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

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Abstract

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

Keywords: telecouplings; global land system; land footprint; physical flow accounting; material flow analysis; input–output analysis

1 Introduction

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

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

The concepts of telecouplings (Liu et al., 2013; Liu and Yang, 2013) and land teleconnections (Güneralp et al., 2013; Haberl et al., 2009; Seto et al., 2012; Yu et al., 2013) provide an analytical framework to investigate socio-economic and environmental interactions over distances, to measure their extent, drivers and impacts and to formulate adequate responses. Measuring telecouplings challenges research and governance due to their complexity involving multiple agents acting across multiple systems at different scales and interacting via physical, monetary and information flows. Studies of the global biomass metabolism investigate the physical flows between and within nature and human systems, tracking flows between distant places and along complex supply chains and considering environmental implications of trade-related teleconnections (Fischer-Kowalski, 1998; Haberl et al., 2009). Human–nature metabolism studies provide a useful basis for understanding the interrelatedness of changes in one place with ecological, economic, and social impacts elsewhere.

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

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

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

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

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

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

2 General concept and main methods of land footprint accounting

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

An important difference between approaches is whether supply chain flows and embodied land use are tracked in terms of monetary values or physical quantities. We henceforth term approaches tracking land along monetary value chains as *environmental-economic accounting*, and approaches using physical volumes as *physical accounting*. *Hybrid accounting* uses a combination of both. An alternative

nomenclature used in a review by Henders and Ostwald (2014) denotes monetary approaches as input–output analysis and physical methods as material flow analysis.

2.1 Environmental-economic accounting

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

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

2.2 Physical accounting

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

Physical accounting models use information on the production, imports, exports and domestic utilization of primary and processed commodities from agricultural and forestry statistics and combine this with technical knowledge on conversion efficiencies for building a consistent commodity tree structure (for a more detailed explanation, see Section 5 and Figure 2b). Existing data sources allow tracking global supply chains of food and wood products. Highly processed products, in particular for non-food uses, cannot be captured by this means. Some studies therefore integrate additional information, for example, from life cycle assessments (LCA), to capture also these products and their supply chains (Bringezu et al., 2012; Kissinger and Rees, 2010).

2.3 Hybrid accounting

In the past few years, hybrid (mixed-unit) accounting became increasingly popular in footprint-type calculations. These methods combine elements from monetary input–output analysis with physical accounting or process-based coefficients and aim at exploiting the advantages of both methods.

Hybrid accounting methods apply a differentiated perspective for the calculation of footprint-type indicators for different products and product groups, depending on the processing stage and data quality and availability. Typically, they apply physical accounting for raw materials and products with a low level of processing, as data for these commodities allow taking into account land intensities and countries of origin at a much more detailed commodity level than is currently possible in global environmental-economic accounting studies. Processed commodities and finished goods with more complex production chains are treated with environmental-economic accounting methods, which allow considering the full upstream resource requirements and thus including all indirect effects (Ewing et al., 2012; Vringer et al., 2010).

This combination of physical and environmental-economic accounting methods is realised in various ways. Some studies apply input–output analysis to derive land intensity coefficients for highly processed products for complementing process-based physical land accounts (Meier and Christen, 2012; Meier et al., 2014). Others set up physical satellite accounts to model crop flows and related embodied land from agricultural production to the first use stage, for example, wheat flows from agriculture to food processing and livestock production, and track the remaining parts of the supply chains within monetary IO models (Ewing et al., 2012; Steen-Olsen et al., 2012; Weinzettel et al., 2013; Weinzettel et al., 2014; Weinzettel et al., 2011). Beyond that, there exist further options for hybrid accounting, not yet applied to land footprint calculations. For example, several material footprint studies integrate detailed statistics in mass units into monetary IOTs, thereby creating mixed-unit IOTs (Buyny et al., 2009; Schoer et al., 2012; Schoer et al., 2013).

3 Mapping the field of land footprint research

The review undertaken for this article covers publications in the thematic area of virtual land flows and tele-connecting land use in primary production with consumption activities. Publications in the areas of virtual water flows, Ecological Footprint¹ and eHANPP (embodied Human Appropriation of Net Primary Productivity), although methodologically related, have not been included in the review of accounting techniques. Table 2 provides a detailed publication list structured according to authors, research institution of the first author, and applied methodology. Detailed descriptions of all reviewed studies can be found in the Supporting Information.

¹ Not to be confused with the land footprint, which in contrast to the Ecological Footprint accounts for actual land (see, e.g., Erb, 2004).

