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Our common cropland: Quantifying global agricultural land use from a consumption perspective

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Abstract

Understanding teleconnections of regional consumption patterns and global land use supports policy making towards achieving sustainable land use. We present an innovative globally consistent hybrid land-flow accounting method to track biomass flows and embodied land along global supply chains. It uses the large FAOSTAT database, which is, for non-food commodities, complemented with a multi-regional input-output model. We employ the hybrid model globally between 1995 and 2010 and present results for 21 regional markets. Results highlight the growing integration in international markets. In 2010, 31% of cropland cultivation was for export markets compared to 16% in 1995. The higher land demand of livestock-based diets, which account for one third of global cropland use, and differences in land use intensities cause large regional variations in extents and composition of land footprints. The utilization of cropland changed towards a growing importance of the non-food sector accounting for 12% in 2010. Comparing land quality weighted cropland footprints across regions further reveals large differences in the appropriation of available global cropland productivity. Because of large uncertainties and quality differences in the actual use of grassland for feeding ruminants, we propose land quality weighted grassland footprints to discuss the additional land use for ruminant livestock products.

Highlights

- We developed a novel, globally consistent hybrid land footprint method.
- In 2010, 31% of cropland cultivation was for export markets compared to 16% in 1995.
- The non-food sector has become increasingly important in cropland utilization.
- Extents and composition of per capita cropland footprints vary widely across regions.
- Progressing globalization requires globally coordinated land use policy responses.

Keywords

Land use indicators; land footprint; consumption based analysis; teleconnections; agricultural trade

1. Introduction

Increasing populations, fast growing demand in emerging economies, and existing resource intensive consumption patterns in developed countries, are placing unprecedented demands on land, water and other natural resources. Meeting food demand by 2050 will require roughly a 60% increase in output from the world's cropland and a 70% increase in the output of meat and dairy (Alexandratos and Bruinsma, 2012). Today, one fifth of global cultivated land is irrigated, producing 33% of the global crop production and 44% of total cereal production (Portmann et al., 2010). Irrigation, the largest global freshwater user, accounts for about 70% of water withdrawals (AQUASTAT, 2016). At the same time water scarcity conditions in (semi-) arid regions in India, Pakistan, Northeastern China, the Middle East, and North Africa, have been increasing in the past decades and pose a risk to food security and economic development (Taylor et al., 2013; Wada and Bierkens, 2014; Wada et al., 2011).

Agricultural intensification on existing cropland is seen as an important response strategy to cope with the looming land scarcity (Lambin and Meyfroidt, 2011) when climate change mitigation and protection of biodiversity are prime concerns. Intensification measures include increase in cropping intensity (i.e. the ratio of harvested area and cropland extent) and higher yields (tons per hectare of harvested area), which may result from mechanization, agro-chemical inputs (seed variety, fertilizer, pest-management) and irrigation development. Land quality is a key factor in the potential for intensification of agriculture and expansion of cropland.

The impacts of land use management and change are caused locally by production systems and agricultural practices, but are driven by demand in response to population growth and changing consumption patterns. Globalization and complex supply chains render it increasingly difficult for consumers to fully understand the resource and environmental impacts of their consumption decisions. Yet, such understanding and quantification is important. For example, direct and indirect impacts of the usage of vegetable oil for food, biofuels and other oleo-chemicals, or of soybean cake for livestock feed, have received significant attention in the context of tropical deforestation (Cuypers et al., 2013; Rudel et al., 2009; Searchinger et al., 2008). Apparent improvements in resource productivity, as well as environmental and working conditions in developed countries, are often dominated by displacements to other countries rather than solely achieved domestically (Wiedmann and Lenzen, 2018).

Achieving effective policy measures to strengthen sustainable land use practices requires an analysis of the inter-linkages between consumption and production patterns. Several of the recently adopted

Sustainable Development Goals (SDGs) (UN, 2015) refer directly or indirectly to agricultural production and consumption, including Goal 2 (end hunger, food security, sustainable agriculture), Goal 6 (availability of water and sanitation for all), and Goal 12 (ensure sustainable consumption and production patterns). Sub-goal 12.8 calls for people everywhere to have the relevant information and awareness for sustainable development and lifestyles in harmony with nature by 2030. However, baseline data for several of the SDG targets are missing and the UN is calling for increased support for strengthening data collection and capacity-building, and to develop national and global baselines where they do not exist (United Nations, 2015, paragraph 57).

Consumption-based accounting or ‘footprint’ analysis (Hoekstra and Wiedmann, 2014; Wiedmann and Lenzen, 2018) aims to understand complex supply chains, ‘tele-connect’ production and consumption, and evaluate respective resource use and environmental or social impacts vis-à-vis defined sustainability goals or planetary boundaries (O’Neill et al., 2018). Footprints will play an increasing role in helping governments, businesses, and consumers understand their true resource dependencies (Moran et al., 2013). This study contributes with a quantitative analysis of agricultural consumption and land resource use, which is a prerequisite for designing effective policy instruments in a globalized world economy. The research focus here is on agricultural ‘land footprints’ in terms of appropriate resource allocation to final consumers including the effects of international trade. Because of large differences in biophysical productivity across global agricultural areas, we will highlight the importance and effect of including land quality in an area-based land footprint.

