buyny et al. 2009; Weinzettel et al. 2014) and would solve many of the described problems (see section on hybrid accounting).

2.4.2 Physical accounting

While footprint models based on environmental-economic accounting use monetary data on economic structures and international trade to allocate natural resource inputs (such as land areas) to final use, physical accounting models aim at reflecting the global production and trade structures in physical units, e.g. tonnes of biomass, in order to trace embodied land areas through international supply chains.

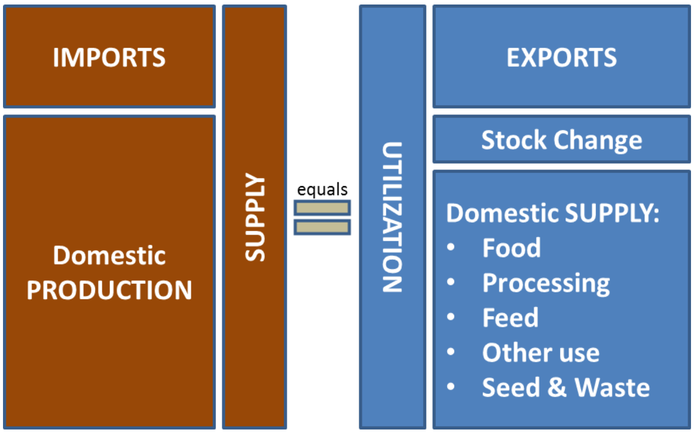
2.4.2.1 How to calculate land footprint indicators with physical accounting approaches

Physical accounting models follow a top-down framework starting from the total biomass production (and the related land areas) and allocating the physical quantities to the consuming country. The approach applies the concept of apparent consumption, where consumption is defined as domestic production + imports – exports.

Information on the supply and utilization of food products is available from agricultural statistics. FAOSTAT, the statistical service of the FAO, is the only agricultural database with global coverage. The supply utilization accounts (SUA) published by FAOSTAT provide time series data on the supply and utilization of agricultural commodities which are balanced in terms of physical quantities by matching supply (domestic production and imports) with uses (food, feed, etc.; see Figure 3). The total quantity of agricultural commodities produced in a country (i.e. domestic production) added to the total quantity imported and adjusted for any change in stocks gives the supply available during a certain period. The utilization side comprises the quantities exported, food supplies used for human consumption ('food'), fed to livestock ('feed'), further manufacturing for food use ('processing'), seed use ('seed'), industrial and other uses ('other use' or 'other utilization'), losses during storage and transportation ('waste'), and changes in stocks ('stock change').

Some physical accounting studies consider flows of unmanufactured or only slightly processed products such as soybeans and soybean cake, while others also examine more complex supply chains of highly processed food and non-food products from biotic sources.

Figure 3: Items in supply utilization accounts (SUA)



The SUA database structure of agricultural statistics is designed to cover each country's entire agricultural sector. Over 200 different primary and processed crop and livestock commodities are linked by a consistent commodity tree structure and balanced annually for each country. Intermediate or processed commodities may be included in a particular SUA commodity in their primary equivalent. For example the SUA commodity wheat includes in its supply of imports not only the import of raw wheat but also all imported wheat products converted into primary wheat equivalents.

For non-food products from biotic sources, such as wood and paper products, textiles, leather products, bio-fuels and bio-chemicals, no such information is disposable. Some studies therefore integrate additional information to capture also these products and their supply chains and use land intensity coefficients via a bottom-up approach. These land intensity coefficients inform about the supply chain wide land requirements for a certain product or activity and can be sourced from life cycle assessments.

2.4.2.2 Key advantages of physical accounting

An important advantage of physical in comparison to environmental-economic accounting is the possibility to apply mass allocation or other types of physical allocation (e.g. according to energy content), while pure environmental-economic accounting is restricted to economic allocation according to prices. This is relevant for the attribution of land to joint products such as oil and cake from soybeans, but also for unprocessed crop commodities in cases where prices of domestically used and internationally traded crops differ (Schoer et al. 2013). High-priced rice, for example, can be imported by country A, while country B rather consumes low-priced rice. Assuming that the land intensity of both types of rice measured in hectares per tonne is equal, the country importing higher-priced rice will be allocated a bigger share of the rice cultivation area than what was actually required to grow the crop. Allocation of land following physical biomass flows instead of the corresponding monetary values avoids this type of error and can therefore produce more robust results, in particular in the case of unmanufactured agricultural commodities.

Moreover, physical accounting operates on a high level of product detail and transparency and thus avoids the error resulting from the homogeneity assumption applied to only few product groups distinguished in environmental-economic accounting. For example, even the most detailed IO tables assume forages and spices to have equal value-to-weight ratios.

The top-down approach of physical accounting fully and consistently covers global biomass flows and thus avoids double counting. However, more complex supply chains are either disregarded or considered applying a bottom-up method (see disadvantage section below). Finally, this approach can also specify the main areas of use of biomass-based products, i.e. food, feed or other purposes.

2.4.2.3 Key disadvantages of physical accounting

Physical accounting models are very data intensive and require huge efforts to be implemented. This is particularly true for calculating or gathering solid land use coefficients for a large number of especially higher processed products. Physical accounting models are therefore often applied to assess the resource requirements of raw materials and basic products, but the availability of coefficients for finished products with highly complex supply chains is generally very restricted (Dittrich et al. 2012).

Physical accounting techniques also produce truncation errors, as based on the available data indirect land requirements are not traced along the entire industrial supply chains. Supply utilization accounts report all flows up to the consumer, except for industrial (non-food) uses of biomass. For the products not covered with SUAs, land intensity coefficients are often taken from various sources including life cycle assessments. Since these studies are technically detailed but rely on assumptions and data from certain representative industries the regional specificity and consistency with national and global land use statistics will usually be impaired.

2.4.3 Hybrid accounting

In the past few years, hybrid accounting became increasingly popular in footprint-type calculations. These methods combine elements from input-output analysis with physical accounting or process-based coefficients (e.g. land use coefficients from life cycle assessments) and aim at exploiting the advantages of both methods.

2.4.3.1 How to calculate land footprint indicators with hybrid accounting

Hybrid accounting methods apply a differentiated perspective to the calculation of footprint-type indicators for different products and product groups, depending on the processing stage. Typically, they apply physical accounting and process-based coefficients for raw materials and products with a low level of processing, as these data allow taking into account specific aspects with regard to different products, applied technologies and countries of origin at a very detailed product level. Processed commodities and finished goods with more complex production chains are treated with the input-output methodology, which allows considering the full upstream resource requirements and thus illustrating all indirect effects (Buyny et al. 2009; Ewing et al. 2012; Schoer et al. 2012b; Vringer et al. 2010).

This combination of different methods is realised in various ways. Some studies integrate detailed statistics in mass units into monetary input-output tables, thereby creating mixed-unit IO tables (Buyny et al. 2009; Schoer et al. 2012a; Schoer et al. 2013). Other approaches apply input-output analysis to derive land intensity coefficients for highly processed products to complement the physical land flow accounts (Meier and Christen 2012; Meier et al. 2014). A third type of hybrid accounting sets up physical accounts to model crop flows and related embodied land flows from agricultural production to the first use stage (Weinzettel et al. 2011; Ewing et al. 2012; Steen-Olsen et al. 2012; Weinzettel et al. 2013; Weinzettel et al. 2014). The resulting information, i.e. environmental extensions representing the intermediate consumption of primary products distinguished by region of origin, is then allocated to the monetary IO model, which is used to cover all supply chains from the first processing step onwards. This enables the application of a different sales structure for each primary product, irrespective of the product groups within the IO model. For example, wheat is partly allocated to the food processing sector (food use) and partly to livestock sectors (feed use).

2.4.3.2 Key advantages of hybrid approaches

The key advantage of the hybrid approach is that the applied detailed physical data allow compensating the disadvantages normally faced with input-output analysis, in particular the problems of aggregation and economic allocation. This especially enhances the assessment of products with a low level of manufacturing (Schaffartzik et al. 2009; Schoer et al. 2012a; Wiedmann 2011). Food products typically undergo only a few processing steps, thus, this type of models is particularly relevant for the case of land flow accounting. At the same time, the above-mentioned advantages of input-output analysis, in particular regarding the full reflection of all supply chains, are kept for products with a higher level of manufacturing. Therefore, hybrid approaches are most promising for the analysis of land flows embodied in non-food land-based products such as textiles, leather, paper and wood products, biofuels, cosmetics, pharmaceuticals, and lubricants.

2.4.3.3 Key disadvantages of hybrid approaches

Some of the disadvantages described for the two basic approaches also apply for hybrid approaches. These include the time lag to publication of input-output tables and the low sector detail, albeit applied only to upstream flows of higher processed products. Furthermore, comparability of results generated with existing hybrid approaches is low as the various models apply different types of hybridisation as briefly described above.

2.4.4 Conclusions from the review

The review clearly revealed some general differences between environmental-economic, physical and hybrid accounting approaches and their specific advantages and shortcomings. The differences are summarized in Table 5 below.

Table 5: Summary of main characteristics of available land flow accounting methodologies

Criterion	Environmental-economic accounting	Physical accounting	Hybrid accounting
Level of commodity detail	- aggregate sectors with limited commodity detail	+ high level of detail for primary and processed crop and livestock products	+ high level of detail possible
Land attribution	- attribution of land to aggregate monetary production data can be problematic	+ specific allocation of land to biomass production according to actual yields	+ allocation of land to biomass production; extension of supply chains with monetary flows at higher stages of processing
Supply chain coverage	+ full coverage of all supply chains; however, sometimes representing only marketed production	- partly incomplete supply chains, especially for flows at high stages of processing	+ potentially covering all supply chains
Allocation logic	- land is allocated according to monetary flows, leading to potential errors due to different value-to-	+ land is allocated according to physical flows, thus avoiding distortions by inhomogeneous prices[10]	+ economic and / or physical allocation

	weight ratios for the same products[9]		
Reliability of source data	- reliability of IO data varies across available sources, geographical regions and different sectors	- reliability of international agricultural statistics for production, land use and trade varies across geographical regions and for different data sources	- see environmental-economic and physical accounting methods
Regional specificity	+ country level	+ country level	+ country level
Consistency with aggregate global land use statistics	+ consistency of input data is fully maintained	+ consistency of input data is fully maintained	+ consistency of input data is fully maintained

Environmental-economic accounting, represented by (multi-regional) input-output analysis, stands out with its comprehensive coverage of the full (global) economy, thus all indirect effects are covered, independently of the complexity of supply chains. IO models therefore avoid truncation errors, as per definition all products, including highly-processed biomass-based products are being considered by the calculations. In addition, all IO models fully consider re-exports, based on the assumption that exports are a weighted mix of imports and domestic production. Major disadvantages include the limited commodity detail determined by the sector definitions of each IO model as well as problems related to the allocation of land flows following monetary structures. Furthermore, only a few countries' IO tables include estimates of the agricultural and forestry production which is not traded on markets (e.g. wood fuel harvested or vegetables grown for subsistence use).

A major advantage of **physical accounting** is the high level of commodity detail, which allows a more detailed and consistent allocation of land to harvested biomass. The aggregation to only few highly inhomogeneous product groups in environmental-economic accounting and inconsistencies between economic and agricultural statistics can lead to significant distortions of results. Physical accounting approaches are also superior regarding the geographical coverage and detail, the level of detail on products and land use types, timeliness of the calculations and (potential) availability of time series. Furthermore, only very few existing models are able to distinguish different categories of end use, such as food, feed, fuel, textiles or cosmetics. If any, only physical accounting approaches seem to attain this detail of results. Finally, physical accounting offers the possibility to apply physical allocation logic, while environmental-economic accounting is restricted to economic allocation.

To illustrate this difference, let us take the example of a country producing a crop, say rice, of varying quality but uniform yield. Furthermore, let the country selectively export the better (i.e. higher priced) quality and use the lesser quality rice for domestic consumption. In this case, environmental-economic accounting methods will attribute a larger share of the rice cultivation area to the import-

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10 Physical allocation tracks land use in physical supply chains and thus follows the physical commodity flows (in tons).

9 Economic allocation tracks land use in economic supply chains and thus follows the monetary flows (e.g. in Dollar or Euro) of commodities / sectors.

ing country than was actually used for production. In this example, land attribution according to physical flows will produce more realistic and robust results.

However, data availability clearly limits the applicability of physical accounting. Take the example of a cotton producing country where cotton lint is processed by domestic textile industries and textiles are then exported overseas. The physical accounting based on available statistics would reliably estimate the land content of the produced textiles but would attribute the respective cotton area to the country of origin rather than to consumption in the countries where the textiles are received simply because processed textiles are not recorded in the FAOSTAT system. In this case an environmental-economic accounting method of the textile sector should be applied to extend the representation of the supply chain for cotton products.

Finally, physical accounting often uses land intensity coefficients based on various sources including life cycle assessments. Since these studies are technically detailed but rely on assumptions and data from certain representative industries the regional specificity and consistency with national and global land use statistics will usually be impaired.

As Table 5 suggests, **hybrid approaches**, building on the available data and methods, have the potential to exploit the specific advantages of the physical and environmental-economic accounting methods and can thereby overcome some of the underlying limitations and weaknesses.

Domestic technology assumption

The evaluation results as summarised above assume that all approaches apply a global multi-region accounting framework using country-specific supply chain information and agricultural statistics. It is also worth noting that the different approaches can also be applied under a “domestic technology assumption”, i.e. assuming that imported goods are produced with the same economic structures, processing efficiencies and crop yields (same land use intensities) as domestic production. In the case of using the domestic technology assumption, data availability and reliability can be expected to be better than for global databases, as national statistical data (e.g. German agricultural production statistics) can be used.