Table 2: Overview of methods for the quantification of land footprints and related publications

Method	IO data set ^a	Research institution ^b	Publications	
Environmental-economic accounting	GTAP	Netherlands Environmental Assessment Agency (PBL)	Wilting and Vringer (2009)	
		Sustainable Europe Research Institute (SERI)	Lugschitz et al. (2011), Bruckner et al. (2012b)	
		University of Maryland (UMD)	Yu et al. (2013)	
		Vienna University of Economics and Business (WU)	Bruckner et al. (2014)	
	WIOD	Joint Research Centre (JRC) ^c	Arto et al. (2012)	
Physical accounting	EXIO-BASE	Norwegian University of Science and Technology (NTNU) ^d	Wood et al. (2014)	
		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)	
		Potsdam Institute for Climate Impact Research (PIK)	Fader et al. (2011), Fader et al. (2013)	
		Humboldt University Berlin (HU)	von Witzke and Noleppa (2010)	
		Université Catholique de Louvain (UCL)	Meyfroidt et al. (2010)	
		University of Helsinki (UH)	Sandström et al. (2014)	
		International Institute for Applied Systems Analysis (IIASA)	IIASA et al. (2006), Prieler et al. (2013)	
		German Federal Statistical Office (StBA)	Mayer et al. (2014)	
		University of British Columbia (UBC)	Kissinger and Rees (2010)	
		Wuppertal Institute for Climate, Environment, Energy (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)
			Norwegian University of Science and Technology (NTNU) / Global Footprint Network (GFN) ^e	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)

^a We specify the used source of IOTs and trade data for studies applying MRIO analysis.

^b 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.

^c See http://www.wiod.org/new_site/project/participants.htm.

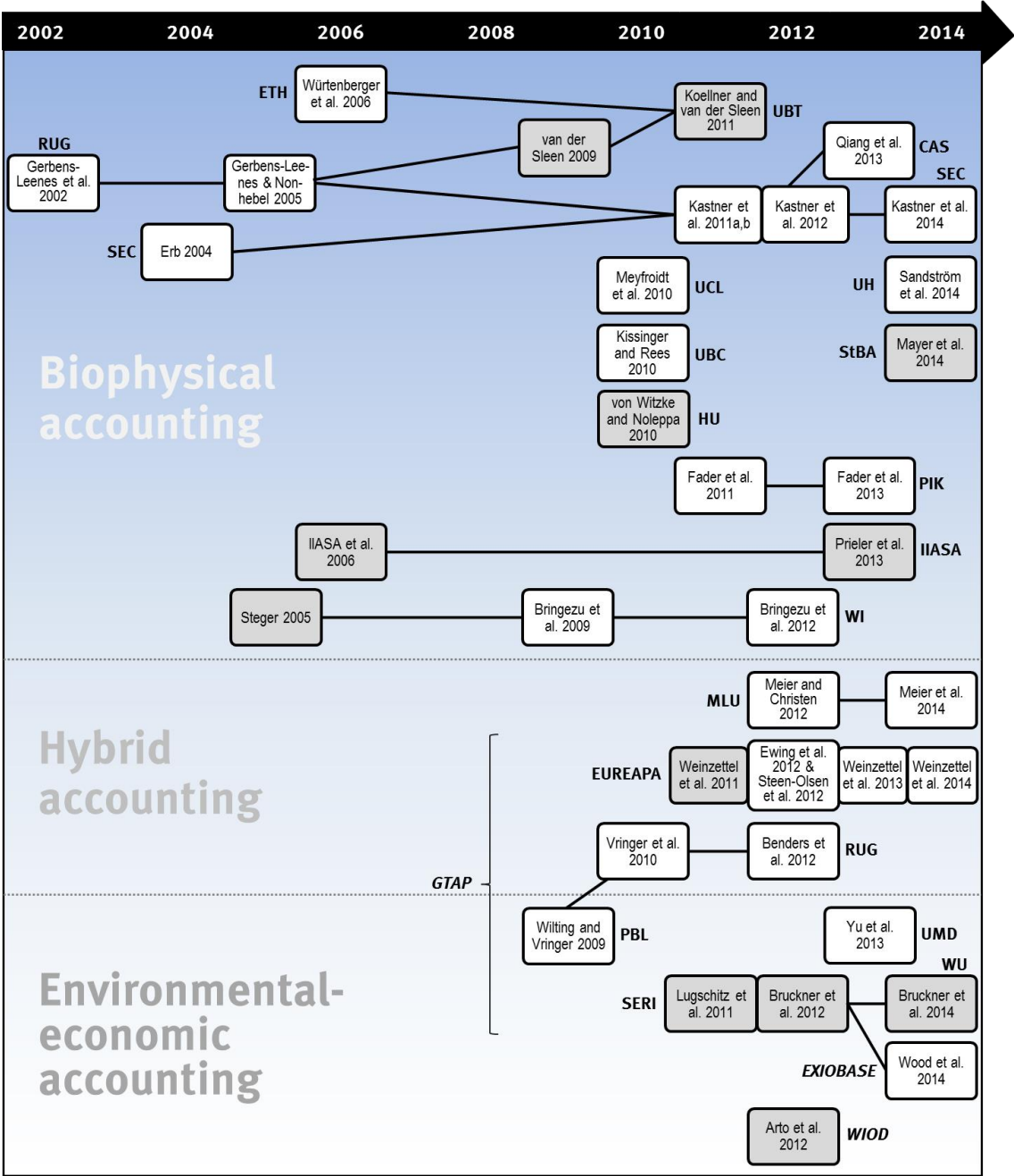
^d See <http://exiobase.eu/about-us/partners>.