A recent review (Bruckner et al., 2015) of existing concepts for measuring tele-couplings in the global land system identified three main approaches: (i) environmental-economic accounting approaches applying input-output analysis and tracking supply chains in monetary values; (ii) physical accounting approaches using an accounting framework based on data in physical units, and (iii) hybrid accounting combining elements from both environmental-economic and physical accounting. Prior studies using hybrid accounting at different regional scales include Vringer et al. (2010), Steen-Olsen et al. (2012), Weinzettel et al. (2013) and Weinzettel et al. (2014). Consistent global statistics comprising physical data on inter-sectoral flows, such as physical input-output tables (PIOT), are lacking (Giljum and Hubacek, 2004; Hubacek and Giljum, 2003) and theoretical discussions and practical applications are needed for further development (Suh, 2004). Further, Life Cycle assessments (LCA) (Antón et al., 2007; Wagendorp et al., 2006) and Life Cycle Impact Assessments (De Haes, 2006; Milà i Canals et al., 2007) have evaluated land use along supply chains. LCA studies are technically detailed, but based on assumptions and data from regionally representative industries. Hence, consistency with national and global land use statistics is usually impaired (Bruckner et al., 2015).

We follow the key conclusions of Bruckner et al., namely treating cropland separately from grassland in biomass flow accounting and land footprint quantification, applying a top-down approach and thereby maintaining global consistency of land attribution along supply chains, and applying a thoroughly designed hybrid, i.e. mixed-unit, accounting method for the calculation of land footprints separately for food (crop-based and livestock) and non-food consumption. Applying a newly developed hybrid land flow accounting method, we estimate land footprints for each year from 1995 to 2010 with global coverage in terms of 21 national/region markets. Major national economies, such as China, India and the USA are included separately. The focus of the analysis presented here is on cropland use of some 1.5 billion hectares globally. Grassland footprint accounting is dealt with in the discussion, where we also refine area-based crop- and grassland footprints with land quality information. This leads to a discussion on global cropland resource utilization from a distributional perspective. We discuss uncertainties and future research needs, and conclude with policy recommendations.

2. Methods and data

Figure 1 summarizes the concepts and integration of data flows implemented in the hybrid approach, which combines physical and environmental-economic land flow accounting. Land footprint calculations start from land attribution to primary production in the countries of origin, followed by tracking the land embedded along global supply chains to final consumption. This requires accounting for joint production (e.g., oil crops producing vegetable oil and oilseed cakes), intermediate products (e.g. livestock feed) and international trade.

The accounting systems applied in the hybrid methodology balance total supply and demand of land embedded in agricultural products, a key rationale used in the System of Environmental-Economic Accounting (SEEA) (UNSD, 2014, 2017). The hybrid methodology is consistent with accounting principles specified in the SEEA for Agriculture, Forestry and Fisheries (SEEA AFF) (FAO, 2016) including treatment of joint products, recording of intra-unit flows, and reporting processed products in a “raw commodity equivalent” weight. In line with SEEA AFF recommendations (3.26), we have developed commodity “paths” or “trees” to establish a linkage between raw and processed commodities. We note also that EXIOBASE, the IO database used in our hybrid accounting methodology, is compatible with the System of Environmental-Economic Accounting. This is stated, e.g., in the most recent publication of EXIBOASE v3 (Stadler et al., 2018).

The models and data applied for the implementation of hybrid land flow accounting are briefly summarized below and Supplementary Material SI-1 presents the methodological details.