However, this simplifying assumption is hard to defend as it can lead to significant errors in cases where land intensities per tonne or per Euro of product vary widely across countries and regions. For example, wheat yields for the year 2007 vary between more than eight tonnes per hectare in Ireland and New Zealand and less than one tonne per hectare in some African and Latin American countries (FAOSTAT 2015). Even within the EU-27, wheat yields between less than two tonnes (Romania) and more than eight tonnes (Ireland) per hectare can be observed with an average of almost five tonnes per hectare. Therefore, results generated with a simplified national model will not reflect the reality of the global production-trade system and will therefore be inconsistent with land use statistics when aggregated to the global level.

However, it should also be mentioned that the use of international statistics may lead to the propagation of potential errors, which can be expected especially in the data reported by developing countries (George and Nachtergaele 2002).

3 Analysis and recommendations

In this chapter we provide a comparative analysis of the various methodological and data options for land footprint calculations, discussing key aspects of the calculation procedures with significant impacts on the overall result. The numerous aspects are discussed as part of the two overarching steps in the calculation: first, how land areas are attributed to primary production and second, how embodied land is tracked along global supply chains. Recommendations regarding the best available options are provided for both calculation steps.

3.1 Land attribution to primary production

Tracking land along global supply chains starts from the primary production in the countries of origin. Thus, global land use data and land intensities of primary commodities, i.e. the extents of the total physical land in the agricultural and forestry systems of each country as required to produce a commodity, are key inputs for tracking land along supply chains. Since land intensities (yields) among crops and across countries vary widely, it is essential for land accounting to retain, to the extent possible, both the commodity and geographical details of the supply chains. The same applies to wood and livestock products, in particular for grassland productivity and resulting land intensity of ruminant livestock herds.

Yet, despite the wealth of data and statistics available, the integration of land data into the socio-environmental-economic accounting framework remains a major challenge (Erb et al. 2007), particularly for environmental-economic accounting methods. Land use information can be inferred from land cover data only to a limited extent, as no unambiguous correlation between land use and land cover can be observed. Furthermore, national land use statistics refer to land use but may not coincide with the actual geography of countries due to reporting inconsistencies. In the following, we describe data sources and specific shortcomings for different land use types.

3.1.1 Types of land use

The agriculture and forestry sectors are the largest users of land. Other sectors such as mining, manufacturing or transport may result in large environmental impacts but they require much less physical land for their production activities, albeit with largely irreversible consequences for the land. Agriculture utilizes arable land for the production of food, feed and fibre from annual crops, keeps land under permanent crops and uses grassland and permanent pastures for grazing and producing feed for ruminant livestock herds. Forests are used for the harvest of industrial roundwood and for wood fuel collection.

The Food and Agriculture Organization of the United Nations (FAO) compiles various annual agricultural land use and production statistics (FAOSTAT 2015). This database contains data on agricultural areas and yields for around 180 crops and is the only available land use database with global coverage. The data are collected from FAO member nations primarily based on questionnaires. Although these data may involve problems due to intentional over- or underreporting or problems owed to a lack of resources and survey capacities, especially in developing countries (Ramankutty 2004), FAO is regarded as an authoritative source for agricultural data and indeed, is the only source available for large-scale global studies related to biomass and land. The FAO online database[11] contains annual agricultural statistics from 1961 to t-2 (i.e. 2012, as of 2014). Printed statistics are available also for earlier years. In 2011, global cropland amounted to 1550 million hectares (Mha) (of which 1396 Mha was arable land and 154 Mha was land under permanent crops) and was distributed over the world's favourable climatic zones and most fertile soils. Permanent pastures and forests covered respectively 3356 Mha and 4027 Mha (FAOSTAT 2015).

There are many potential problems associated with the interpretation of FAO cropland statistics (Ramankutty 2004). Member nations are asked to report harvested areas, which exclude both non-cropped arable land and cropped but not harvested areas (e.g. due to flooding or draught losses). Temporary grassland and fallow land are not reported by all member nations and seem to vary widely in their proportional extent. Small-scale subsistence agriculture is sometimes not accounted for. Correct reporting of intercropping, i.e. crops that are interplanted with others, poses a challenge to the national reporting authorities. Reported extents of grassland and forests are often even less reliable compared to cropland area statistics due to various reasons including differences in definitions

11 See **http://faostat.fao.org**.

across countries. Also, grassland and forest ecosystems cover a very wide range of land productivity, from conditions in sparsely vegetated semi-arid climates to tropical forests with very high productivities. In addition, area extents of current actually used grass- and forest lands are not or incompletely reported in the available global databases.

To account for these differences in accuracy, sharpness and availability of land data and to improve the interpretation of results, it is strongly recommended to calculate land footprints separately for cropland, grassland and forests.

Recommendations

- **Distinguish land use types: It is strongly recommended to calculate land footprints separately for cropland, grassland and forest land in order to account for differences in accuracy, sharpness and availability of land use data by broad primary sectors (crops, livestock, and wood production) and to facilitate better impact oriented interpretation of the results.**
- **Global agricultural and forestry statistics: The Food and Agriculture Organization (FAO) of the United Nations compiles national statistical data and is the only available consistent global dataset on land use and agricultural and forestry production and thus the only available source for large-scale global studies related to biomass production and land use. We recommend using these publicly available country-level, time series databases for the agricultural and forestry sector in land footprint accounting. Whenever possible, data from national statistical sources can be used to extend or replace international statistics.**

3.1.2 Cropland use

Interpretation problems of cropland statistics arise from crop rotations that happen within a single year (multi-cropping). Multi-cropping is an important issue in countries such as Bangladesh, where farmers often reap two or more harvests per year. Yields of 6 tons of rice per harvested hectare thus could actually conceal real annual yields of 12 or 18 tons per physical hectare. Bruckner et al. (2012a), IIASA et al. (2006) and Prieler et al. (2013) adjust land use data for multi-cropping by scaling down harvested areas to the physical areas, in cases where multi-cropping practices increase harvested areas above the level of physical (actual) cropland areas. In the case of Bangladesh, for example, applying this procedure increases all yields of temporary crops by about 60%, thus implying that each physical hectare is harvested 1.6 times a year. This approach can be considered conservative and will still underestimate the actual yields for many countries.

Furthermore, economic activities might not only depend on the land areas they directly use. One can argue that fallow land, although it is out of production and thus out of use for a certain period, forms part of the agricultural production system as fallow periods are a necessary element in many traditional crop rotation systems. Therefore, fallow land should be added to cropland for the correct representation of land resources required for crop production.

Some national statistical institutes provide cropland statistics of good quality, but the use for global analyses is limited, as only cropland inventories of one or a few countries are depicted. FAOSTAT as well as most national statistics report physical cropland areas (usually separately for arable land and land under permanent crops) as well as sown or harvested areas of individual crops. The multi-cropping index (MCI) is a commonly used measure of cropping intensity. Multiple use of physical land can be calculated as the ratio of the sum of harvested areas of all individual crops and the physical cropland area. This measure of multiple use of cropland varies considerably across countries and has been increasing at the global level from 0.90 in 2000 to 0.97 in 2011 (FAOSTAT 2015), which reflects an intensification trend of agricultural production systems and indicates rising land productivity.

To reflect these obvious differences between physical cropland used in agriculture and reported harvested areas, and between cultivation cycles of annual and perennial crops, we recommend accounting for multi-cropping and fallow periods when attributing physical cropland to primary crop production. From the literature considered in this report, Bruckner et al. (2012a), IIASA et al. (2006) and (Prieler et al. 2013) go beyond harvested areas as basis for the calculation of land intensities and also account for multi-cropping and fallow periods.

Land intensities differ between annual crops and permanent crops in accordance with their agronomic characteristics. Perennial crops include for example orchards, vineyards, olive groves and oil palm, coffee, tea and natural rubber. These crops occupy the land for long periods and reported harvested areas refer to the annual production cycle. Annual crops are sown each year and in sub-humid and humid conditions of the sub-tropical and tropical regions two or three rain-fed crops per year are possible. In the case of Bangladesh, for example, a MCI of 1.6 was determined, implying that each physical hectare is harvested 1.6 times within a year on average.

For the purpose of cropland attribution to primary crops, FAO data permit computing average land intensities in each country separately for annual crops and permanent crops. Applying these factors evenly to the harvested areas of individual crops of each group ensures that all cropland is attributed to the primary production and the attribution respects agronomic knowledge and practice in each country.

Recommendations

- **Country- and crop-specific yields: Since yields (land intensities) among crops and across countries vary widely, robust and consistent accounting of land flows requires using country and crop specific technology and land use information. It is therefore essential for land flow accounting to retain in the tracking procedures both the commodity and geographical details of land-based production and commodity flows and avoid aggregation at an early stage in the supply chain to the extent possible.**
- **Multi-cropping and fallow: Account for multi-cropping and fallow periods when attributing physical cropland to primary crop production. Calculate average multi-cropping intensities, separately for annual and perennial crops, across all crops cultivated in a country and apply respective intensities to harvested areas of individual crops to estimate physical land associated with production.**

3.1.3 Use of grassland and forests

While reported cropland areas can be considered as being fully utilized by the agricultural systems for accomplishing the reported annual crop production volumes, the grassland and forest area statistics are usually less detailed and incomplete regarding the extent of areas, which are actually utilized for rearing livestock or for wood harvesting.

FAOSTAT land use data report grassland and forests defined as follows (FAOSTAT 2015):

- Permanent meadows and pastures is the land used permanently (five years or more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land).
- Forest area is the land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. Forest is determined both by the presence of trees and the absence of other predominant land uses.

Lacking data on actual use of grassland and forest land, land footprint methodologies have often assumed reported grassland and forest land areas as the underlying physical land base required for the production of the primary produce. However, such simple approaches overestimate land requirements and disregard differences in land productivity of used versus unused grass- and forest land. Therefore, more refined estimation methods are needed.

3.1.3.1 Grassland

There is a lack of reliable data on the extent of land used for grazing. This has mainly two reasons. On the one hand, remote sensing data provide only a poor basis for the establishment of grazing data, due to the physical heterogeneity of grazing areas (Erb et al. 2007; Harris 2000). On the other hand, irregularities in available census data (Asner et al. 2004) point to discrepancies in statistical reporting. Large uncertainties in the FAO data on pasture land result from inconsistent definitions of this land use category across countries. Statistics do not correspond with real grazing areas. The case of Saudi Arabia, where about 80% of the land surface is reported to be permanent pastures (see FAOSTAT 2015), underpins the problem. This can result in large differences between countries in the derived grazing areas per animal and may have considerable effects on the results.

Grazing areas constitute the largest fraction of global human land appropriation and its expansion is a major driver of deforestation in the tropics, highlighting the importance of overcoming these obstacles. One way to overcome them is to estimate grassland use by calculating the grass demand (in tonnes) of the reported livestock herd (Krausmann et al. 2008) and deriving the respective grassland areas based on global grassland productivities obtained, e.g., from the detailed grid-cell based biogeographical GAEZ model (Global Agro-Ecological Zoning, IIASA/FAO 2012).

3.1.3.2 Forest areas

A differentiation between managed forest land, which is harvested for wood fuel or timber and undisturbed natural forests is not trivial. Forest statistics show the area covered by trees and almost never separately report actually productive or harvested areas[12].

Many studies such as Bringezu et al. (2012), Bruckner et al. (2012a), Erb (2004), and Prieler et al. (2013) therefore adopt a sustainable yield approach calculating the forest area required to harvest the reported timber production according to the net annual increment of forests in the country of origin, i.e. assuming that each year the increment is harvested and stocks remain constant. This can be done based on productivity estimates from physical models such as GAEZ (IIASA/FAO 2012), or based on increment rates reported by the FAO Forest Resource Assessment (FRA, see FAO 2010).

3.1.3.3 Unit of measurement

While estimates of grassland and forestland used for production bear substantial uncertainties, wood production statistics report the volumes harvested for each country and various calculation schemes provide rather reliable estimates of grazing volumes. Some experts therefore suggest increasing robustness by using mass units instead of area units for the measurement of the grazing and forestry footprint. Also from an environmental point of view production volumes may be a better measure than production areas. A certain amount of wood, for example, can be produced from one hectare by clear-cutting or from 100 hectares taking the annual regrowth only. The environmental impacts per hectare obviously vary substantially in these two cases while the environmental impact per tonne can be expected to be more similar.

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[12] The TBFRA-2000 report on "Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand" (UNECE/FAO 2000) includes estimates for actual forest lands available for wood supply. In contrast to the FAOSTAT database TBFRA-2000 data is available for selected countries and for the year 2000 only.

Recommendations

- **Grassland and forestry data: For countries where no reliable data are available, grassland and forest land actually used for livestock and wood production should be estimated rather than assuming all reported grassland and forest land as being part of the production cycle. For instance, regional data or model-based simulations of grassland productivity, net annual forest increments, etc. together with estimated livestock feed balances and reported timber harvests can be used to fill information gaps needed for enhancing estimates of forest and grassland utilization of livestock and wood production.**
- **Country-specific land intensities of animal and wood products: Realistic and consistent accounting of land actually embedded in the consumption and trade of ruminant livestock products and forestry products requires using country-specific technology and land use information (i.e. country-specific livestock herds, feeding practices, timber harvesting).**
- **Land or material footprint: Due to data uncertainties the possibilities to calculate a robust land footprint indicator for pastures and forests is limited. We therefore propose alternatively using weight units instead of area units for the measurement of the grazing and forestry footprint, i.e. calculating the material footprint instead of the land footprint.**

3.1.4 Consistency with the System of National Accounts

According to the current standards and guidelines, both National Accounts (as the source of IO tables) and land use statistics capture all market activities as well as non-commercial or non-market production such as kitchen garden production and all kinds of subsistence agriculture. The share of non-market activities can be particularly high for land-based parts of the economy. In some countries subsistence agriculture and forestry cover large parts of the provision of food and wood. The consistency between these two statistical sources cannot be ensured, especially for developing countries. Thus, accounting methods that directly combine IO tables and land use statistics (i.e. environmental-economic accounting approaches) could substantially under- or overestimate virtual land flows.