^e See <http://eureapa.org/>.

The development of land use accounting methodologies is a very dynamic and rapidly expanding field. We illustrate the genesis of the field of research on global land flows along a time line between the years 2002 and 2014 (Figure 1). Boxes represent publications (white boxes for peer reviewed and grey boxes for non-peer reviewed publications) connected via solid lines indicating contribution of one or more co-authors or research institutions to the particular study. The applied IO databases are

mentioned in italic letters, where applicable, while abbreviated institution or model names are written in roman letters. For full institution names please refer to Table 2.

Figure 1: Genesis of the various research strands in land footprint research



This illustration, although not claiming to cover all available publications concerned with consumption-based land use accounting, shows that some of the first studies applying physical accounting for the calculation of land footprints were developed in the early 2000s. 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 quarters of the reviewed studies were published in or after 2010.

The following sections provide a comparative analysis of the various methodological and data options employed in land footprint calculations. We discuss key aspects and implications of the calculation procedures structured by 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.

4 Land use in 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. 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 and forestry land use and production statistics (FAOSTAT, 2014). This database is the only available land use database with global coverage. The data are compiled by FAO primarily based on questionnaires delivered by individual countries. Although some of the data reported by countries may be incomplete or inaccurate (Ramankutty, 2004), FAO is regarded as an authoritative source for land use and especially agricultural data and indeed, is the only source available for large-scale global studies related to biomass and land. In the following, we describe some important details, which need to be considered when compiling land data for the set-up of flow accounts for cropland, grassland and forestland, or when interpreting results from land footprint studies. Built-up areas and other artificial land, although subject to particularly high environmental impacts, are not taken into account by the reviewed land footprint studies and are therefore not further described here.

4.1 Cropland

Attribution of physical cropland to primary crop production may result in interpretation problems when farming practises include multiple crops within a single year. Multi-cropping is prevalent in many tropical countries where farmers often obtain from one field two or more harvests per year. Yields of 6 tons of rice per harvested hectare thus could actually conceal annual yields of 12 or 18 tons per physical hectare when multi-cropping is applied. Conversely, economic activities might not only depend on the land areas directly used in a particular year. Especially in low-input agricultural production systems extended fallow periods are a necessary element in many traditional crop rotation systems. Only three out of the reviewed studies (Bruckner et al., 2012b; IIASA et al., 2006; Prieler et al., 2013) adjust cropland use data for multi-cropping and fallow.

4.2 Grassland

There is a lack of reliable data on the extent of grassland used for livestock grazing and forage production (i.e. pastures). Moreover, grassland statistics report extents but do not specify biomass productivity. For instance, an extreme case is Saudi Arabia, where as much as 79% of the land surface is reported to be permanent meadows and pastures (FAOSTAT, 2014), albeit mostly with very low productivity. All this may result in large differences between countries in the derived grazing areas per animal and may have considerable effects on the land footprint results. Grazing areas constitute the largest fraction of global human land appropriation and its expansion has been a major driver of deforestation in the tropics. Reliable accounting of pasture footprints is hence desirable. Some studies, therefore, try to estimate the required grassland areas instead of relying on statistical sources. This is, for example, done by calculating the grass demand of a reported livestock herd (Krausmann et al., 2008) and deriving the accordingly required pasture areas based on global grassland productivities, which can, for example, be obtained from the grid-cell based biogeographical GAEZ model (IIASA/FAO, 2012).

4.3 Forestland

While reported cropland areas can be considered as being fully utilized by the agricultural systems for accomplishing the reported annual crop production quantities, significant parts of the forestland on the

planet are not managed or are used only extensively. Land use statistics are usually incomplete regarding the purpose and use of forests. Therefore, land footprint studies have often assumed all reported areas as the underlying physical land base required for the production of the primary produce (timber or wood fuel), thereby overestimating land requirements. However, a differentiation between managed forest land and undisturbed natural forests is not trivial. Only for few countries and years, data on the actually productive or harvested areas are available (FAO, 2010; UNECE/FAO, 2000). As it seems currently impossible to account for actually used forestland, many studies decide to adopt a sustainable yield approach (Bringezu et al., 2012; Bruckner et al., 2012b; Erb, 2004; Prieler et al., 2013). These studies calculate the forest area required to harvest the reported timber production, assuming that forests are sustainably managed and on average only the net annual increment is harvested.