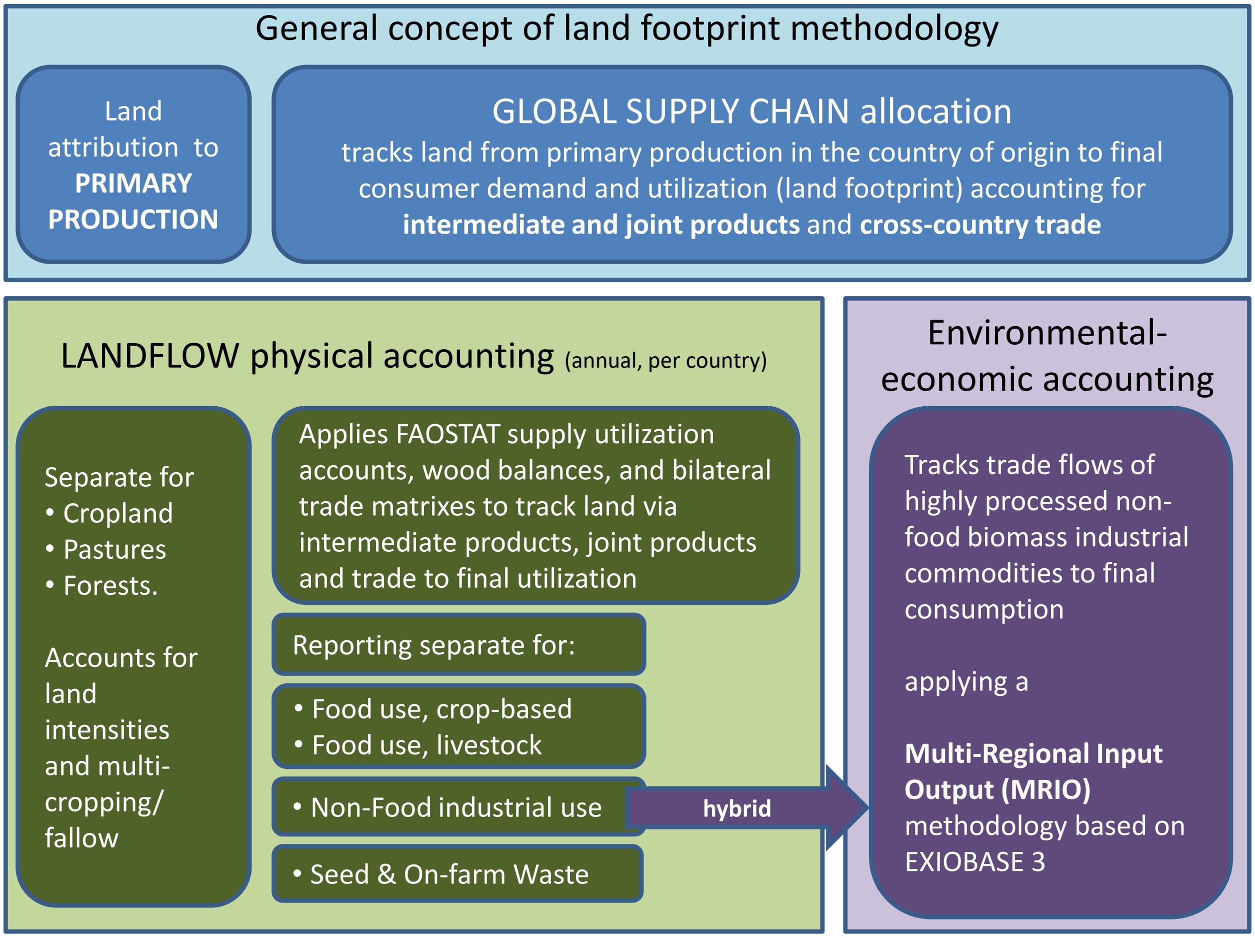

Figure 1: Land footprint methodology, general concept and hybrid approach combining physical and environmental-economic accounting

Tracking land along global supply chains requires global land-use data and land intensities[1]. Agriculture utilizes arable land for the production of food, feed and fiber from annual and permanent crops (*cropland*), and uses grassland and permanent pastures for grazing and the production of feed for ruminant livestock herds (*grassland*). The productivity of cropland (yields) varies widely among crops and across countries. The methodology of the applied land accounting model therefore retains, to the extent possible, both the commodity type and geographical details of the supply chains. This is implemented by using data from the Food and Agriculture Organization of the United Nations (FAO), that is, annual land use and agricultural and forestry production statistics (FAOSTAT, 2016). The LANDFLOW physical accounting model applies country- and crop-specific yields and accounts for multiple cropping in the attribution of physical cropland to primary crop production.

The global supply chain allocation in hybrid accounting combines physical and environmental-economic accounting. For physical accounting, LANDFLOW tracks the flow of cropland and grassland along supply chains using the high level of commodity detail reported in the FAO land use data and physical volumes (tons) of agricultural production and bilateral trade. Domain boundaries of the FAOSTAT databases restrict the tracking of highly processed non-food agricultural products to final utilization. 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 shoes respectively is not recorded in the FAOSTAT data. Other examples of trade that cannot be tracked with FAOSTAT data include biofuels produced from vegetable oils or clothes produced from fibers (e.g. cotton).

Hence, in hybrid accounting, we further track the ‘non-food’ sector applying environmental-economic accounting in the form of a multi-regional input-output model (MRIO). It employs the MRIO database EXIOBASE (Stadler et al., 2018), which depicts monetary flows between all economic sectors of countries and world regions in a particular year. The most intricate task in hybrid accounting is linking physical with economic accounts by defining the use of crop commodities by non-food industries, that is, constructing the appropriate environmental extensions of the MRIO model. In some cases, the identification of sectors is straightforward. For example, fiber crops are supplied to the ‘Textiles’ sector, while tobacco leaves are further processed by the sector ‘Tobacco products’. In other cases, however, a

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[1] Agriculture and forestry sectors are the largest users of land. Other sectors such as mining, manufacturing or transport, generally require less physical land for their production activities, albeit with large environmental impacts including sometimes irreversible consequences for the quality of land and water resources.

clear allocation is not easily possible (e.g. for commodities such as alcohol, vegetable oils or animal fats). We refer to SI Table 7 for a detailed list of using sectors per crop commodity. The method is explained in more detail, including a description of the used variables and equations, in the Supplementary Information.

Calculations operate on an annual basis for the period 1995 to 2010 for pre-defined 28 (LANDFLOW) and 21 (MRIO) markets globally (Table 3 in SI1). The markets were selected to: (i) ensure consistent linkage between the LANDFLOW and MRIO modelling systems; (ii) represent major national economies (e.g. Brazil, China, India, USA), and (iii) allow a logical hierarchy of regions and national economies. Results are presented as three-year moving averages (i.e. 2010 represents 2009-2011) to smoothen short-term fluctuations and noise caused by random outliers, and to accentuate longer-term trends.