Recommendations

- **Physical data for first stages of supply chain: Errors resulting from inconsistencies between National Accounts and land use statistics can only be avoided applying physical or hybrid accounting methods. A physical accounting approach based on detailed commodity production and trade data should therefore be used for the first stages of the supply chains. When industrial uses cannot be tracked further by the physical accounting methods due to data limitations, environmental-economic accounting of flows from these sectors based on monetary IO tables should be applied to extend those supply chains to final consumption (i.e. hybrid approach).**

3.2 Tracking land flows along global supply chains

IO tables depict the inter-sectoral flows within and between economies. Based on these data, all global supply chains can be traced. Physical accounting models are based on production and trade statistics reporting quantities such as FAOSTAT; yet, consistent statistics comprising physical data on inter-sectoral flows are lacking. Therefore, physical accounting approaches either use land intensity coefficients for processed products or they convert these products into their raw material equivalents for which land intensity coefficients (yields) are available from statistical sources (see chapter 2 above).

3.2.1 Overview of sources for supply chain data

Table 6 shows the main characteristics of the currently available datasets used for environmental-economic and physical accounting of global resource flows along supply chains. It includes all currently available and expected multi-regional input-output databases (namely Eurostat, EXIOBASE, WIOD, OECD, GTAP and Eora) contrasted with FAOSTAT, which is the most widely used data source for physical land accounting models. The table provides a comprehensive and compact overview on the available data sources and their limitations for the application in land flow accounting.

Table 6: Global data sets for the construction of land flow accounting models[13]

	Eurostat	EXIOBASE	WIOD	OECD	GTAP	Eora	FAOSTAT
Regions	28 EU countries, Norway, candidate countries, EU aggregate	44 + 5 RoW	27 EU countries, 13 other major economies + RoW	48 countries (all OECD countries and other major economies)	108 + 21 RoW (less detail in earlier versions)	189	239 UN member countries
Agricultural & forestry sectors	2	17	1	1	13	1-17	~200c
Food / non-food biomass processing sectors	5	10 / 10	1 / 4	1 / 3	8 / 5	~1-40	~100c
Total number of sectors	60i	200c, 163i	35i	36i	57c	20-500c/i	~300c
Time series	for most countries 2008, 2009	1995-2011	1995-2011	1995, 2000, 2005	1997, 2001, 2004, 2007	1990-2011	1961-2011
Update frequency	SUTs annually, IOTs every five years	unknown	unknown	5 year steps, time lag 5 years	3 year steps, time lag 5 years	unknown	annually, time lag 2 years
Units	values	values	values	values	values	values	quantities, values
Sector classification & technology assumption	i x i	i x i with FPA; c x c with ITA	i x i with FPA	i x i with FPA	mixed	mixed	n.a.
Type of data source	official EU statistics	academics	academics	official OECD statistics	academics	academics	official UN statistics
Availability	free	free	free	free	$215-$5,550	free (CC)	free

13 Note: i = industries, c = commodities, FPA = fixed product sales structure assumption, ITA = industry technology assumption.

As illustrated in Table 6, the different data sets have complementary strengths. Eurostat's IO database is an official statistical database available for Europe, but has its deficits in particular in terms of sectoral disaggregation and does not include data for non-EU countries, thus only capturing a fraction of the global economy. GTAP has its major strength in the number of countries and the disaggregation of a large number of sectors in the agricultural and food production areas, while not providing fully transparent documentation. WIOD and OECD have the closest link to national statistics and the least degree of data manipulation. However, sector detail is lowest for these two databases. EXIOBASE has its main advantage in providing a high sectoral detail, but is so far only available for the years 2000 and 2007, with differing sector classification, and is lacking transparent and comprehensive documentation. The largest number of countries and a long time series is provided by the Eora system, which also provides long-time series data, but involves significant modelling to generate data. Moreover, sector detail is low for the globally consistent version of Eora (26 sectors) and varying for the full version (between 20 and 500 sectors).

Yet, land footprint calculations based on global IO datasets have been contested for quality issues. A recently published paper discusses some implausibilities of land footprint calculations for China based on MRIO analysis (Kastner et al. 2014b). Physical accounting approaches revealed significant net imports of embodied land (Qiang et al. 2013), while MRIO-based calculations show net exports (Weinzettel et al. 2013; Yu et al. 2013). This effect might be partly explained through distortions introduced by the assumption for constructing the IO tables (e.g. industry technology versus product technology assumption, see chapter 3.2.1.1). It may also be a result of the significant uncertainties related to the data and assumptions applied for the construction of harmonised IO data sets, which often try to increase the sector detail far beyond that of data from official statistical sources. Both MRIO studies considered in the comparison by Kastner et al. (2014b) use GTAP, which effectively shows significant intermediate flows of about 20% of agricultural outputs (even higher for animal products) to various manufacturing industries, while according to FAO statistics only about 10% of all agricultural commodities used in China are utilised for non-food purposes (Narayanan et al. 2012; FAOSTAT 2015). In a MRIO framework, large countries have a relatively big influence on the overall results. Assuming that the IO table for China used in the GTAP database might contain errors, e.g. stemming from a lack of information for the disaggregation of sectors, this could eventually explain the effect revealed by Kastner and colleagues.

FAO provides one of the most comprehensive sets of global agricultural and forestry statistics. These are collected through annual questionnaires, national / international publications, and information gathered during country visits or provided by the local FAO representatives. The FAO's supply utilization accounts (SUA), described in chapter 2.4.2, provide statistics on the supply and utilization of over 200 different primary and processed crop and livestock commodities and are linked by a consistent commodity tree structure representing physical supply chains. However, for non-food products from biotic sources, such as wood and paper products, textiles, leather products, bio-fuels and bio-chemicals, no such information is disposable.

FAO acknowledges several shortcomings of the data it receives. Notably, these include data gaps and incomplete reporting by countries, sometimes questionable reliability and inconsistent definitions (George and Nachtergaele 2002). The Statistics Division of the FAO endeavours to overcome these shortcomings. Most uncertainties are expected for some developing countries, while for developed countries the overall picture can be regarded as reliable (see George and Nachtergaele 2002).

All available data sources lack detail in distinguishing different modes of production such as integrated production (Boller et al. 2004) or organic agriculture (Willer et al. 2008).

3.2.1.1 Assumptions for the construction of Input-Output Tables

In most cases, input-output tables (IOTs) are derived from supply-use tables (SUTs). Different assumptions for constructing IOTs from SUTs can be applied. For industry-by-industry tables, the most prominent assumptions are:

a) The **industry technology assumption** (ITA), on the one hand, assumes the same input structure for each product being produced by a specific industry. For example, radios and TVs, are produced by NACE sector 26.4 (Manufacture of consumer electronics).[14] Although different raw materials and technologies are used to manufacture a radio or a TV, the ITA would assume equal inputs for the two production processes.
b) The **product technology assumption** (PTA), on the other hand, assumes that a product has the same input structure in whichever industry it is produced. For example, a specific electronic appliance will be regarded equal, albeit produced by NACE sector 26 (Manufacture of computer, electronic and optical products) or by sector 27 (Manufacture of electrical equipment).

The choice of a specific technology assumption might significantly influence the land footprint results generated with an IO model. For instance, when farmers produce not only agricultural products but also manufacturing goods or certain services, as it is the case to varying extents all over the world (say, for example, farm holidays), an IOT derived using the ITA, which is probably the most widely used assumption for constructing product-by-products IOTs, would allocate agricultural products as an intermediary input to the production of these services and manufacturing goods. In other words, the tourism services offered by the farm eventually appear to require substantial amounts of cereals, vegetables or raw milk in their production processes. Moreover, the exports of these goods and services may as a consequence incorrectly shift land use to a third country. This error is of course most relevant for regions where farmers traditionally generate a significant share of their income producing manufactured goods and services.

The application of the PTA would avoid the problems related with the described example, as farm holidays would be considered to have the same input structure as hotels and other businesses in the tourism sector. However, if input-output analysis is only applied for non-food products as part of a hybrid accounting approach, as proposed above, the effect will be less important than in the case of pure environmental-economic accounting.

ITA can be implemented straight-forward and is only producing non-negative values, which is a precondition for a meaningful economic interpretation, while PTA may produce negative values which need to be dealt with separately, e.g. applying the approach presented by Almon (2000). This procedure is technically more elaborate and has not yet been applied to global IO datasets (as shown in Table 6).

Recommendations

- **Physical rather than monetary databases: On the one hand, detailed IO data sets such as GTAP and EXIOBASE struggle with uncertainties related to the data and assumptions applied in the disaggregation procedures. For more aggregate IO data sets such as Eurostat, WIOD, OECD and Eora, on the other hand, the homogeneity assumption for product groups is considered to produce significant errors, particularly for the case of agricultural commodities and related land flows. Therefore, given the current data situation we recommend applying a detailed physical attribution scheme for tracking land flows along the supply chains based on FAOSTAT to the extent possible. In other words, detailed commodity flows should be tracked via their**

[14] NACE is the statistical classification of economic activities in the European Community, see http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-RA-07-015/EN/KS-RA-07-015-EN.PDF.

Recommendations

physical quantities (tonnes) and associated land areas should be attributed in proportion to physical volumes.

- **Choice of IO data set: For studies using monetary IO data, i.e. economic or hybrid accounting studies, the selection of the database should consider the respective strengths of the databases, e.g. sector detail for EXIOBASE, country detail for Eora and GTAP, and the use of only marginally manipulated data from official sources for Eurostat, WIOD, OECD and Eora. The selection of one of these databases should balance pros and cons in the light of a particular research question or policy issue.**
- **Further disaggregation of IO tables: Disaggregation of IO tables has only limited benefit as the uncertainties related with assumptions and auxiliary data used for the disaggregation compromise the robustness of results generated with such IO datasets. Nevertheless, a more detailed reporting of economic accounts by statistical offices, particularly adding detail in the areas of agriculture and food processing (including bioenergy and biomaterial sectors), would provide a robust basis for land flow accounting.**
- **Choice of technology assumption for IOT generation: For agricultural commodities, PTA can be assumed to be more appropriate than ITA. Currently no MRIO dataset using PTA is available. However, this is less relevant for hybrid than for environmental-economic accounting approaches, as hybrid models use IO information only for a fraction of the supply chains.**
- **Integration of environmental and economic accounts: Moreover, land use statistics should be integrated with economic statistics according to the standards defined by the SEEA.**
- **Development of biomass PIOT: Finally, physical supply and use tables (or physical flow accounts), as defined in the SEEA Central Framework (United Nations et al. 2014), should be compiled by statistical offices in order to provide a physical representation of the economy, particularly for primary and manufacturing industries. However, solid and comprehensive datasets with global coverage cannot be expected within the next years. Alternatively, supply utilization accounts from agricultural statistics can be used to set up a global biomass PIOT based on currently available data.**

3.2.2 Allocation of products in the supply chain

An important difference between environmental-economic and physical accounting methods is whether supply chain flows (and embedded land uses) are tracked in terms of monetary values or physical quantities. This is on one hand relevant for joint production processes (e.g. crushing of soybean resulting jointly in soybean oil and soybean cake) requiring rules to attribute the land embedded in the raw material to the jointly produced commodities. On the other hand, land embedded in products needs to be allocated to different utilization categories or sectors, which can be done assuming heterogeneity or distinguishing different qualities and prices.

3.2.2.1 Joint products

A consistent treatment of joint products such as oil and cake from soybeans needs to be ensured in order to avoid double counting. Many studies already do so by allocating land areas to joint products in relation to their weight (Bringezu et al. 2009), energy content (Kastner et al. 2011b), carbon content (Kastner et al. 2011a) or value shares (Prieler et al. 2013; Statistisches Bundesamt 2013). Furthermore, the protein content was discussed by Kastner et al. (2011b) as another weighting scheme for allocation.

Economic allocation, i.e. allocation of joint production according to the value share of each component, is often used in life cycle assessments and is recommended by the Dutch Handbook on LCA (Guinée JB et al. 2002) as a baseline method, as it reflects the economic incentives of producers. Economic allocation is the standard form of land flow attribution in environmental-economic accounting models and can also be applied in physical accounting approaches, when using prices to convert physical quantities into monetary values (see, e.g., Prieler et al. 2013; Statistisches Bundesamt 2013). However, it can be argued that agricultural production decisions in many cases are not (only) driven by economic incentives. Allocating land according to energy or protein content, on the other side, would be problematic for the case of energy-rich oil and protein-rich feed production from oil seeds. Either of the two joint products would be attributed the lion's share of the embodied land. And finally, in cases where a raw product is processed into a small quantity of a high-value product and a large quantity of a low-value by-product, weight based forms of allocation would load most of the burden on the user of the by-product, thereby diverting attention from the main product and potentially misleading policy advice.

3.2.2.2 Product heterogeneity

Product flows within countries are often assumed to be homogeneous, regardless of its utilization, while in fact a crop used for domestic consumption, exports, or processing might differ in quality and price. For example, a comparison of global trade flows of rice has shown that rice import flows to high-income countries may increase up to an order of magnitude allocating flows according to prices as opposed to a weight-based allocation, while for low-income countries imports are lower using economic allocation. As a reason we therefore assume quality and related price differences between rice imports of high- vs. low-income countries. This error is discussed extensively by Schoer et al. (2013).

Recommendations

- **Economic allocation of land use for joint products: Ensure consistent treatment of joint production processes along the supply chain. We argue that the consistent use of economic allocation for attributing land to joint products is an appropriate compromise, as it can be applied to all joint products consistently, while other allocation logics could only be implemented very specifically on a case-by-case basis. Economic allocation can either be achieved by applying monetary supply use structures (as in environmental-economic accounting) or by translating physical quantities into values using price information (in physical accounting).**
- **Physical allocation of products to different uses: Land embodied in a country's supply of a certain crop or commodity should be allocated according to physical quantities as far as possible, as price variations for different utilisations otherwise impair the results. This implies that a physical accounting approach should be applied for these supply chains.**

3.2.3 Supply chains of food products

Input-output tables depict the inter-sectoral flows within and between economies. Based on these data, all global supply chains can be tracked. Data in the input-output tables, however, are highly aggregated to only a few agricultural product groups and are reported in monetary units, which do not allow applying physical allocation logic, as discussed before.