5 Tracking land flows along global supply chains

This chapter introduces the available data options and analyses the characteristics of accounting methods based on monetary and physical supply chain data. Monetary IOTs, used in environmental-economic accounting methods, depict the inter-sectoral flows within and between economies and to final consumers. Based on these data, all global supply chains can be tracked. Physical accounting models are based on production, trade and available supply chain statistics reporting quantities. Yet, consistent statistics comprising physical data on inter-sectoral flows, such as physical IOTs (Giljum and Hubacek, 2004; Hubacek and Giljum, 2003), are lacking.

5.1 Overview of sources for supply chain data

Table 3 provides an overview of 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 MRIO databases (namely EXIOBASE, WIOD, OECD, GTAP and Eora, albeit only three of them have been used for land footprint assessments yet) contrasted with FAO-STAT, which is the most widely used data source for physical land accounting models. Figure 2 shows an illustration of the basic structure of (a) input–output tables and (b) supply–utilization accounts.

Table 3: Global data sets for the construction of land footprint accounting models

	EXIOBASE	WIOD	OECD	GTAP	Eora	FAOSTAT
Countries and regions	44 + 5 RoW	40 countries (27 EU countries and other major economies) + RoW	48 countries (all OECD countries and other major economies)	108 + 21 RoW (less detail for years before 2007)	189	236 UN countries/regions
Agricultural & forestry sectors	17	1	1	13	1-17	> 200 primary production items
Food / non-food biomass processing sectors	10 / 10	1 / 4	1 / 3	8 / 5	~1-40	~150 agricultural SUA items
Total number of sectors	200c/163i	35i	36i	57c	20-500c/i	2 raw and 7 processed forestry items
Time dimension	2000, 2007 (currently updated to 1995-2011)	1995-2011	1995, 2000, 2005	1997, 2001, 2004, 2007	1990-2011	1961-2013 (printed statistics available for earlier years)
Update frequency	unknown	unknown	5 year steps, time lag 5 years	3 year steps, time lag 5 years	unknown	annually, time lag 1-3 years
Units	EUR	USD	USD	USD	USD	tons, USD
Industry or commodity classification & technology assumption	industry with FSA, commodity with ITA	industry with FSA	industry with FSA	mixed	mixed	commodity (no technology assumption required)
Data provider	academics	academics	official OECD statistics	academics	academics	official UN statistics
Availability	free	free	free	USD 215-5,550	free	free

Note: i = industries, c = commodities, ITA = industry technology assumption, FSA = fixed product sales assumption

5.1.1 Monetary supply chain data

As illustrated in Table 3, the different MRIO data sets have complementary strengths. The main advantage of EXIOBASE is the high sectoral detail, but is so far only available for 2000 and 2007. 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. GTAP has its major strength in the large number of countries and the disaggregation of a large number of sectors in the area of agriculture and food production. However, as data is supplied by individuals, agencies and institutions from around the world, it is a difficult task to ensure high quality and consistency. The largest number of countries and a long time series is provided by the Eora system with varying sector detail (between 20 and 500 sectors) and integrating supply–use and input–output tables.

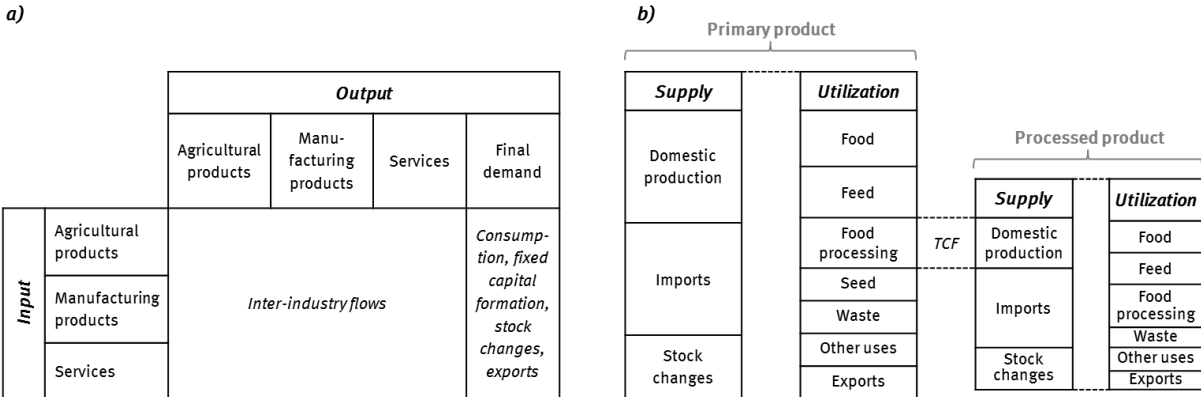
Yet, some global IO datasets are contested for quality or transparency issues. For example, a recently published article discusses some alleged flaws of land footprint calculations for China based on MRIO analysis (Kastner et al., 2014b). Physical accounting approaches revealed significant net imports of embodied land (Qiang et al., 2013), while MRIO-based calculations show net exports (Weinzettel et al., 2013; Yu et al., 2013). Both MRIO studies considered by Kastner et al. (2014b) use GTAP, which shows significant intermediate flows of about 20% of agricultural outputs, and even more for highly land-intensive animal products, to various export-oriented manufacturing industries. In contrast, according to the SUAs provided by FAOSTAT (2014) only about 10% of all agricultural commodities