3. Results

With the newly developed hybrid accounting model, we established a database that connects globally national cropland production with consumption presented in terms of 21 markets between 1995 and 2010. Cropland in supply versus cropland in utilization is presented for 17 crops and 8 livestock commodity groups listed in A-1.1.2. Extents of cultivated cropland (“Production”) and cropland embedded in imported commodities (“Imports”) represent a market’s total cropland in supply. Utilization consists of cropland in consumption, reported separately for crop-based food use (“Food, crops”), livestock food use (“Food, livestock”) and non-food products (“Non-food”, e.g., biofuels, oleo-chemicals from vegetable oil, textiles from cotton or wool, tobacco, and tires from natural rubber), and cropland embedded in exported commodities (“Exports”). We allocate land equivalents of seed production and on-farm waste, such as harvest loss, to the utilization item “Seed/On-farm waste”. Crops may be taken from stock (“From stock”, included in cropland in supply) or put on stock (“To stock”, included in cropland in utilization). We use the term cropland footprint for the total area of cropland embedded in a country’s consumption including indirect consumption (e.g. feed use) and the land allocated to seed production and on-farm waste. In each year, and globally by market cropland in the supply of agricultural products equals cropland in utilization, thereby presenting a comprehensive picture of area extents embedded in production, trade, intermediate use and consumption.

3.1 Global cropland footprint developments and trade

In 2010, some 1.5 billion hectares were cultivated for crop production. Half of these cropland extents were used for the cultivation of crops directly consumed in human diets. About one third were used for the cultivation of feed crops, indirectly providing animal proteins and fats for human consumption (e.g., meat, milk, eggs). Some 12% were cultivated for the non-food sector including specialized industrial crops (e.g. cotton, tobacco, natural rubber), as well as other crops and livestock products intended for industrial use (e.g., biofuels, biopolymers, textiles, leather, and oleo-chemicals). The remaining 8% of cropland represents the land equivalents associated with seed production and on-farm waste (Figure 2).

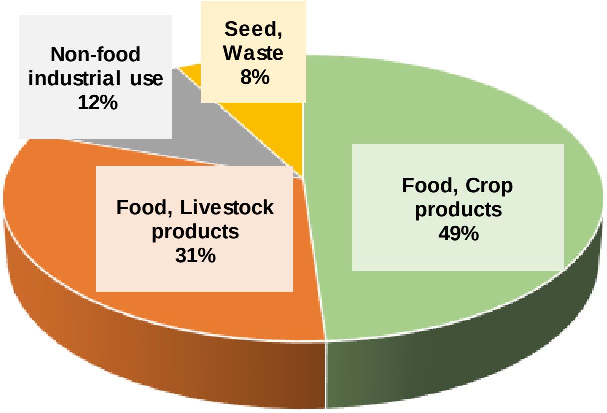

Figure 2: Global cropland footprint, 2010

During the last decade, cropland extents remained almost stable globally. The composition of the cropland utilization has however changed towards an increasing use for non-food products (Table 1). The food utilization components decreased (i.e., food production became more land efficient) – only the non-food component increased by 35% from 132 million hectares (Mha) in 1995 to 178 Mha in 2010. This compares with a global population increase of 20% over the same period.

Today, almost one third of global cropland, 31 % or 468 Mha, embedded in agricultural products enters international trade. Extents of global cropland embedded in agricultural commodities entering international trade increased by almost 90 % compared to 1995, when 16 % or 250 Mha of cropland was embedded in trade. This means that producers and consumers of are increasingly geographically separated. The main commodities traded include cereals, oil crops, stimulants (coffee, cacao, tea), and livestock products.

Million hectares	**1995**		**2000**		**2005**		**2010**		**Growth 1995 – 2010**
Food, Crops	756	49.8 %	763	50.6%	755	50.1%	744	49.0%	-12 (- 2 %)
Food, Livestock	500	33.0 %	488	32.4%	487	32.3%	477	31.4%	-23 (- 5 %)
Non-Food	132	8.7 %	134	8.9%	147	9.8%	178	11.7%	+46 (+ 35 %)
Seed & Waste	130	8.5 %	121	8.1%	119	7.9%	119	7.8%	-11 (- 8 %)
TOTAL	1,510	100 %	1,506	100 %	1,508	100 %	1,518	100 %	0%
Trade	250	16 %	368	24 %	418	27 %	468	31 %	+ 218 (+87 %)
Population [10^9]	5,739		6,126		6,514		6,915		+ 1,173 (+ 20 %)

Table 1: Development and composition of global cropland utilization and trade, 1995 to 2010

In SI2-2.1, we present a summary of net trade patterns by main commodity groups and regions for 2010. Large quantities of wheat, maize, oil crops, and meat products were exported from the USA and Canada (53 Mha), making Northern America the largest net exporting region. Oil crops, derived vegetable oil, oilseed cakes, and stimulants, were the main export commodities of Latin America, the second largest net exporting region (41 Mha). Non-EU Europe (including Russia) was a significant net exporter of cereals, vegetable oils, and to a lesser extent, oil crops. The largest net importing regions were the Middle East (40 Mha), China (36 Mha), and the EU (35 Mha). The Middle East is a net importer of almost all agricultural commodities, but above all wheat. China and the EU are net importers of especially oil crop products. Northern America, the EU, Australia and Japan import significant amounts of stimulants (11 Mha).