In contrast, physical accounting models are based on very detailed production and trade statistics reporting quantities for several hundreds of products. Yet, statistics providing physical data of inter-sectoral commodity flows are limited. Therefore, physical supply chains are modelled using technical knowledge represented by conversion factors from a starting product to one or several derived products. The most widely used source for such conversion factors is the FAO report "Technical Conversion Factors for Agricultural Commodities" (FAO 2003). However, regional or temporal differences due to differences in technologies or nutritional preferences are not captured by the technical conversion factors, which are only available as a global average.

In the case of animal products, which are responsible for around 60% of the overall land footprint of food consumption in Germany (Statistisches Bundesamt 2013), the low sectoral detail of IOTs is particularly problematic. In many IO models agriculture is represented as one aggregated sector, which does not allow deriving any specific information, for instance, on feed use. This results in one average land use intensity factor for aggregate agricultural production even though in reality the land intensities of animal and plant-based products, or even for different animal products as, for example, ruminants and chicken, are very different and need to be considered separately in the land accounting model.

Furthermore, fodder crops as well as grazed biomass have very low economic values and are often produced at the animal farm where they are fed, thus not entering the IOTs or being mixed with other crops of higher economic value. This potentially results in a misallocation of feed flows to sectors other than animal husbandry, shifting land use intensity from animal products to others.

Therefore, available agricultural statistics should be used to compute appropriate and specific land intensities for livestock products. This can be realised either in a top-down approach, starting from feed supply statistics, livestock herds and permissible diets and apportioning recorded market and non-market feed to different livestock types and production. Another option is a bottom-up calculation, using feed conversion ratios for different animal products. Due to its consistency with land use data, top-down accounting approaches are preferable. Furthermore, land intensities of animal products vary significantly between regions, emphasising the inappropriateness of the domestic technology assumption for imported goods. Interesting methodologies were developed by Mayer et al. (2014) based on German statistics and by IIASA et al. (2006) (see also Prieler et al. 2013) based on global FAO statistics.

Recommendations

- **Physical accounting of food supply chains: Apply a detailed physical accounting approach for food products, well documented in FAO statistics, in order to achieve high detail and robustness of results.**
- **Country-specific land use intensities: Realistic and consistent accounting of land actually embedded in the consumption and trade of ruminant livestock products and forestry products requires using country-specific technology and land use information (i.e. country-specific livestock herds, feeding practices, timber harvesting). We strongly discourage the use of the domestic technology assumption and recommend applying a top-down approach for crop and animal products in order to maintain global consistency of land attribution along supply chains (see also chapter 3.2.5).**

3.2.4 Supply chains of non-food products

Not for all commodities and their supply chains conversion factors are provided by the FAO (FAO 2003), so that product trees are truncated at a certain stage of processing. That is particularly the case for non-food biomass products such as biofuels and other bio-materials and the derived products (e.g. soap from oil crops, textiles from fibre crops, tobacco products, and tires from natural rubber). These processed products can be considered using bottom-up coefficients, mainly from LCA studies. This procedure produces uncertainties related to the use of various data sources which often include grey literature and unpublished sources. Since these studies are technically detailed but rely on assumptions and data from certain representative industries the regional specificity and consistency with national and global land use statistics is usually impaired.

As data domain boundaries for physical accounting do not allow tracking the full supply chains of non-food products, economic accounts (IO tables) can be applied in order to track secondary products from processing industries to final uses. This is particularly relevant, considering that with a possible rise of the bio-economy, non-food uses of biomass may increase substantially in future years. The development of the EUREAPA model, so far applied to the cases of the ecological, water and carbon footprints (Weinzettel et al. 2011; Steen-Olsen et al. 2012; Ewing et al. 2012; Weinzettel et al. 2014), as well as the work done by Meier and colleagues (Meier and Christen 2012; Meier et al. 2014) and Vringer and colleagues (Vringer et al. 2010; Benders et al. 2012) contributed significantly to the development of hybrid accounting by integrating detailed physical biomass and land accounts and input-output analysis.

Recommendations

- **Economic modelling of non-food supply chains: Use a hybrid accounting approach extending the physical accounting model by using monetary flows from IO tables for processing industries where no data are reported in agricultural supply utilisation accounts. This is particularly the case for non-food use of crops and derived products, and for manufactured forestry products.**
- **In order to anticipate future trends, agricultural statistics, and particularly supply utilisation accounts, should be extended to cover also the main industrial uses, e.g. for energy purposes or in the chemical industry.**

3.2.5 Top-down vs. bottom-up

At various places in the report, we argue that top-down approaches are in any case preferable as compared to bottom-up approaches, as they ensure consistency with national or global land use statistics, i.e. total in-flows equal total out-flows. As opposed to studies on global flows of metals or carbon emissions embodied in products, for the case of biomass and land flows the available data allow to construct both, environmental-economic and physical top-down accounting models.

Furthermore, in a top-down accounting approach, physical supply chain information can be integrated with monetary input-output data constructing mixed-unit IOTs. This integration has the advantage of consistently adding together all parts of the model into one matrix framework, which can be solved using basic linear algebra. Moreover, a symmetric IO structure would also allow the application of analytical tools such as structural decomposition analysis and structural path analysis in order to further investigate supply chains and developments over time. However, a full integration maintaining most of the detail of the base data would result in a matrix of the dimension of about 40,000 by 40,000 and has not yet been realised.

Recommendations

- **Top-down accounting: Follow a top-down approach, starting with land attribution to the production of primary products and following the supply chain to final consumption.**
- **Matrix representation: If technically feasible, a consistent top-down accounting model can be realised by full matrix integration of all physical and monetary supply chain data into a hybrid (mixed-unit) IO table.**

3.2.6 Trade

Globalization and increasing trade in agricultural and forestry products is an essential element of development strategies in many countries resulting in substantial cross-country flows of primary and manufactured products. In order to track land embodied in products, huge sets of bilateral trade data need to be employed, raising questions of data quality and consistency, which are discussed below. However it should be noted that consistent bilateral trade data are mandatory for tracking global supply chains.

3.2.6.1 Consistency of trade data

It has long been recognized that the international trade data reported by importers and exporters often do not match for a variety of reasons (Ferrantino et al. 2012; Tsigas et al. 1992). Bilateral trade flows are reported separately by importers and exporters, often resulting in large discrepancies in reported trade flows. Reasons for inconsistencies are manifold, including

- time lags (e.g. exports reported in one year could reach a destination only in the following year);
- loss and shrinkage (exported quantities could be destroyed or lost on the way to the destination, e.g. due to physical evaporation);
- type of trade reported (some countries report general trade including re-exports, while other report special trade, i.e. imports for the domestic use);
- data gaps in the reporting of one of the trading partners;
- misreporting, e.g. customs tax avoidance by misrepresenting a commodity on import or not reporting a trans-shipment;
- inconsistencies in reporting of place of origin / final destination (e.g. some countries may report final destination and omit intermediate trade via a third country);
- mismatches between the imports reported by one country and the exports reported by another are not reconciled. An exception is, for instance, trade between the US and Canada, two countries which share and harmonize trade data.

Globally consistent natural resource flow accounting requires consistency between imported and exported commodities. There is no commonly accepted method for reconciling differences in bilateral trade statistics. For example, the bilateral trade data of agricultural commodities in 2010 recorded in FAOSTAT amount to more than 600,000 data records, which are harmonized in the LANDFLOW model by constructing a symmetric trade matrix using the larger value of each pair of recorded trade flows. The trade data in the GTAP database are based on the UN COMTRADE database, which are reconciled according to a methodology described in Ghelhar (1996). EXIOBASE applied the RAS approach (Miller and Blair 2009) for the balancing of trade data.

3.2.6.2 Import content of exports

The standard procedure in land flow accounting methods is to assume one average import content for domestic uses and exports. However, the increasing importance of the international fragmentation of production processes and resulting high variations in the import contents of different supply chains call for a more detailed accounting approach, taking these differences into consideration as done for the analyses conducted at the German Federal Bureau of Statistics (Statistisches Bundesamt 2013; Mayer et al. 2014). This approach is dependent on data that are currently not available from international statistical sources and therefore need to be gathered from national statistics. Against this background, a consideration of differing import contents for all countries in a land flow accounting model is hardly feasible.

3.2.6.3 Re-exports

One main challenge of land flow accounting is posed by the fact that in bilateral trade statistics the country of origin is the country where the last value added step occurred. Thus, the true origin in the case of re-exports is lost in this information. For the purpose of land accounting, re-exports have to be defined more widely than is commonly done. For tracking embedded land a re-export occurs also if a country imports a primary commodity (e.g. soybeans) and exports secondary products derived from this raw material (such as soybean cake or livestock products based on soybean cake). We consider this flow of secondary products to be a re-export, as we are interested in linking environmental factors at the place of primary production to the place of final consumption.

One approach taken in some land flow studies applying physical accounting was to assume the exporting country to be the producing country. This assumption is problematic: For instance, take country A importing large amounts of a good from country B, which country B does not produce or only in very small quantities. The assumption that such a product originated from country B necessarily results in accounting errors. Clearly, country B must have imported the product (and its embedded land) from elsewhere. Some studies apply global average yields (and implied land intensity coefficients) when encountering the problem that the country of origin cannot be the producer of the respective crop (see e.g. Kissinger and Rees 2010). Yet, this may still cause poor estimation because yields of the world's largest exporters will usually exceed the global average.

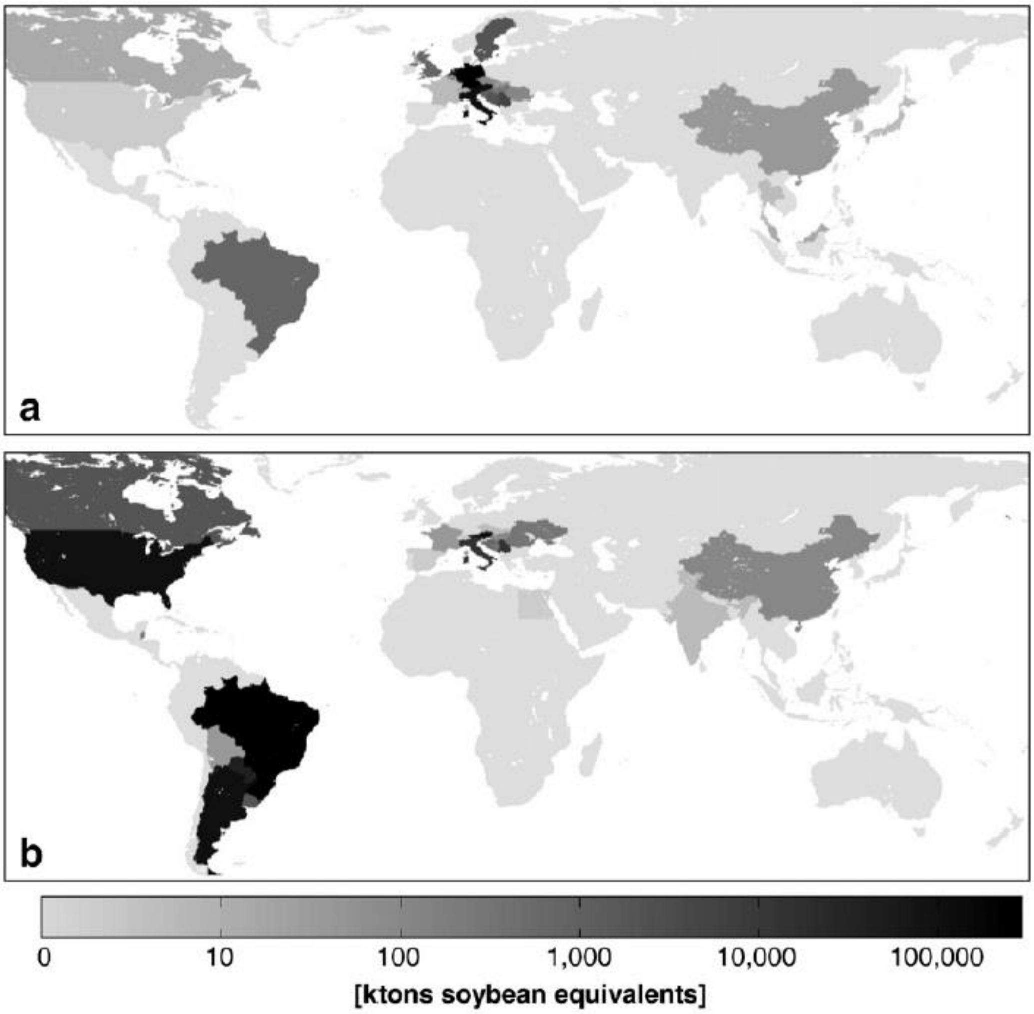
A thorough approach is used in the LANDFLOW model, where the land intensity of commodity utilization items (various domestic use categories and exports) of a processed commodity is calculated from land embedded in the production of domestic raw materials as well as in the imported raw materials and the estimated processed commodity. This allows for estimating land and adjusting for re-exports by recalculating land in global trade flows in an iterative process until convergence is reached and a stable solution is found. This approach ensures that transit trade flows and production based on imported primary raw materials are accounted for and treated as such.

The German Statistical Office (StBA) manually adjusted trade data for re-exports for the most important crops and trade volumes by back-tracking flows to producing countries using COMTRADE data (Mayer et al. 2014). Re-exports in a wider sense, i.e. exports of processed products produced with imported raw materials (e.g. chocolate produced with imported cocoa), were considered by building specific supply accounts for exports (i.e. distinguishing exports from imports and from domestic production) under the assumption that imported raw products are not exported without processing, i.e. exported raw products originate from domestic production.