used in China are utilised for non-food purposes. This inconsistency between agricultural and economic statistics could explain the effect revealed by Kastner and colleagues.

5.1.2 Physical supply chain data

FAO provides the most comprehensive set of global agricultural and forestry statistics reported by countries and quality-checked by FAO. FAO’s supply–utilization accounts (SUA) provide time series data on the supply and utilization of agricultural commodities (see Figure 2b) which are balanced in terms of physical quantities by matching supply (domestic production and imports) with uses (exports, stock changes and domestic supply including food, feed, processing, seed, waste and other use). The SUA database structure is designed to cover each country’s entire agricultural and food processing sector (FAO, 2001). Over 200 different primary and processed crop and livestock commodities can be linked to form a consistent commodity tree structure using technical conversion factors (see TCF in Figure 2b) provided by FAO (2003). 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 wheat but also all imported wheat products converted into primary wheat equivalents. Yet, due to FAO’s focus on food security, information on inter-sectoral commodity flows captured in the SUAs is limited to food products. Non-food products from biotic sources, such as biofuels and bio-chemicals, are lumped into the utilization category ‘other uses’ and tracked only to their first processing stage.

Figure 2: Structure of an input–output table (a) and of a supply–utilization account (b). TCF = technical conversion factor.



5.2 Attributing land use to supply chains

A crucial element of physical flow accounts, as defined by the System of Environmental-Economic Accounts (SEEA) Central Framework (United Nations et al., 2014), is to consistently link environmental and economic statistics. While physical supply chain data arise from the same statistical sources as land use data, namely agricultural statistics with underlying consistent classifications, monetary supply chain data originate from the system of national accounts, with possible inconsistencies and gaps for example with regards to non-market production. While the current standards and guidelines for both national accounts and agricultural statistics capture all market activities as well as non-commercial or non-market production (FAO, 2011; United Nations, 2009, p. 466), full consistency between these two statistical sources cannot be ensured. In some countries subsistence agriculture and forestry cover large parts of the provision of food and wood (Kostov and Lingard, 2004; Morton, 2007). Thus, accounting methods that directly combine economic and agricultural statistics, i.e. environmental-economic accounting approaches, could substantially overestimate land intensities of exports from those countries.

5.3 Value-based and mass-based allocation

The major difference between environmental-economic and physical accounting approaches is whether supply chain flows and embodied land use are tracked in terms of monetary values or physical quantities. If all flows of the product groups specified in a model within and between countries were fully homogenous in terms of prices, the use of monetary or physical supply chain data for tracking embodied land flows could be considered equal from a conceptual point of view, disregarding differences in data availability. However, this is not the case. Quality and resulting price differences in product flows result in differences of value-based and mass-based allocation methods. In order to demonstrate the effect of differing prices of export flows, we calculate the ratio δ_i of rice footprints for countries i derived with an environmental-economic accounting model using EXIOBASE (Tukker et al., 2013) to those calculated with a physical accounting model based on FAO's statistical databases (FAOSTAT, 2014), described by $\delta_i = r_i^{econ} / r_i^{phys}$, where r_i^{econ} and r_i^{phys} represent the rice footprint of country i calculated with the environmental-economic and the physical mass-based accounting approach, respectively. Results are significantly correlated with per capita income ($R^2 = 0.665$), indicating that the rice footprint of wealthier countries increases when flows are allocated according to monetary values as opposed to a mass-based allocation, while for low-income countries footprints are lower when using economic allocation. Quality and related price differences between rice imports to high-income and low-income countries can be assumed to cause these differences, a discrepancy which is discussed extensively by Schoer et al. (2013).