3.2 Regional cropland in supply, utilization and trade

The extents and composition of cropland utilization, participation in global trade, and the cropland self-reliance ratio, varies widely across countries and regions. Figure 3 connects global production from cropland with net trade and consumption by major country/region. Note that all bars in light green “Production” sum up to the global 1,518 Mha of cropland extents. In Northern America, the European Union, and the region ‘Other Europe & Russia’, more than half of the cropland in utilization is required for the consumption of livestock-based food. In contrast, in India and Africa the majority of cropland utilization is for crop-based food consumption.

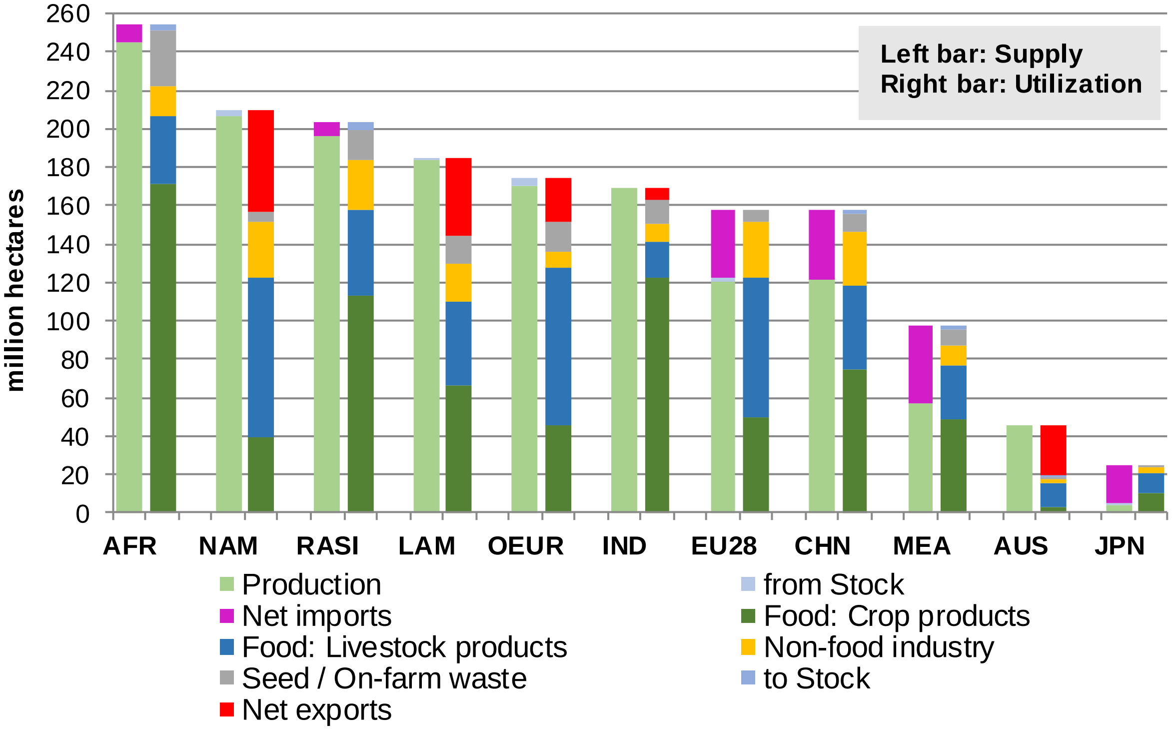

Figure 3: Cropland in regional supply and utilization of crop and livestock products by major region, 2010

NAM Northern America; EU28 European Union; OEUR Other Europe & Russia; LAM Latin America; CHN China; IND India; RASI Rest of Asia; JPN Japan; AUS Australia; MEA Middle East; AFR Africa

Elsewhere, we present an example of a more detailed database for Germany and the EU28 depicting all items of supply (e.g., production and imports) and utilization (e.g. exports, food use, food processing, feed use, and other use) for all 17 crops and 8 livestock commodity groups including the derived cropland footprint (Fischer et al., 2017a).

3.3 Cropland self-reliance

The cropland self-reliance ratio (SRR), that is a country's ratio of cropland in production to cropland in consumption, varies widely. Table 2 lists the main regions by descending levels of SRR of the year 2010. In Australia, national consumption uses one-third of the cultivated cropland in the country, the remainder going to exports. At the other end of the scale, consumers in Japan require five times more land than the domestically cultivated cropland area. Compared to 2000, cropland used in 2010 increased in Latin America, Africa and the region 'Rest of Asia'. In the other regions, cropland extents were almost stable or decreased by small amounts. In Latin America cropland use increased foremost in response to demand from export markets. In contrast, cropland expansion in Africa and ‘Rest of Asia’ resulted from higher domestic demand, which was mainly driven by population growth.

	2000				**2010**			
Million hectares	**Prod**	**Cons**	**SRR**	**Net EXP**	**Prod**	**Cons**	**SRR**	**Net EXP**
*Net exporting region**								
Australia	48	16	300%	30	46	18	255%	27
Northern America	230	181	127%	50	207	157	132%	53
Latin America	161	143	113%	18	184	144	128%	41
Other Europe & Russia	176	175	100%	-2	170	152	112%	22
India	170	163	104%	5	169	163	104%	6
Net importing region								
Rest of Asia	181	184	99%	-6	196	200	98%	-7
Africa	222	227	98%	-1	245	251	97%	-10
China	129	140	92%	-12	122	156	78%	-36
European Union (EU28)	128	164	78%	-36	121	157	77%	-37
Middle East	58	83	70%	-25	57	95	60%	-40
Japan	4.8	30	16%	-26	4.6	25	18%	-20
TOTAL (World)	1,508	1,507	100%		1,522	1,518	100%	

*Except Other Europe & Russia in 2000; Note: Small differences in TOTAL and in Net exports deviating from the difference between production and consumption are due to stock changes (not shown in this table).