A study by Kastner et al. (2011b) proposes a mathematical approach using matrix algebra to track in physical terms the origin of a product. Using this technique, a major advantage of environmental-economic accounting can also be implemented in physical accounting approaches. The following figure shows a comparison of the origin of the soybeans contained in soy products consumed in Austria when using officially reported trade data for 2005 (Figure 4a, based on FAOSTAT) without accounting for re-exports as compared to the results of calculation considering re-exports using the approach by Kastner et al. (Figure 4b).

Bilateral trade data list Germany, Italy and The Netherlands as principle countries of origin for soy products imported into Austria. Two of these trade partners, Germany and the Netherlands, do not grow soybeans on their own (at a relevant scale). The example illustrates that re-exports have to be addressed in a systematic manner with consistent calculation steps and transparent assumptions. When considering re-exports, the single largest source of soy products imported by Austria becomes Brazil, followed by Argentina and the United States. These are also the top three producers at the global level.

Figure 4: **Origin of the soybeans in soy products consumed in Austria in 2005; according to (a) the reported bilateral trade links without considering re-exports; and (b) the result of the calculations by Kastner et al. (2011b) considering re-exports**



Source: Kastner et al. (2011b)

Recommendations

- **Balance trade data: Set up a globally consistent balanced set of bilateral trade data by correcting inconsistences in the reported data. In the case of the construction of MRIO systems, the RAS approach is widely used for these issues. Moreover, some studies correct inconsistencies between import and export data by giving preference to either of them.**
- **Consider different import contents: Account for differences in the import contents of domestic uses and exports for the region under investigation.**
- **Account for re-exports: Imports need to be traced back to their origin. This is true for raw products, as transit trade is often included in trade statistics, and for processed commodities.**

3.2.7 Consumer demand and final utilization

The aim of land flow accounting is to attribute all observed land uses to various categories of consumption. In input-output analysis, used in environmental-economic accounting, final demand is used as a proxy variable for consumption. This assumes that the paying agent (country or industry) equals the consuming agent (country or industry). However, in some cases this assumption does not hold true. For instance, food aid that is provided to another country is not represented in trade statistics[15]. Another example is caterings and company-subsidised canteens, where the eventual consumer is not the payer and land embedded in canteen food will be incorrectly attributed to the company's customers, which may be a firm or a household in a third country.

Physical accounting approaches face yet another problem, namely that supply chains may end in the utilization item 'Other Utilization[16]' of the Supply Utilization Accounts (SUAs) explained in chapter 2.4.2. Further processing steps, trade of these processed goods and their end uses cannot be tracked because of limitations in the tracking depths of the respective data system (see also chapter 3.2.4). In this case the embedded land is attributed to the country where the last recorded use occurred, which may differ from the actual consuming country when such industrially processed goods are traded.

Table 7 summarizes for cropland three important variables relevant for assessing the importance of this limitation on the basis of results from the LANDFLOW model (Prieler et al. 2013). The first column highlights the distribution of land used for the production of primary crops, reported in seven major crop groups, across the global total cropland area of 1500 million hectares. The second column shows for each crop group the proportion of embodied cropland areas associated with international trade of the respective product group. The third column reveals the share of cropland area within each crop group, which is reported in the SUAs as 'Other Utilization'. LANDFLOW assumes no further trade of higher processed commodities in this category.

For example, of the total 243 million hectares used for the production of oil crops, almost 40% is used for commodities consumed outside the country of primary production via embodied cropland in international trade of primary and processed oil crop products. Therefore a significant share of cropland 'relocation' is already captured in this commodity group. Almost 12% of total utilization of oil crop products in the FAO SUA is attributed to 'Other Utilization', i.e. non-food commodities (industrial products, e.g. soap from oil, biodiesel). If such a higher processed industrial commodity is traded (e.g. cross-country biodiesel trade), this trade flow, and as a consequence its embodied land flows, are outside the reporting system of the FAO supply utilization accounts and can therefore not be tracked to final utilization.

Results of Table 7 indicate the attribution of cropland is fairly robust for five out of eight crop groups, namely cereals, roots and pulses, fruits / vegetables / nuts, stimulants and fodder crops. For these commodities the share of embodied cropland attributed to 'Other Utilization' is relatively low (below 6%). Also only 10% of ruminant livestock products are associated with 'Other Utilization' (e.g. leather).

[15] However, according to Kastner et al. (2014) food aid shipments only account for 0.7% of the total global production for export (on average between 2007 and 2009).

[16] This utilization category in the FAO supply utilization accounts refers to quantities of commodities used for non-food purposes, e.g. oil for soap. Moreover, also quantities of the commodity in question consumed mainly by tourists are included here. Finally, this variable also covers pet food and statistical discrepancies, defined as an inequality between supply and utilization.

Table 7: Land in global production, trade and 'Other Utilization' of crops in 2007

	Cropland in global production (Mha)	Embodied cropland associated with international trade (%)	Embodied cropland associated with 'Other Utilization' (%)
Cereals	749.0	15.0	2.6
Roots and pulses	128.7	6.9	2.8
Sugar crops	29.7	26.2	11.3
Oil crops	243.0	39.8	11.8
Fruit, nuts, vegetables	121.4	10.5	0.8
Stimulants	23.0	61.7	5.3
Non-food fibre crops	42.4	43.2	100.0
Fodder crops	190.0	0.0	0.0
All crops	1527.2	17.8	6.6

Source: LANDFLOW calculations based on FAOSTAT (2011)

This limitation is most relevant for the group of non-food fibre and rubber products, where all raw materials are processed into industrial goods. In this case physical accounting of cropland based on agricultural Supply Utilization Accounts tracks the trade of raw materials (45% of land in total fibre and rubber production) to the destination of industrial use but cannot track the trade and final use of these industrial products (e.g. when Germany imports rubber for tire production the land consequently embodied in the rubber tires is not accounted for when these tires are traded). Note, however, that non-food fibre and rubber products are associated with only 3% of total global cropland.

LANDFLOW calculations show that globally an estimated 30 Mha or about 12% of the total cropland attributed to the production of oil crops concerns the use in non-food / non-feed industrial products (e.g. soaps, cosmetics, biofuel, etc.). For comparison, cropland in oil crops attributed to feed use in 2007 is about 80 Mha, i.e. roughly one third of the total cropland used for the production of oil crops. Finally for sugar crops (total global cropland in sugar crops in 2007 was about 30 Mha), the share of land attributed to 'Other Utilization' was 11.3%.

Although a large share of the products dedicated to 'Other Utilization' is consumed in the region / country of industrial processing, trade of processed industrial goods should be accounted for and the data system boundaries of FAOSTAT result in some uncertainty of the attributed cropland to final uses especially for the product groups of plant-based fibres, natural rubber and oil crops.

The uncertainty (due to data system limitations for tracking highly processed industrial commodities) of attributing land embodied in crop products using the SUA-based physical accounting approach, applied for example by the LANDFLOW model, is estimated to be less than 7% of global cropland. This estimate would materialize to the full extent only if all industrial products with embodied cropland were traded and consumed outside the country / region of industrial production.

Hybrid accounting approaches as recommended in this report could extend the tracking analysis using monetary information for situations where the "Other Utilization" item is subject to further trade and processing before final consumption.

Recommendations

- **Track flows to consumers: Use a hybrid accounting approach tracking physical flows to final consumption as far as possible and extend supply chains for processing industries using monetary IO tables, where SUAs are cut-off at industrial uses.**

3.2.8 Detail of reporting

A high level of reporting detail is not only important for the robustness of results but also for its applicability in policy making. A land footprint indicator should distinguish between different land uses (e.g. cropland, grassland and forests), countries (specifying the origin of products and the actual place of land use), crops (e.g. rice, wheat, soybeans) and final uses (e.g. vegetarian food, animal food, waste, non-food products). The physical accounting approach attains a higher level of detail than environmental-economic accounting, albeit without the possibility of separating different final demand categories (e.g. household consumption, government consumption and capital fixation). By combining the two approaches (i.e. using a hybrid method) additional detail can be added for non-food products.

Recommendations

- **Final demand vs. end use: Depending on the purpose of the analysis, environmental-economic accounting is more appropriate if information on the land footprint is required to distinguish different final demand categories. Physical accounting, on the contrary, is able to distinguish different categories of designated end use such as food, feed, and non-food uses. In most cases, detailed information on the end use of land-based products, including vegetarian versus animal products and industrial uses, will enhance applicability and usefulness for policy making, thus giving preference to physical and hybrid accounting methods.**
- **Maximize detail for non-food commodities: Keep track of flows of non-food commodities via IO models in order to identify the sectors involved in these supply chains and to determine the final demand products (e.g. wearing apparel) and categories (e.g. household demand) where they end up.**

3.3 Summary of recommendations for the further development of land flow accounting methods

This section provides a summary of all recommendations for further development concluded from the review of existing land flow accounting methodologies. The recommendations are listed according to the two overarching calculation steps in land flow accounting: first, how land areas are attributed to primary production and second, how embodied land is tracked along global supply chains.

3.3.1 Recommendations for the land use module

Account for different land use types:

- It is strongly recommended to calculate land footprints separately for cropland, grassland and forest land in order to account for differences in accuracy, sharpness and availability of land use data by broad primary sectors (crops, livestock, and wood production) and to facilitate better impact oriented interpretation of the results.

Account for country- and crop-specific land use patterns:

- Since yields (land intensities) among crops and across countries vary widely, it is essential for land accounting to use country- and crop-specific technology and land use information and to retain in the tracking procedures both the commodity and geographical details of land-based production and commodity flows and avoid aggregation at an early stage in the supply chain to the extent possible.
- The Food and Agriculture Organization (FAO) of the United Nations compiles national statistical data and is the only available consistent global dataset on land use and agricultural and forestry production and thus the only available source for large-scale global studies related to biomass production and land use. We recommend using these publicly available country-level, time series databases for the agricultural and forestry sector in land footprint accounting. Whenever possible, data from national statistical sources can be used to extend or replace international statistics.

Account for multi-cropping and fallow periods:

- Apply agronomic logic and data to differentiate in the calculation of multi-cropping and land intensities among annual and perennial crops.
- Calculate average multi-cropping intensities, separately for annual and perennial crops, across all crops cultivated in a country and apply respective intensities to harvested areas of individual crops to estimate physical land associated with production.

Ensure robustness of grassland and forest land data:

- For countries where no robust data is available, grassland and forest land actually used for livestock and wood production should be estimated rather than assuming all reported grassland and forest land as being part of the production cycle.
- For instance, regional data or model-based simulations of grassland productivity, net annual forest increments, etc. together with estimated livestock feed balances and reported timber harvests can be used to fill information gaps needed for enhancing estimates of forest and grassland utilization of livestock and wood production.
- Due to data uncertainties the possibilities to calculate a robust land footprint indicator for pastures and forests is limited. We therefore propose alternatively using weight units instead of area units for the measurement of the grazing and forestry footprint, i.e. calculating the material footprint instead of the land footprint.

Ensure consistency between the applied statistical sources:

- Errors resulting from inconsistencies between National Accounts and land use statistics can only be avoided applying physical or hybrid accounting methods.
- A physical accounting approach based on detailed commodity production and trade data should therefore be used for the first stages of the supply chains. When industrial uses cannot be tracked further by the physical accounting methods due to data limitations, environmental-economic accounting of flows from these sectors based on monetary IO tables should be applied to extend those supply chains to final consumption (i.e. hybrid approach).

3.3.2 Recommendations for the supply chain module

Maintain global consistency of land attribution along supply chains. This entails:

- Follow a top-down approach, starting with land attribution to the production of primary products and following the supply chain to final utilization.
- Avoid the domestic technology assumption. Account for country-specific supply and utilisation patterns and conversion rates, particularly for processed food and non-food products such as animal products, biofuels and biomaterials. This implies considering country-specific livestock herds, feeding practices, processing technologies, as well as trade and manufacturing patterns.
- Set up a fully consistent and balanced representation of bilateral trade flows by correcting inconsistencies in trade statistics. In the case of the construction of MRIO systems, the RAS approach is widely used for these issues. Moreover, some studies correct inconsistencies between import and export data by giving preference to either of them.
- Account for differences in the import contents of domestic uses and exports for the region under investigation.
- Imports need to be traced back to their origin, fully considering re-exports and transit trade. This is true for raw products, as transit trade is often included in trade statistics, and for processed commodities.

Apply a detailed physical attribution scheme for tracking land flows along the supply chains:

- Use global agricultural statistics – particularly supply utilisation accounts and trade data – for the modelling of global physical supply chains, rather than tracking land flows along monetary supply chains.
- Apply a high commodity detail, i.e. single crops and commodity flows are tracked via their physical flows (e.g. in tonnes) and associated land areas are attributed in proportion to physical volumes.
- Land embodied in a country's supply of a certain crop or commodity should be allocated according to physical quantities as far as possible, as price variations for different utilisations otherwise impair the results. This implies that a physical accounting approach should be applied for these supply chains.
- Ensure consistent treatment of joint production processes along the supply chain. We argue that the consistent use of economic allocation for attributing land to joint products is an appropriate compromise, as it can be applied to all joint products consistently, while other allocation logics could only be implemented very specifically on a case-by-case basis. Economic allocation can either be achieved by applying monetary supply use structures (as in environmental-economic accounting) or by translating physical quantities into values using price information (in physical accounting).
- Depending on the purpose of the analysis, environmental-economic accounting is more appropriate if information on the land footprint is required to distinguish different final demand categories. Physical accounting, on the contrary, is able to distinguish different categories of designated end use such as food, feed, and non-food uses. In most cases, detailed information on the end use of land-based products, including vegetarian versus animal products and industrial uses, will enhance applicability and usefulness for policy making, thus giving preference to physical and hybrid accounting methods.