5.4 Joint products

A consistent treatment of joint products (e.g. oil and cake from soybeans, milk and meat from cattle) needs to be ensured in order to avoid double counting. Many studies consider this 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. In the case of oil seeds, which produce jointly energy-rich oil and protein-rich feed, allocation according to energy or protein content would attribute the lion's share of the embodied land to only one of the two joint products. And in cases where the main product incorporates only a small share of the total weight of the starting product, while the major part of the physical quantity is going into a low-value by-product supply chain, weight based forms of allocation may be inadequate. Economic allocation, i.e. allocation of joint production according to the value share of each component, is often used in life cycle assessments as it reflects the economic incentives of producers. Economic allocation is the standard allocation form in environmental-economic accounting models and can also be applied in physical accounting approaches, when using prices to convert physical quantities into monetary values.

5.5 Animal products

In Germany around 60% of the overall land footprint of food is due to the consumption of animal products (Statistisches Bundesamt, 2013). Thus, the treatment of livestock production has a particularly important role in land footprint accounting models. Due to the low sectoral detail of IOTs, environmental-economic accounting is not well suited for tracking land in the supply chains of animal products. In most IOTs 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 for all agricultural produces even though in reality the land intensities of, for example, ruminants and poultry are very different.

In physical accounting systems, agricultural statistics are used to compute specific land intensities for different livestock products. This can be realised either in a top-down approach, starting from livestock herds, their diets including feed crops and biomass from grazing together with feed supply statistics by apportioning reported market and non-market feed to different livestock types and products.

The second option is a bottom-up calculation, using feed conversion ratios for different animal products. In contrast to this method, top-down accounting approaches, whether tracking physical or monetary flows, are consistent with land use data, i.e. land demand of all countries sums up to global land use. Such methodologies were developed by the German statistical office (Mayer et al., 2014) based on German country statistics and by IIASA (IIASA et al., 2006; Prieler et al., 2013) and Meyfroidt et al. (2010) based on global FAO statistics.

5.6 Non-food products

Non-food products are relevant, considering that with a possible rise of the bio-economy, non-food uses of biomass may increase substantially in future years (Carlson, 2007; Hertel et al., 2013; Sheppard et al., 2011). Non-food biomass supply chains include i) specialized industrial crops (e.g. textiles from fibre crops; cigarettes from tobacco leaves; tires from natural rubber); ii) commodities, which are used for both food/feed as well as a wide range of bio-based industrial products (biofuels from sugar or oil crops; leather products or wool from livestock); and iii) forestry products (e.g. furniture from roundwood). These products are fully captured by the environmental-economic accounting method, as all upstream flows of agricultural products across non-food industries up to final consumption are included in the IOTs in sufficient detail. In contrast, available data for physical accounting approaches lack information on the further utilization of highly processed non-food products from biotic sources.

Some studies disregard the data gap and attribute land embodied in non-food products to the country where the last recorded use occurred (IIASA et al., 2006; Kastner et al., 2014a; Kastner et al., 2011b), which may differ from the actual consuming country when such industrially processed goods are traded. Others disregard non-food products or consider them using coefficients from process-LCA (Bringezu et al., 2012; Bringezu et al., 2009; Kissinger and Rees, 2010; Mayer et al., 2014; von Witzke and Noleppa, 2010). Since LCA studies are technically detailed but rely on assumptions and data from certain representative industries the regional specificity and representativeness and, as a consequence, consistency with national and global land use statistics is usually impaired.

Alternatively, monetary IOTs can be applied for the tracking of non-food products from processing industries to final uses, thus building a hybrid top-down approach. The EUREAPA model, so far applied to the cases of the ecological, water and carbon footprints (Ewing et al., 2012; Steen-Olsen et al., 2012; Weinzettel et al., 2014; Weinzettel et al., 2011) applies such a hybrid accounting approach by integrating detailed physical biomass and land accounts and input–output analysis.

5.7 Tracking land in traded products

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 completeness, quality and consistency. One main challenge of consumption-based land use 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. Therefore, additional steps and assumptions are needed to account for land associated with re-exports.

Applying the Leontief model (Leontief, 1936), as used in environmental-economic accounting methods, upstream flows can be tracked across countries. Physical accounting studies sometimes simplify by assuming the exporting country to be the producing country (Fader et al., 2011; Würtenberger et al., 2006). This assumption is problematic for crops that are not produced in the re-exporting country, or produced with yields differing from that of the country of origin. Some studies apply global average yields when the country of origin cannot be the producer of the respective crop (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 (IIASA et al., 2006), where the land intensities of imported commodities are adjusted for re-exports by recalculating land in global trade flows in an iterative process. The German Statistical Office 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 (for example, 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 and consequently, that exported raw products originate from domestic production. A study by Kastner et al. (2011b) proposes a mathematical approach using matrix algebra similar to the Leontief model to track the origin of a product in physical terms.