Table 2: Cropland in production, consumption, self-reliance ratio (SRR) and net exports, 2000, 2010

Between 2000 and 2010, SRR changed for all regions except India, Africa and the aggregate region of ‘Rest of Asia’, albeit for different reasons. Latin America and ‘Other Europe & Russia’ increased their net exports of crops and cropland based livestock products, the former through cropland expansion, and the latter by decreasing land in domestic consumption. Northern America, another major net exporter, increased its SRR by reducing the acreage of cropland needed for domestic consumption. In contrast, China and the Middle East reduced their SRR by increasingly relying on imports of crop and livestock products for their own consumption. Japan, another major net importer, decreased both its cropland in production and embedded in consumption, thereby somewhat increasing its SRR.

3.4 Per capita cropland in production and consumption

The cultivation and usage of global cropland has intensified since 1995. In 2010, consumption of the global population of 6.9 billion required on average 2,196 m^2 of cropland per capita, almost one fifth lower than in 1995 when 5.7 billion relied on 2,645 m^2 per capita (Table 3). This trend can be explained by higher yields, abandoning of marginal cropland in some regions and changing of relative regional population weights in the global food consumptions (i.e. increasing importance of less developed regions with lower average consumption levels). In contrast to food-related footprints, the non-food footprints increased from 230 to 258 m^2 per capita, indicating the growing importance of the non-food sector for cropland usage.

Square meters per capita	**1995**	**2000**	**2005**	**2010**	**Change 1995 to 2010**
Food, Crops	1,317	1,246	1,159	1,076	- 241 (- 18%)
Food, Livestock	872	797	747	690	- 182 (- 21%)
Non-Food	230	219	226	258	+ 28 (+ 12%)
Seed & Waste	226	198	184	172	- 54 (- 24%)
TOTAL	2,645	2,459	2,316	2,196	- 449 (- 17 %)

Table 3: Per capita global cropland footprint, 1995 to 2010

Table 4 compares regional year 2000 and 2010 per capita cropland in both production (i.e., cropland extents cultivated domestically) and consumption (i.e. the cropland footprint). The green color highlights regions, which are net exporters of and red marks net importers. When the cropland in consumption is of the same order as cropland in production, a country/region is self-sufficient – here defined as between 90 and 110% SRR (no color).

Region	**2000**			**2010**		
	POP	Consumption	Production	POP	Consumption	Production
	(10^6)	square meters per capita		(10^6)	square meters per capita	
AUS	19	8,659	25,180	22	8,506	20,766
OEUR	242	7,227	7,259	235	6,456	7,255
NAM	315	5,739	7,310	346	4,526	5,981
LAM	526	2,711	3,062	596	2,416	3,084
AFR	758	3,002	2,932	974	2,577	2,512
EU28	488	3,356	2,625	506	3,111	2,385
MEA	282	2,940	2,068	345	2,763	1,651
RASI	1,040	1,768	1,742	1,190	1,680	1,650
IND	1,042	1,566	1,632	1,206	1,350	1,405
CHN	1,288	1,091	1,000	1,367	1,139	890
JPN	126	2,396	383	127	1,993	359
World	**6,126**	**2,459**	**2,462**	**6,915**	**2,196**	**2,200**

Table 4: Regional per capita cropland in consumption and production, 2000 and 2010

Except for Latin America, per capita cropland in production has decreased in all world regions. The largest relative decreases of almost 20 % occurred in Australia, Northern America, the Middle East and Western Asia. Per capita cropland in consumption (land footprints) decreased globally, especially in Northern America (-21 %) and Japan (-17 %). The exception is China, where strong income growth and a shift towards a livestock intensive diet, has resulted in a small increase (+4 %) of the per capita cropland footprint. This was also caused by rising imports, which shifted the country from 92 % SRR in 2000 to 78 % in 2010.

Extents and composition of per capita cropland use varies widely across countries and regions (Figure 4). The largest cropland footprints of over 4,000 m^2 per capita, currently occur in countries where cropland resources are abundant (Australia, Russia, Canada, and the USA). Except for Russia, these countries are also major net exporters of cropland embedded in agricultural products, thus using their ample domestic cropland resources to supply other countries. In Latin America, which is also a main exporter, the per capita cropland footprint is only marginally above the world average. The European Union, the Middle East and Japan, are net importers with per capita cropland use between 2,000 and 3,000 m^2. The lowest per capita footprints occur in highly populated Asian countries including China and India with 1,139 and 1,350 m^2, which is significantly less than the global average of about 2,200 m^2.