Track land embodied in non-food biomass flows:

- Use a hybrid accounting approach extending the physical accounting model by using monetary IO tables for processed commodities where no physical volumes are reported in agricultural sup-

ply utilisation accounts. This is particularly the case for non-food use of crops and derived products, and for manufactured forestry products.
- In order to anticipate future trends, agricultural statistics, and particularly supply utilisation accounts, should be extended to cover some major land-based non-food commodities, e.g. biofuels or bioplastics. Extend the reporting scope from food balances to biomass balances.

Use robust IO statistics and further advance IO tables:

- For studies using monetary IO data, i.e. economic or hybrid accounting studies, the selection of the database should consider the respective strengths of the databases, e.g. sector detail for EXIOBASE, country detail for Eora and GTAP, and the use of only marginally manipulated data from official sources for Eurostat, WIOD, OECD and Eora. The selection of one of these databases should balance pros and cons in the light of a particular research question or policy issue.
- Disaggregation of IO tables has only limited benefit as the uncertainties related with assumptions and auxiliary data used for the disaggregation compromise the robustness of results generated with such IO datasets. Nevertheless, a more detailed reporting of economic accounts by statistical offices, particularly adding detail in the areas of agriculture and food processing (including bioenergy and biomaterial sectors), would provide a robust basis for land flow accounting.
- The choice of a specific technology assumption for the generation of IOTs will have influence on the results. For agricultural commodities, PTA can be assumed to be more appropriate than ITA. Currently no MRIO dataset using PTA is available. However, this is less relevant for hybrid than for environmental-economic accounting approaches, as hybrid models use IO information only for a fraction of the supply chains.
- Moreover, land use statistics should be integrated with economic statistics according to the standards defined by the SEEA.
- Finally, physical supply and use tables (or physical flow accounts), as defined in the SEEA Central Framework (United Nations et al. 2014), should be compiled by statistical offices in order to provide a physical representation of the economy, particularly for primary and manufacturing industries. However, solid and comprehensive datasets with global coverage cannot be expected within the next years. Alternatively, supply utilization accounts from agricultural statistics can be used to set up a global biomass PIOT based on currently available data.

It is important to note that the recommendations described here refer to an optimum in the light of the defined criteria and the current state of data availability and quality. In practice, policy context and purpose need to be taken into account when developing a land accounting method. Efforts should be adapted to a specific purpose in order to achieve a reasonable relation of costs and benefits. We acknowledge that besides a technical optimum there may be a differing cost-benefit optimum.

4 Conclusions

- None of the currently available accounting approaches evaluated in detail in this report covers *all* of the recommended features. However, all key recommendations are met in at least a few studies. For the land use model, this includes the following recommendations: Multi-cropping and fallow periods are considered by Bruckner et al. (2012a), IIASA et al. (2006) and Prieler et al. (2013) and are dealt with in the development of EXIOBASE version 3.
- Various studies, including Bringezu et al. (2012), Bruckner et al. (2012a), Erb (2004), and Prieler et al. (2013), use modelled grassland and / or forestry data and thereby try to avoid uncertainties related with reported data. Most other studies only calculate cropland footprints.
- In order to enhance consistency between the applied data sources, EXIOBASE version 3 improves the link between agro-environmental and economic statistics. The EUREAPA model (Weinzettel et

al. 2011; Ewing et al. 2012; Steen-Olsen et al. 2012; Weinzettel et al. 2013; Weinzettel et al. 2014) uses a sophisticated hybrid approach, applying detailed physical data to overcome gaps in the economic part of the model. Finally, physical accounting approaches do not face this inconsistency challenge, as only physical data are being used.

For the supply chain module, some recommendations are met by environmental-economic accounting studies, while others can only be fulfilled by physical or hybrid accounting studies:

- All environmental-economic accounting studies use a top-down approach and thereby maintain global consistency of land attribution along supply chains. But also some physical accounting models are fully (Kastner et al. 2014a; Prieler et al. 2013) or partly (Bringezu et al. 2012; Mayer et al. 2014) designed following a top-down approach, including a comprehensive or selective consideration of transit trade.
- Only Mayer et al. (2014) consider differences in the import contents of domestic uses and exports.
- All physical accounting studies use a detailed physical allocation scheme for tracking land flows along the supply chains. The hybrid method developed by Weinzettel et al. (2013) applies detailed physical data for flows from primary production to the first stage of processing / use. No hybrid model yet integrates the full amount of available agricultural statistics, which is the aim of this research project. Furthermore, a research group consisting of the Vienna University of Business and Economics, the Norwegian Technological University Trondheim and the University of Bonn are currently working on a global physical IO table based on FAO data, which will be integrated with existing MRIO models (Econ-BioSC project).
- All physical and most hybrid accounting models are able to distinguish different categories of designated end use such as vegetarian food, animal food, non-food commodities (e.g. bioenergy) and waste.

Although being a young field of research, available studies and methods already provide a valuable basis on which further developments can build upon. Some methods are already now close to meeting the criteria defined in this study. Generally, we see the physical accounting methods in a better position to providing the basis for further developments.

Top-down applications of the physical accounting approach (e.g., Kastner et al. 2014a; Prieler et al. 2013) can be extended with MRIO models in order to further trace non-food uses of bio-based materials, i.e. building a hybrid accounting method. If technically feasible, a consistent top-down accounting model combining physical and monetary values can be realised by creating a fully integrated hybrid or mixed-unit IO table, which would allow the application of analytical tools such as structural decomposition analysis and structural path analysis in order to further investigate supply chains and developments over time.

When deriving a land footprint indicator for a specific country, national statistics and country details should be considered for extending or replacing international data sources in cases where national data are considered more reliable or where they can add some details, such as done by Mayer et al. (2014) for Germany.

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6 Annex

6.1 Descriptions of the reviewed studies

6.1.1 Studies based on environmental-economic accounting

In recent years, a number of Land Footprint studies have been published, which are based on environmental-economic accounting, most of them applying multi-regional input-output (MRIO) analysis. Currently only few datasets for the construction of global multi-regional input-output models are available, namely GTAP, WIOD, OECD, EXIOBASE and Eora. As the properties, advantages and limitations of these models are tightly related to the applied data base, the following evaluation is structured along these global input-output data sets.

In MRIO databases in general it is not (yet) possible to disaggregate the various primary uses of crops produced on certain land areas (e.g. food, feed, bio-energy, etc.), as input-output sectors and product groups do not disaggregate the various use types. For example, in the GTAP database, there is only one product group covering all "oil seeds", independently whether they are used as animal feed, for energy production or for material uses, e.g. in the chemical industry.

In contrast to physical accounting approaches (see below), all MRIO-based methods possibly allow identifying the industry or product group, which is the last stage in the supply chain before delivering a product to final demand. The full structure of inter-industry deliveries is illustrated in the IO tables, thus the supply chains can be analysed using additional analytical methods (tools such as Structural Path Analysis allow quantitative assessments of the supply-chain structures). All existing MRIO databases allow separate calculations of the land footprints of private household consumption as well as for government consumption, investments, inventory changes and exports as well as imports.

Compatibility with the system of national accounts is generally high across all MRIO approaches, as the establishment of input-output tables is closely connected with the set-up of national economic accounts and by definition takes a sector perspective, which is also the basis of e.g. the NAMEA system.

The land modules of MRIO based calculations are simple. In most cases, land use data on the level of single crops is retrieved from the FAO database and then aggregated to the sector classification of the respective MRIO database. For this first step, it is important to note that only in a minority of cases (for example, Bruckner et al. 2012a; Prieler et al. 2013), an approach for correcting crop production statistics for multi-cropping as well as for adjusting FAO pasture area data with data on the actual amounts of grazed biomass has been implemented, while most studies applied the original FAO data without further corrections.

After aggregation of the land use data to the available sector detail of the MRIO database, the sum of the land areas for all products produced in a sector is divided by the monetary production value of that sector in each country, in order to calculate the land intensity of production in each sector. The unit used is hectares per monetary unit (€ or $). The vector of land intensity per sector then enters the further calculation steps of environmentally-extended input-output analysis (see Miller and Blair 2009).

6.1.1.1 Global Trade Analysis Project (GTAP)

The Global Trade Analysis Project (GTAP) database is the MRIO database most widely applied for land-related assessments so far (Wilting and Vringer 2009; Vringer et al. 2010; Lugschitz et al. 2011; Bruckner et al. 2012a; Ewing et al. 2012; Karstensen et al. 2013; Weinzettel et al. 2013; Yu et al. 2013). GTAP is an economic database of harmonized input-output tables and bilateral trade data established and maintained at Purdue University, Indiana, USA[17]. The latest version 8 of GTAP disaggregates 129 countries / world regions and thus represents a very high geographical coverage. GTAP8 contains information for 57 product groups, of which 8 refer to primary crop production and one to timber production. This disaggregation level also determines the extent to which land use data linked to agricultural and forestry activities can be disaggregated. In addition to these primary production sectors, a number of food production and processing sectors are being distinguished, including various types of meat and animal products.

GTAP data exist for various points in time, the latest data referring to the year 2007, and is updated every 3 to 4 years.

Regarding transparency, GTAP has some clear deficits, as the data manipulation procedures necessary to transform original IO tables into the standardized GTAP format are not well documented. In many cases, the quality of the underlying IO data cannot be properly evaluated. National tables are collected from uncountable sources and provided by experts from all over the world. Data quality varies and cannot be assured. Furthermore, type and structure of the underlying national tables are not consistent (e.g. following different industry or commodity classifications and applying different technology or sales assumptions). It is furthermore not clear how the relatively high sectoral detail for agricultural activities is obtained. Since the data and assumptions used for disaggregating the agriculture sector from the original input-output data are crucial for the calculation of land footprints, this lack of knowledge leaves uncertainties regarding the robustness of land footprint results generated with the GTAP database.

Land use data for GTAP-based land footprint assessments were almost exclusively taken from FAO. The land use data on the level of single crops is first aggregated to the 13 agriculture and forestry sectors in GTAP and then linked to the monetary tables in each country.

6.1.1.2 World Input-Output Database (WIOD)

The second MRIO database, which has been explicitly applied to calculate land footprints of EU-27 countries (see Arto et al. 2012) is the World Input-Output Database (WIOD)[18]. In comparison to GTAP, WIOD disaggregates a smaller number of countries (40 countries plus Rest of the World), with only a few important agricultural production countries outside the OECD being covered (e.g. Brazil, Indonesia). Compared to GTAP, WIOD also has a lower resolution regarding sectors and product groups (35 industries, 59 products).

With regard to Land Footprints, a particularly weak point is the limit to only one sector, containing all agricultural and forestry production, and two product groups (agricultural products and forestry products) in the product perspective. This also puts a severe constraint to the number of land categories, which can be distinguished in the assessments. In the study for the EU-27, four types of land areas were separately analysed (temporary crops, permanent crops, permanent pastures, and forestry). However, as only one agricultural sector is distinguished in the WIOD database, an identical economic structure has to be applied to allocate e.g. temporary crops and permanent crops. As a result, the same percentage share of temporary versus permanent crops ends up in the different categories of final demand.

Differences to other MRIO data bases can particularly be observed for the availability of time series with WIOD data being available for each year between 1995 and 2010. Also the transparency and quality of the underlying data is higher for WIOD compared to GTAP, as official national IO tables were the starting point of the data harmonisation procedures.

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17 See **https://www.gtap.agecon.purdue.edu/databases/v8**.

18 For a description of the WIOD see Dietzenbacher et al. (2013).

In the land footprint study (Arto et al., 2012), arable land and pasture data was sourced from FAO-STAT, forest areas used for production purposes from the FAO Forest Resource Assessment.

6.1.1.3 OECD input-output database

Another potential source for MRIO-based Land Footprint assessments is the OECD input-output database (OECD 2009). This database has not yet been explicitly applied to the case of land, but has been used for the calculation of Carbon and Material Footprints (Nakano et al. 2009; Wiebe et al. 2012; Bruckner et al. 2012b). The OECD database is very close to the officially published IO tables, with a transparent documentation of the required steps taken to transform the IO tables into a harmonised format. Therefore, the OECD database is characterised by high transparency and good data quality. Regarding the sector breakdown, OECD is comparable to WIOD, with only one aggregated agriculture / forestry / fishing sector, which significantly limits the potential use of this database for the case of Land Footprints. OECD MRIO data are so far only available for only three years: 1995, 2000 and 2005.

6.1.1.4 EXIOBASE

The EXIOBASE system was developed in various European research projects and particularly designed for environment-related applications (Tukker et al. 2013). Therefore, in EXIOBASE, national IO tables were further disaggregated in order to provide a higher industry / product detail in environmentally sensitive sectors, including agriculture and food industries. It was applied to the calculation of the carbon, water, land and material footprint (Tukker et al. 2014). The EXIOBASE has a total of 169 industrial sectors and almost 200 product groups. In the agricultural area, EXIOBASE is oriented towards the GTAP classification with eight primary crop production sectors plus one sector for timber production. EXIOBASE distinguishes a similar number of products and thus land use categories as GTAP. EXIOBASE data are so far only available for two years, 2000 and 2007, but time series (1995-2011) are currently being built in the ongoing FP7 project “DESIRE”[19]. The transparency of data manipulation procedures required to disaggregate standard IO tables to the EXIOBASE classification is not satisfying, but currently being improved. Additionally, a larger number of auxiliary data is being used, which cannot always be judged regarding the data quality.