5.8 Determining the end user

The aim of consumption-based land use accounting is to attribute all observed land uses to various categories of consumption. In input–output analysis, underlying the environmental-economic accounting approaches, final demand is used as a proxy variable for consumption. This assumes that the paying agent equals the consuming agent. 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 statistics². Another example is caterings and company-subsidised canteens, where the eventual consumer is often not the payer and land embodied 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 based on agricultural SUAs face the problem that supply chains of non-food commodities may end in manufacturing industries, as described in section 5.6. Further utilization and trade of these goods cannot be tracked because of limitations in the data domain of the SUA data system. Attributing product flows to final utilization according to SUAs, the embodied land is assigned to the country where the last recorded use occurred, which may differ from the actual consuming country when such industrially processed goods are traded.

Obviously all fibre crop production is dedicated to non-food uses. In addition, globally, an estimated 10-12 percent of ruminant livestock products, sugar and oil crop production is used for non-food purposes (EC, 2013). This limitation is also relevant in the forestry sector. Hybrid accounting approaches can be used to extend the tracking analysis using monetary information for situations where the final utilization item of SUAs is subject to further trade and processing before final consumption.

6 Advantages and limitations of accounting methods

The review of land use accounting methods has clearly revealed some major advantages and limitations of environmental-economic, physical and hybrid accounting approaches. We found the most relevant differences for 1) the level of commodity and country detail, 2) the consistency of the applied base data, 3) the scope of supply chain coverage, and 4) the applied allocation logic. These differences are summarized in Table 4 and further described below.

² However, according to Kastner et al. (2014b) food aid shipments only account for 0.7% of the total global production for export (on average between 2007 and 2009).

Table 4: Main characteristics of consumption-based land use accounting methods

	Environmental-economic accounting	Physical accounting	Hybrid accounting
Level of detail	(-) aggregate sectors with limited commodity detail; often aggregate country groups and rest of world region(s)	(+) high level of detail for primary and processed crop and livestock products; all UN member countries distinguished	(+) high level of commodity and country detail possible
Data consistency	(-) attribution of land use data to aggregate monetary production data can be problematic	(+) specific allocation of land use to biomass production according to reported national yields	(+) allocation of land use 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 complete supply chains
Allocation logic	(-) land embodied in a sector's output is allocated to different uses according to monetary flows, potentially leading to biased attributions due to different value-to-weight ratios	(+) land is allocated according to physical commodity flows, thus avoiding distortions by utilization-specific differences in value-to-weight ratios	(+) applies physical allocation to the extent possible; complements with monetary IO data where needed

Note: (+) advantage, (-) disadvantage

6.1 Environmental-economic accounting

Environmental-economic accounting, applying multi-regional input–output analysis, stands out with its comprehensive coverage of the full (global) economy, allowing to track flows along increasingly complex international supply chains (Chen and Chen, 2013). IO models therefore avoid truncation errors, as per definition all products, including highly-processed biomass-based products are being considered by the calculations (Lenzen and Dey, 2000). In addition, all IO models fully consider re-exports, based on the assumption that exports are a weighted mix of imports and domestic production. Finally, IO models follow a top-down logic which ensures consistency and avoids double counting as all supply and use chains are completely represented (Daniels et al., 2011; Feng et al., 2011).

A major disadvantage of input–output analysis is the limited commodity and regional detail determined by the sector and region definitions of each IO model (Bruckner et al., 2012a; Wiedmann et al., 2011). The assumption of a homogenous product output of each product group leads to inaccurate results, for example, when crops with widely diverging mass-value-ratios are aggregated into one product group. Even the most detailed IO data sets available combine, for example, spices and fodder crops into one aggregated product group.

Another uncertainty arises from the fact that economic allocation tracks land use in economic supply chains assuming proportionality between monetary flows and embodied land (referred to as ‘allocation logic’ in Table 4), which can cause distortions due to the fact, that value-to-land ratios of a product may differ for different uses, as has been illustrated above for the case of rice (see also Liang and Zhang, 2013; Weisz and Duchin, 2006, for a discussion of the effect of price differences in IO models). Furthermore, problems related to the consistency between agricultural and economic statistics when allocating land use to IOTs may result in large errors, particularly for goods and countries with a high share of non-market production. Other disadvantages of input–output analysis include the large time-lag for the publication of IOTs, in particular those harmonised for MRIO models, and the high sensitivity of IO 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 (Mekonnen and Hoekstra, 2011).