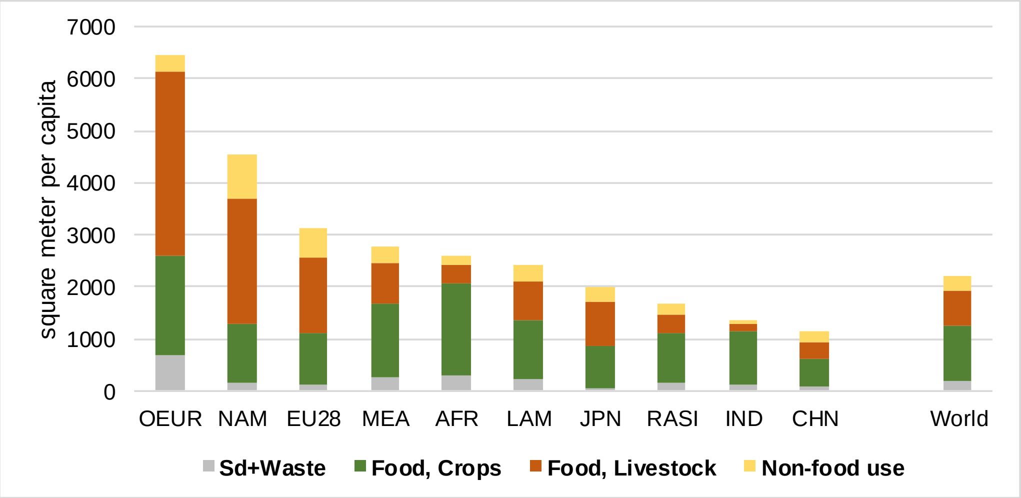

Figure 4: Per capita cropland footprint by major markets, 2010

3.5 Livestock cropland footprint

Our results show that one third of global cropland or 509 Mha (2010), are used for the production of feed and fodder crops to raise livestock herds. Some 60 % (304 Mha) of the livestock cropland footprint relate to ruminant livestock products (bovine meat, milk), and 40% (205 Mha) to products from pigs and poultry (e.g. pig and poultry meat, eggs). A main reason for the difference in cropland usage is the higher feed conversion efficiency of pigs and poultry compared to ruminant livestock.

The vast majority (94%) of livestock consumption is for food use (meat, dairy products, eggs), and the remainder for non-food products (mainly products from wool, hides and skins). There are large regional variations in the extents, composition and per capita livestock cropland footprints (Table 5, Figure 5).

	Per capita livestock cropland footprint [m2 per capita]	**Livestock cropland footprint** [million hectares]	*of which:* **Ruminants**		**Pigs & Poultry**	
NAM	2547	88	70	80 %	18	20 %
EU28	1561	79	48	61 %	31	39 %
OEUR	3681	87	60	70 %	26	30 %
LAM	779	46	15	32 %	32	68 %
CHN	361	49	10	20 %	39	80 %
IND	157	19	18	94 %	1	6 %
RASI	399	47	48	57 %	20	43 %
JPAU	1696	25	27	73 %	7	27 %
MEA	864	30	18	60 %	12	40 %
AFR	388	38	18	53 %	18	47 %
World	**736**	**509**	**304**	60 %	**205**	40 %

Table 5: Composition and extent of regional livestock cropland footprint, 2010

Cropland use for livestock products is skewed towards industrialized countries, in particular for ruminant livestock products. Two thirds (67% or 205 Mha) of the global ruminant livestock cropland footprint is associated with the consumption of one fourth of the global population (i.e. 1.7 billion who live in Northern and Latin America, Europe, Russia and Australia). In China and Latin America the majority of feed and fodder from the cropland associated with livestock consumption is for diets from pigs and poultry livestock.

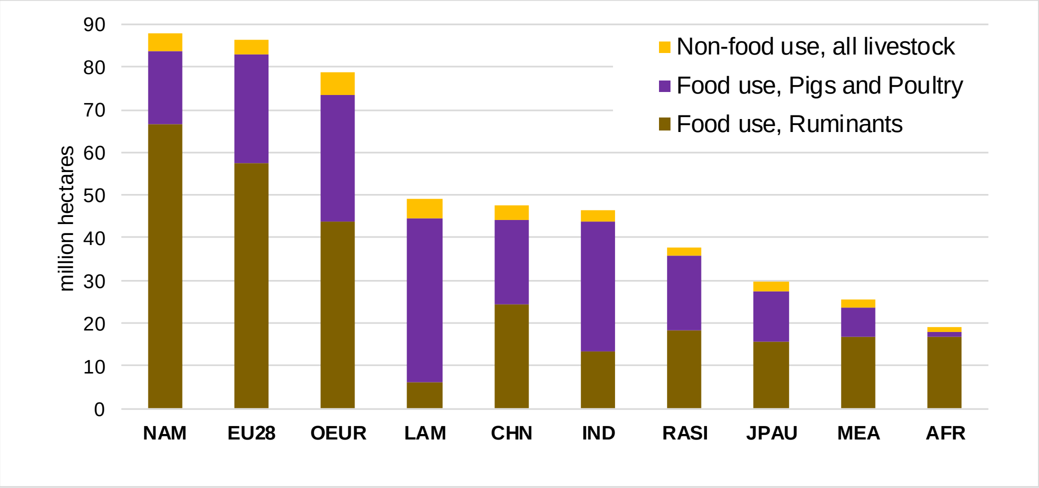

Figure 5: Composition of livestock cropland footrpint, 2010

4. Discussion

The focus of this paper is on the cropland footprint–an important indicator or proxy for human appropriation of and impacts on natural ecosystems. In addition to cropland, agriculture also uses huge extents of grassland to feed ruminant livestock herds. To account for differences in the quality and land use intensity as well as data availability and reliability for cropland and grassland, we report grassland footprints separately from cropland footprints in section 4.1. Area-based land footprints facilitate the delineation of the "safe operating space" for humanity (Rockström et al., 2009), which is a key requirement for achieving sustainable land use systems. However, the land footprint as a solely area-based indicator is insufficient and too unspecific to uncover in many cases the land-related environmental impacts, or to account for important differences in the global distribution of bio-productivity. Some implications of including measures of land quality and productivity in footprint accounting are discussed for grassland (4.1) and cropland (4.2). Finally, we discuss uncertainties (4.3).