6.1.1.5 Eora

Another available option for MRIO-based Land Footprint assessments is the Eora MRIO system (Lenzen et al. 2013). Eora has not been directly used for the calculations of Land Footprints so far, but studies exist for the issues of drivers for biodiversity (Lenzen et al. 2012) and Material Footprint of nations (Wiedmann et al. 2013). With 187 countries and country groups, Eora provides the highest spatial resolution of all MRIO systems presented so far. The number of sectors and product groups disaggregated in Eora differs from country to country, depending on the officially available data. This also determines the number and type of land use data that can be attached to an Eora-based land model. In case no official IO table is available, a mathematical optimisation algorithm creates IO tables with 26 industries from national accounts and other economic production data. This algorithm is applied for 69 of the 187 countries disaggregated in Eora and concern mainly developing countries. According to the authors, several routines are applied, which shall assure quality and consistency of the resulting IO tables (Lenzen et al. 2013). Eora so far delivers a time series of IO tables from 1990 to 2011.

6.1.2 Studies based on physical accounting

The following evaluation is clustered along the organisations the researchers were affiliated to at the time their work was published. Where researchers from more than one organisation have been contributing, we considered only the affiliation of the first author. In one case, we group more than one

19 See **www.fp7.desire.eu**.

organisation together, as the first author changed his affiliation and published together with researchers from other organisations.

6.1.2.1 University of Groningen (RUG)

The first consumption-based calculations of the land requirements of a country were done by Gerbens-Leenes et al. (2002) with a predecessor study published in Dutch language (Gerbens-Leenes 1999). Gerbens-Leenes et al. calculated land intensity coefficients in m² year kg-1 for different food items. The study covers animal and crop products and is based mostly on data from Statistics Netherlands (CBS) and FAO. The researchers first examine the land requirements per kg crop as a weighted average of Dutch crop production and imports. Then, information on the amounts of basic agricultural commodities needed for the manufacturing of food items were used to compute land intensity coefficients for food items. These coefficients are then multiplied with the amounts of food consumed by an average Dutch household. Food consumption per food item was derived from the CBS expenditure survey and data on food prices. A shortcoming of this approach is that it does not take into account consumption outside the house, e.g. at work or in bars and restaurants.

6.1.2.2 IIASA (LANDFLOW model)

The LANDFLOW model, developed by the International Institute for Applied Systems Analysis (IIASA), so far is the only existing model for assessing land embodied in international trade and national consumption, which realises a purely physical accounting approach on the global level (IIASA et al. 2006; Prieler et al. 2013). LANDFLOW uses the large harmonized time series country data from different domains of the FAOSTAT agriculture and forestry databases (FAOSTAT 2015). They include i) land use data; ii) primary crop production (harvested area, production, yields); iii) livestock production (animal stock numbers, off-take, carcass weight); iv) commodity supply and utilization accounts (SUA) of primary and derived products; vii) production of raw timber materials and wood-based products; vi) bilateral commodity trade data in physical units and dollar values.

LANDFLOW first attributes physical land areas separately for cropland, pastures and forest land to primary commodities. Land intensities (ha / ton of produce) are deter-mined by reporting biomass production for crops and supplemented by modelled biomass productivity from the Global Agro-Ecological Zones (GAEZ) database (IIASA/FAO, 2012) for grassland and forest land where data is missing. Cropland attribution accounts for multi-cropping and fallow periods. Second, FAO's supply utilization accounts (SUA, see chapter 2.4.2) for agricultural products and wood balances for the forestry sector are connected with harmonized trade matrices to track physical quantities and embodied land areas from primary production via intermediate products (notably animal feed), joint products (e.g. livestock producing milk, meat and hides; soybean producing soy oil and soy cake) and cross-country trade to final (apparent) utilization.

LANDFLOW generates consistent trade matrixes for all SUA commodities using the FAO bilateral trade statistic data reported in physical quantities (tons). For the purpose of reconciling imports and exports to achieve consistency across all partner pairs LANDFLOW uses the larger of each pair of reported trade volumes. LANDFLOW calculates and adjusts for re-exports by solving for all reported agricultural and forestry commodities a system of linear equations that determines by an iterative process the land content of traded products.

The LANDFLOW livestock module treats ruminants (e.g. cattle, sheep) separately from other livestock (mainly pigs and poultry) according to their feed requirements and associated land utilization. Feed requirements together with feed use of different sources form the basis for attributing cropland use and pastures to the two animal groups. Feed sources are allocated to livestock categories in proportion to energy requirements of the respective livestock herds and according to suitability of feed sources for use in animal diets, i.e. while respecting dietary characteristics of animal types and the total amounts of recorded feed types, the feed energy balance of each animal type is satisfied as closely as possible.

The LANDFLOW model shows a particularly high product detail, especially of food products, as over 100 primary and processed crop commodities (using land use data from some 190 primary crops), and 27 livestock products are distinguished and tracked in the model.

As harvested areas are available for each primary product and country, the level of detail with regard to agricultural land data is very high. In addition, multi-cropping and fallow periods are accounted for in a way that land attributed to primary crop production matches the FAO country statistics of crop land (i.e. arable land and land under permanent crops). Almost all other reviewed land footprint studies fail to account for these agricultural management practices, which differ across countries.

Land attribution in LANDFLOW consistently deals with joint products such as vegetable oil and cake from oil crops, sugar and molasses from sugar crops as well as several joint animal products (e.g. meat, milk, offal, fats and hides from cattle; meat & eggs from poultry).

Coverage of supply chain depth is somewhat limited for some product groups (e.g. fibres, rubber, non-food use of vegetable oils) due to the domain boundaries of the FAOSTAT databases, where trade of highly processed agricultural and forestry goods and hence ultimate final uses of such highly processed commodities cannot be tracked within the LANDFLOW system. LANDFLOW tracks flows of raw materials to non-food industrial uses (as reported in FAO's utilization category 'Other uses') but cannot track the trade of highly processed industrial commodities coming from these industries. For instance, once animal fats enter the industrial sector to produce cosmetics, or tanned leather from skins and hides are turned into leatherwear or shoes, the trade of cosmetics or respectively shoes is not recorded in the FAOSTAT data. Other examples of trade that cannot be tracked on the basis of FAO data include biofuels produced from vegetable oils, clothes produced from fibres (cotton), or furniture made from wood.

LANDFLOW operates on an annual basis and FAOSTAT reports data with a one to three year time lag. LANDFLOW calculations are on a detailed commodity level. For reporting, commodities are summed up and commonly presented in terms of the following main commodity aggregates: First, *crop products* from cropland include eight sub-categories: 1) Cereals; 2) Roots & tubers; 3) Sugar crops; 4) Oil crops; 5) Fruits / Veg / Spice; 6) Stimulants; 7) Industrial crops; 8) Fodder crops. Second, two sub-categories of *livestock products*: i) Ruminants (e.g. cattle, sheep) using cropland and pastures, ii) other livestock (mainly pigs and poultry) relying on cropland for feed only. Third, *forestry products* from forest land include three sub-categories: 1) Wood products (sawnwood and panels); 2) Pulp and Paper; 3) Wood fuel.

LANDFLOW differentiates between the utilization categories food use, separate for vegetarian and livestock diets, 'other use' (mainly industrial), exports and equivalents for seeds and wastes (from field to farm gate). The LANDFLOW model provides clear and comprehensive descriptions of the model structure and the underlying assumptions.

6.1.2.3 German Federal Bureau of Statistics (StBA)

StBA developed a methodology to calculate Germany's land footprint in the time frame of 2000 to 2010 (Statistisches Bundesamt 2013; Mayer et al. 2014). The methodology is oriented at the approach developed for the German water footprint (Statistisches Bundesamt 2012; Flachmann et al. 2012). It specifies Germany and its 48 main trading partners plus one rest of the world region. The approach calculates land footprints for cropland and grassland for overall agricultural production including the livestock sector, i.e. 160 crops plus 8 categories of live animals, plus processing activities for 14 2-digit product groups from trade statistics. Calculations were undertaken for the time period of 2000 to 2010, base data would be available for an update with a time lag of 2 years (t-2). A number of technical reports clearly describe the applied methodology in high detail.

The StBA methodology is the only methodology among all reviewed approaches, which is fully compatible both with the German agricultural statistics, as trade data were adapted to be consistent with the special trade system. Another distinct feature of this methodology is that it allows disaggregating the results by main areas of use, i.e. 14 commodities made of crop products and 4 categories of animal products (meat, sausage products, dairy products separate for drinking milk, butter and cheese, and eggs).

Land use data for the StBA model were sourced from agricultural statistics for Germany and from FAO crop production statistics for imports. Land use for joint crop products was allocated according to the prices of the joint products following the principle of economic allocation. A detailed livestock module traces flows of feed from market-crops and grazing through the livestock system to the consumers. Requirements of cropland for feed and fodder production were calculated summing up inland production and feed imports as reported in foreign trade statistics. Significant efforts were made to allow allocating total feed supply to eight animal types, using information on the feed intake per animal and year, calculated based on livestock data and adjusted for the average lifetime of animals. Imported animal products were multiplied with land use coefficients derived for Germany, except for beef, where information from a WWF study was used.

Processed or manufactured products were converted back to their raw material equivalents using conversion factors from the FAO report on Technical Conversion Factors for Agricultural Commodities (FAO 2003). The approach on average reaches 70% product coverage. Due to the complexity of supply chains, only 70% of processed food products could be considered. This was complemented with additional estimates, hence attaining 92% product coverage.

Trade data are adjusted for re-exports for the most important crops and trade volumes by back-tracking flows to producing countries using COMTRADE data (manually implemented iterative procedure similar to LANDFLOW). This approach is probably still overestimating imports from European countries. However, it is an important correction to the raw data. Countries of origin were identified for 75.8% of the overall land requirements of imported products.

Re-exports in a wider sense, i.e. exports of processed products produced with imported raw materials (e.g. chocolate produced with imported cocoa), were considered building specific supply accounts for exports (i.e. distinguishing exports from imports and from domestic production) under the assumption that imported raw products are not exported without processing, i.e. exported raw products originate from domestic production.

6.1.2.4 Institute of Social Ecology (Erb 2004)

One of the very first coefficient approaches applied to the case of land footprints was presented by Erb (2004) at the Alpen-Adria University's Institute of Social Ecology (SEC). He developed a model for one country (Austria) to quantify the actual demand for domestic and foreign land for a very long time period (1926 to 2000). The model disaggregates 207 trading partners of Austria and a total of 61 agricultural products, of which 39 are primary products and 22 processed products. Erb distinguishes between a large number of land use categories, including pasture area, arable land area including permanent crops, forest area, as well as built-up area and energy land, the latter calculated as the corresponding CO2 equivalents of energy use multiplied with the average global sink-capacity of forests for carbon. The model is particularly strong with regard to the transparency of the methodology as well as the quality of the data sources, as official Austrian statistical data was combined with FAO and UN statistics.

Land area data were sourced from the FAO database for agricultural production, however without corrections for multi-cropping. Another, however, not specified, source was used for grassland data. For forest areas, two approaches were applied: 1) a production approach (using actual felling rates) based on FAO and UN statistics and 2) a sustainable yield approach, which calculated the hypothetical area needed according to the net annual increment of forests in the country of origin.

How processed products were transformed into primary equivalents is not specified, but presumably FAO conversion factors were applied. Also it was not documented in detail, how animal products were modelled. Re-exports were not considered on the import side. For exports a weighted mix of domestic production and imports was calculated.

6.1.2.5 University of Groningen – Institute of Social Ecology – Chinese Academy of Sciences (Kastner et al.)

Kastner and colleagues set up global models to trace embodied agricultural land (Kastner et al. 2011b; Qiang et al. 2013; Kastner et al. 2014a) as well as embodied forest land (Kastner et al. 2011a). This work is based on earlier work done at the University of Groningen (Gerbens-Leenes et al. 2002; Gerbens-Leenes and Nonhebel 2005) and integrates experiences gained earlier at the Institute of Social Ecology. The main novelty of the model developed by Kastner et al., which are well documented and described in the publications, is that they set up detailed bilateral trade matrices for various products and apply matrix algebra (similar to the use of a Leontief inverse matrix in input-output analysis, see above) in order to model international supply chains and thus trace direct and indirect linkages between producing and consuming countries. This approach is particularly designed to allow for a consistent accounting of re-exported agricultural and forestry products, both processed and raw.

FAO also serves as the main data provider for this approach, which uses production and trade statistics, Food Balance Sheets as well as Technical Conversion Factors from FAO. Also land data stem from FAO, but are not corrected for multi-cropping. For the forestry-related study, data was taken from the FAO Forest Resource Assessment.

The model disaggregates 172 countries and covers all primary agricultural products along with a number of processed products, however, the latter not being specified in detail. Processed products are transformed into equivalents of primary products according to the energy content in the agricultural studies and the carbon content in the forestry-related study. This approach is also used for the allocation of coupled products. Animal products are not considered in these models but are accounted for via national level feed balances in a more recent and yet unpublished work.

The approach has first been applied to a case study on Austrian soy consumption (Kastner et al. 2011b) and then been used to investigate embodied land related to China's crop trade (Qiang et al. 2013). Lately, it was also extended to all 255 countries covered in the FAO database (Kastner et al. 2014a). Time series calculations for the Austrian soy case have been presented for 1986-2005, and for Chinese external trade for 1986-2009, and for all countries globally for 1986-2009. The calculations depend on FAO statistics on the supply and utilization of crops and food commodities that are available for the period of 1986-2009 and are published with a time lag of 4 years.

As with most physical land footprint accounting methods, this approach does not allow distinguishing the main areas of final use of a certain product, nor can the industry be specified, which delivered a certain product to the final user.

6.1.2.6 Swiss Federal Institute of Technology (ETH)

A model to assess embodied land of Switzerland's international trade relations was established by Würtenberger and colleagues (2006). The study investigated the virtual land trade related to arable crops for Switzerland and its 125 main trading partners. The analysis was undertaken for the year 2001, but can also be applied to more recent years. With all products being aggregated into 8 product groups, the aggregation level of this model is relatively high compared to other coefficient-based approaches. The model also includes processed products, which were converted to primary product equivalents with the help of “transfer coefficients”. However, the source and quality of these coefficients cannot be judged, as no further information is provided by the authors. Animal products were defined out of scope in this study. Also coupled production was not specifically treated.