Recent research has been devoted to the consistent integration and the refinement of IOTs and MRIO systems to calculate footprint-type indicators (Dietzenbacher et al., 2013; Lenzen et al., 2012; Lenzen et al., 2013; Tukker and Dietzenbacher, 2013). Examples of research projects include the EU-FP6 projects EXIOPOL and FORWAST, the EU-FP7 projects OPEN:EU, CREEA, DESIRE and WIOD, and the Eora database developed at the University of Sydney. The intention of many of these initiatives is to create consistent systems with a higher level of detail, in particular in environmentally-sensitive primary sectors, thus avoiding mistakes resulting from the high level of aggregation of IOTs.

6.2 Physical accounting

The major advantages of physical accounting are the possibility to apply greater commodity detail and to allocate land according to reported biomass flows and technical conversion factors. 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). Other advantages include the detailed country-level geographical coverage, and the availability of data for long time series with timely and regular updates.

Current limitations of physical accounting methods relate to supply chains of highly manufactured biotic products, in particular those of non-food products such as textiles. Such chains cannot be modelled on the basis of available agricultural statistics alone. Disregarding the trade of non-food products or applying LCA coefficients will generally produce some distortions and inaccuracies in results.

6.3 Hybrid accounting

As Table 4 suggests, hybrid accounting, building on all available data and methods both in terms of monetary value and physical quantity, has the potential to exploit the specific advantages of the physical and environmental-economic accounting methods and can thereby overcome some of their limitations and weaknesses. Our main conclusions basically mirror those arrived at by LCA practitioners and energy systems analysts for whom hybrid accounting methods combining process and IO analysis have a long tradition (Bullard et al., 1978; Heijungs and Suh, 2002), and their advantages are well recognized and investigated (Lenzen and Crawford, 2009; Suh et al., 2004; Suh and Nakamura, 2007). The key advantage of hybrid approaches is that the applied detailed physical data allow compensating the problems of aggregation and economic allocation normally faced with input–output analysis. This especially enhances the assessment of the global flows of primary products and has been recommended for products with a low level of manufacturing (Feng et al., 2011; Schaffartzik et al., 2009; Schoer et al., 2012; Weinzettel et al., 2014; Wiedmann, 2011). Food products typically undergo only a few processing steps. Thus, this type of models is particularly appropriate for land footprint accounting. At the same time, the advantages of environmental-economic accounting, specifically regarding the full representation of all supply chains, can be maintained for products with higher levels of manufacturing. Therefore, hybrid accounting methods 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, and other biomaterials.

Nevertheless, some of the disadvantages described for the two basic methods still apply for hybrid approaches. These include the time lag to publication of IOTs and their limited level of detail, albeit affecting only the upstream flows of higher processed products. Furthermore, comparability of results generated with existing hybrid approaches is currently not warranted as the various models apply different types of hybridisation, establishing the link between physical and environmental-economic accounting at different stages of the supply chains.

7 Conclusions

Global telecouplings via commodity supply chains, and in particular distant interlinkages in the global land system, are high on the research agenda as well as upcoming in the international policy debate. A number of studies of the global biomass metabolism, tracking flows between distant places and along

complex supply chains, have been performed during the last decade. The field has evolved along various different pathways and the comparability and robustness of current methods is disputed (Kastner et al., 2014b). With this review paper we provided a concise overview of currently available data and methods, seeking to bring the different strands of methodological development together in order to set a common agenda for further progress towards more robust and standardised land footprint accounts.

We argued that physical accounting is well suited for the analysis of global land flows, in particular as the applied level of detail and the allocation logic of tracking embodied land use along actual physical commodity flows. Due to a lack of information on the utilization of non-food products in agricultural statistics and similar limitations for forestry statistics, we suggest to supplement physical accounting with monetary input–output analysis (i.e. environmental-economic accounting). In this way it is possible to track all embodied land flows in a top-down system from primary production to final consumption. The resulting hybrid accounting method combines available data sources in monetary and physical units, and can potentially be integrated into a global mixed-unit input–output model, obtaining a high level of transparency and reproducibility. Moreover, implementing a hybrid accounting model in an IO framework would allow using analytical tools from input–output economics such as structural path and decomposition analysis (Hoekstra and van den Bergh, 2002; Lenzen, 2007).

A robust and transparent accounting framework for global biomass flows can serve as the basis for various further analyses of the relocation of environmental burden related to land use throughout global supply chains. Therefore, our findings are applicable to a range of land use-related footprint indicators including those for materials (particularly biomass), water, HANPP, deforestation, biodiversity loss and the Ecological Footprint. Although others than land-related footprint indicators would probably also benefit from hybrid accounting methods, the specific data situation in the areas of agriculture and forestry particularly facilitates the development of hybrid methods for land use-related footprint indicators.

We conclude that a thoroughly designed hybrid accounting method provides a solid ground for policies aimed at achieving global sustainable land use. In an era of increasing competition for land and growing interlinkages due to globalization, such a tool is urgently needed.

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