Land use data were taken from the FAO database without adjusting for multi-cropping. Trade data were obtained from Swiss national sources. Re-exports have not received consideration in this methodology.

6.1.2.7 Potsdam Institute for Climate Impact Research (PIK)

Applying the hydrology and agro-biosphere model LPJmL, a research group from PIK (Fader et al. 2011; Fader et al. 2013) primarily investigated the blue and green virtual water as well as virtual land trade of all countries world-wide, for 11 crops of global importance (temperate cereals, maize, rice, tropical cereals, temperate roots, tropical roots, rapeseed, groundnuts, soybeans, pulses, and sunflower). Additionally, they also calculate the land savings through international trade. Compared with other studies using physical accounting, this model only treats a very small number of primary crops and completely disregards higher processed products.

Using a grid classification (of 0.5° resolution) instead of a country approach, this approach stands out regarding the geographical detail from all other reviewed land footprint models. The authors apply yield data from the LPJmL model instead of FAO data used for most other methods. UN Comtrade is the main source for trade data, which are a kind of bottleneck for the grid cell-based analysis, as they are only available on the national level. Re-exports of agricultural crops are not considered. Calculations were so far only undertaken for the average of the period 1998-2002.

6.1.2.8 Humboldt University Berlin (HU)

Trade of “virtual land” of the European Union with the rest of the world was the focus for the analysis undertaken by von Witzke and Noleppa (2010). The authors aimed to assess how much agricultural land outside Europe was required to satisfy European consumption and how international trade of virtual land would change under alternative policy and technology assumptions. Calculations were done for the year 2007/08, but base data would be available to update the approach for more recent years.

The study considered a large number of products, i.e. 40 primary crops and 240 processed plant- and animal-based products, accounting for roughly 80% of the overall EU external trade with agricultural products. Main agricultural data sources used to set up the model include the Eurostat Agricultural Statistics, the FAPRI US and World Agricultural Outlook database and FAOSTAT. Corrections for multi-cropping are not applied. Regarding international trade, the authors use the Eurostat External Trade data set and do not consider re-exports.

Processed products were converted into agricultural raw products using a broad spectrum of processing parameters. Various weights, measures and conversion factors, based on e.g. FAO and U.S. Department of Agriculture (USDA) publications, were updated using additional sources. Meat and dairy products were converted into crops using feed ratios and feed mix percentages. Approaches on dealing with coupled products and information on crushing factors were used to avoid double counting of land areas.

The main weakness of this approach is that based on the existing documentation, the study is non-reproducible, in particular as the applied land intensity coefficients stem from a large variety of sources, i.e. reports, statistics and other mostly not peer-reviewed publications. Not all of these sources are referred, a more detailed description of own assumptions or estimations is omitted. It is therefore impossible to evaluate the quality and consistency of the coefficients. Furthermore, consistency of the coefficients-based results with official land use statistics (bottom-up vs. top-down) is not cross-checked.

6.1.2.9 Wuppertal Institute for Climate, Energy, Environment (WI)

Two recent studies on land embodied in international trade were published by the Wuppertal Institute. One study assessed the global land area required to meet the German consumption of agricultural products for food and non-food use (in particular biofuels) for the years 2004 to 2006 and potential changes until 2030 under various scenario assumptions (Bringezu et al. 2009). A later study focused on the global land use related to European consumption in the year 2007 (Bringezu et al. 2012).

The Wuppertal model is characterised by a very high product detail, with calculations being done for a total of 773 commodities (primary crops, plant based products and animal based products according to the 6-digits HS classification) in the European study. A further positive characteristic of the approach as carried out for the German case is that primary areas of use of biomass products are represented in great detail, being separated into material use (pharmaceutical plants, dye plants, fibres, starch, sugar, plant oils and fats, lubricants and additives), energetic use (biodiesel, plant oils as direct fuel, bioethanol, BtL, biogas as fuel, plant oils for electricity / heat, biogas for electricity / heat), plant-based nutrition and animal-based nutrition.

Land use data were taken from the German Ministry for Agriculture and various other data sources for processed and traded products. Animal products are based on feedstuff and production statistics of the German Ministry for Agriculture, thus implicitly assuming all imports coming from intensively managed systems. This represents one main weakness of this approach, as no regional specificity is adopted, i.e. for many commodities German productivity levels are assumed. EUROSTAT is used as the main source for international trade data in physical units; re-exports are not considered for European imports; for exports a weighted mix of domestic production and exports is calculated.

Generally, also the Wuppertal approach is difficult to assess with regard to its quality and consistency with official land use statistics, as the applied land intensity coefficients are taken from a large number of sources, including reports and other not peer-reviewed publications.

6.1.2.10 University of British Columbia (UBC)

In their study on the US external trade, Kissinger and Rees (2010) investigate the ecosystem area embodied in US imports of renewable resources. This model disaggregates the US and its 59 major import partners and covers 169 primary and manufactured products, including animal products such as live cattle, beef and lamb products (but not fowl or pork). The products are aggregated into 10 product groups. Calculations were done for the period from 1995 to 2005 and could be updated based on the described data sources. The methodology is generally clearly described, but further explanations of the used coefficients (see below) are missing.

For land use data, this approach applies FAO and USDA data for croplands, FAO data for pastures and the Canadian National Forestry Database for data on annual growth rates of forests. The conversion of processed or manufactured products back to their raw / fresh material equivalent is done using information from USDA, FAO (Technical Conversion Factors Guide) and industry sources e.g. for sugar, coffee and juices. For pasture land, the authors relate FAO grassland statistics to meat production and derive pasture requirement coefficients. Coupled production is not addressed in this approach.

Trade data is sourced from US databases (USDC, USDA). The authors do address the issue of re-exports and when encountering the problem that the country of origin is not a producer of the respective crop (but a re-exporter), they apply global average yield values. Imports to the US that are re-exported to other countries are also separately identified and excluded from the US land footprint.

6.1.3 Studies based on hybrid accounting

Acknowledging the limitations of environmental-economic and physical accounting approaches, several studies have tried to integrate elements of physical accounting into IO assessments of land footprints or vice versa.

6.1.3.1 RUG-PBL model

In order to assess the global land use and GHG emissions related to private consumption in the Netherlands, Vringer and colleagues (2010) and Benders et al. (2012) construct a hybrid IO model (RUG-PBL model). They build on experiences from previous hybrid energy models and apply this method to calculate the environmental load of Dutch consumption in terms of global warming potential, acidification, eutrophication, summer smog, and land use. In the model, the product life-cycles are split into two parts: major processes, i.e. those that have a significant impact on the overall results such as mining and energy sectors, are modelled using physical process analysis, while all remaining processes are modelled with a simplified, 4-region input-output model (Netherlands plus three other world regions) based on GTAP. Therefore, the processes of a product life cycle are partly described in physical terms and partly in financial terms. The basic goods, packaging materials, transport, direct consumption in the households, and waste processing are described in physical terms by means of process analysis. Capital and residual goods, manufacturing, and trade are described in economic terms by means of input-output analysis. Land use data are obtained from FAOSTAT. For all calculations, the assumption is made that imports are produced with the same technology and environmental load as in the Netherlands. An incomplete documentation of the method and a lack of specifications for the sources data impede a full evaluation.

6.1.3.2 EUREAPA model

The EUREAPA model has been developed and tested for the case of the Ecological, Water and Carbon Footprint ("Footprint Family") (Weinzettel et al. 2011; Ewing et al. 2012; Steen-Olsen et al. 2012; Weinzettel et al. 2013; Weinzettel et al. 2014). The authors state that in order to fully consider a higher product detail in the MRIO framework, the IO tables would need to be disaggregated and all bilateral trade relations would need to be adjusted accordingly. As this is a very laborious task, the authors suggest an alternative procedure with less effort: they create physical satellite accounts, which illustrate to which countries and sectors primary agricultural products are delivered in the first step. Using FAO data, the physical use structures of primary agricultural products can be modelled in a detail of single products. But instead of linking agricultural products (and their related land area) to the MRIO system at the point of primary production, the environmental data are allocated to the first recipient of this primary production, either in the domestic or a foreign economy. This allows keeping the full product detail, without changing the overall MRIO sector structure.

Therefore, this approach reaches a very high detail in the distinguished products and related land areas. The underlying MRIO system is based on the GTAP database, so the limitations of this database also apply to the EUREAPA model.

6.1.3.3 German Federal Bureau of Statistics – RME

The German Federal Bureau of Statistics (StBA) developed a detailed and comprehensive approach for calculating the imports, exports and material consumption for Germany in raw material equivalents (RME), including the indicators RMI and RMC. The StBA RME approach, unless developed for the calculation of material flows, could be extended by land use and serve as a basis for land flow accounts with only small efforts.

The methodology consists of three main elements (Buyny et al. 2009):

- National input-output tables for Germany (73 x 73 sectors);

- the calculation of the RME of selected imports to Germany with the help of LCA-based coefficients;
- and the establishment of specific hybrid input-output tables, i.e. tables that include both monetary and physical units in the technology matrix (A matrix), for each considered raw material ("physical material flow tables").

The German approach thus addresses several shortcomings of other approaches. First, the use of detailed additional information on the physical flow of certain raw materials allows implementing a deeper level of disaggregation than the standard IO table would enable, which only separates 3 extractive industries and 8 extraction products. Through this additional modelling, a total of 39 abiotic and 16 biotic raw materials can be separately considered in the calculations. For each of the 55 raw materials, detailed supply-use accounts in physical units (i.e. tonnes) were established, in order to model the first stages of each production chain in detail (from extraction via processing to intermediate products). This is done for the first stages of production, because the potential errors originating from allocating several different materials to only one sector in the input-output model are much larger at the first stages of processing than at later stages of the production chain where various materials are incorporated in higher manufactured products and the allocation more closely follows the monetary flows. In order to create these physical supply-use accounts on the level of single materials, detailed German supply-use data (3000 products by 120 production activities) plus additional data (e.g. physical supply-use tables for wood products) are used, partly from non-published StBA-internal sources.

Second, the indirect material flows related to imports are generally calculated applying the modified German input-output tables and applying the domestic technology assumption, i.e. assuming that imports from other countries were produced with the same input factors as applicable in Germany. In order to avoid mistakes for goods that are produced differently in Germany or not at all, an exemption to this general procedure is made for a number of raw materials, which are separately modelled applying LCA-based factors. The factors have been compiled from various literature sources and partly modelled with the LCA software "Umberto". A detailed technical report informing about the approach and results concerning the material intensity coefficients is available (Lansche et al. 2007).

For wheat, for example, Canadian yields and production system properties have been assumed for all imported quantities; Italian conditions for rice imports; Egypt was taken for potato imports. As crop yields differ greatly between countries, a robust land flow accounting method should consider the respective yields of the country of origin.

The results for the German hybrid model published so far (Buyny et al. 2009) cover the time period from 2000 to 2005, however, longer time series could be calculated, as German supply-use tables are currently available for 1995-2010.

6.1.3.4 Eurostat – RME

In a series of projects, carried out by external consultants, Eurostat developed a methodology for assessing the indirect material flows related to European imports and exports and calculated the RMI and RMC indicators. The Eurostat RME approach, unless developed for the calculation of material flows, could be extended by land use and serve as a basis for land flow accounts with only small efforts.

Aggregate results for the EU-27 have been presented in a time series of 2000-2011. For the Eurostat methodology, a number of publications and detailed technical reports (Schoer et al. 2012a; Schoer et al. 2012b; Schoer et al. 2013) as well as a range of online material and data sets are available[20], making this methodology very transparent.

As for the StBA RME calculation approach, imports into the EU-27 are calculated using the domestic technology assumption. An exception are 62 selected products and product groups, mainly metal ores and energy carriers, for which specific material intensity coefficients of imports were calculated (here called "LCA products"). The main data source for these coefficients was the ecoinvent 2.0 database (see www.ecoinvent.org). However, as the authors state, ecoinvent is not very reliable regarding metal ores, therefore additional research was undertaken using data from USGS and mining reports to derive appropriate ore grades for metal imports into the EU-27. Although metal ore grades significantly differ between countries of origin, it was decided to apply global average ore grades, because huge variations in ore grades between years and countries were observed, with a potentially distorting effect on the overall results.

As with the StBA RME approach, the original aggregated IO table for the EU-27 was significantly modified, in order to adapt it to the requirements of assessing embodied material flows. While the StBA RME model keeps to original sector structure (73 x 73 sectors) and provides additional detail through implementing physical input-output structures on the level of single raw materials (see above), the Eurostat RME model disaggregates the whole input-output table. Starting from the original 60 x 60 products tables from Eurostat, the IO table was expanded to a 166 x 166 products table by using additional information, such as total output of more detailed product groups and detailed German supply and use structures, which are not publicly available. With this method, more than 50 product categories, 48 different material extraction sectors (15 biomass, 10 fossil fuels, 18 metal ores, 5 minerals), and ten categories of final demand can be specified.

In addition to detailing the sectors, in order to allow separating a larger number of single materials, a mixed-unit input-output table was created by replacing the monetary information for some sectors in the IO table with data in physical units. This was done, e.g., for biomass products, for sectors containing abiotic raw materials and basic metals as well as for energy carriers. The authors argue that for these products physical use structures are more appropriate for depicting the flows of materials through an economy compared to monetary structures. In reality, different users of a certain raw material or energy carrier, pay different prices for the same product (Schoer et al. 2012b) and thus monetary use structures are not simply a unit conversion from the underlying physical structure (see also Hubacek and Giljum 2003).

The Eurostat RME model can thus be regarded a very advanced approach, applying a highly detailed, mixed-unit input-output model, where a number of imported products are calculated with specific material coefficients. However, except for a range of metals and metal products, domestic technology assumption is used. Therefore, the method would need to be further developed for the calculation of robust land flow indicators.

[20] See **http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/documents/**.