4.1 Grassland use for ruminant livestock products

In contrast to cropland, definitions of grassland differ across countries, in particular in semi-arid climates or mixed grassland-shrub-forest ecosystems. Moreover, extents of grassland actually used for grazing and the intensity or duration of use are not recorded in most countries and not included in FAO land use data. This requires additional assumptions for land footprint calculations, which introduce an additional source of uncertainty. At the same time, grazing areas constitute a huge fraction of human land appropriation, its expansion has been a major driver of deforestation (Boucher et al., 2011; Rudel et al., 2009), and ruminant livestock systems have often been associated with detrimental impacts on natural ecosystems (Steinfeld et al., 2006). Reliable accounting of grassland footprints is hence desirable but somewhat uncertain. Below, we make an attempt to put the grassland use for ruminant livestock into perspective.

FAOSTAT reports "permanent meadows and pastures" covering some 3,360 Mha of widely varying quality and productivity globally. These range from marginal qualities in the Northern Sahel or Central Asia, to highly productive grassland in large parts of Europe and South America. Spatially detailed grassland productivity data obtained from the Global Agro-Ecological Zones database (FAO and IIASA, 2012; Fischer et al., 2012) show a wide range in productivity from over 8 t/ha (dry weight) in lush tropical grasslands to less than 1 t/ha in arid regions. Statistical data on extents of grassland actually used for grazing is lacking. As working hypothesis we assumed that all statistically reported grassland is attributed to ruminant livestock herds–a common approach that has been applied in other footprint studies (Bruckner et al., 2014; Yu et al., 2013) as well.

Furthermore, because of wide grassland productivity ranges, we define normalized (reference) grassland extents by weighting according to land productivity. For instance, by selecting a reference biomass yield of 5 t/ha (dry weight) (reflecting an above global average productive grassland as is typical in Central-Europe and Southern America), the reported global permanent meadows and pastures extent of 3,400 Mha when normalized is equivalent to 1,400 Mha of the reference pasture with a total annual production of about seven billion tons biomass. A-2.2 presents the grassland production for reported and normalized grassland areas for selected countries. For 2010, applying such a land productivity weighted normalized grassland in footprint calculations, reveals that 16 % of normalized grassland extents (or available grassland biomass) were used for ruminant livestock commodities entering international trade, which is significantly less than the 31 % share in the case of cropland (see Table 1).

The estimated consumption share of a country in global grassland resources depends on whether FAOSTAT reported grassland or normalized land productivity weighted grassland extents are used in the calculations. For example, China's reported grassland of 400 Mha includes significant amounts of areas in semi-arid and arid Northwest where biomass productivity is low. Average grassland biomass productivity across the whole country is only 1 t/ha. A major fraction of China's grassland footprint originates from (less productive) domestic grassland, and the share of China's footprint in the global total is therefore lower for a land productivity weighted grassland footprint (7 %) compared to an un-weighted area footprint (16 %).

Furthermore, the grassland area embedded in consumption depends on the assumptions regarding grassland actually used for grazing. Assuming all reported permanent grassland to be used for grazing may overestimate actual use and provides only a first rough estimate. As a possible improvement, we suggest that actual use of grassland areas could be estimated based on national ruminant livestock feed balances, that is, amounts of grassland biomass required in each country for meeting the feed requirements of ruminant livestock herds in addition to recorded crop fed (see e.g. (Bouwman et al., 2013; Herrero et al., 2013)). Such estimates combined with grassland productivity data, can provide a better understanding of required grassland area use. For example, the LANDFLOW livestock module calculates feed balances for the allocation of recorded food items to the two livestock groups (ruminants, pigs and poultry), which can for ruminant animals be compared with estimated biomass supply from permanent meadows and pastures. Still, some uncertainty of the actual grassland use remains and only improved monitoring of grassland use can provide reliable data on biomass appropriation.

4.2 Land quality weighted cropland footprints

The importance of differences in biophysical characteristics for the comparability of grassland footprints across countries also applies to cropland, albeit to a somewhat lesser extent, as cropland has historically developed in the most fertile regions of the world. Cropland productivity depends on many factors including the quality of climate, soil, and terrain resources, farmers' access to technology and expertise, land management (especially irrigation and availability of agro-inputs), and socio-economic circumstances. Similar to the concept of the Human Appropriation of Net Primary Productivity (HANPP) (Haberl et al., 2007) and its trade adjusted embodied HANPP (eHANPP) (Erb et al., 2009; Haberl et al., 2012), we report in addition to area-based cropland footprints, a normalized land quality weighted cropland footprint. Land quality weights were obtained from the Global Agro-Ecological Zones assessment (FAO and IIASA, 2012; Fischer et al., 2012), which provides for current (year 2010) rain-fed and irrigated cropland spatially detailed estimates (5 arc-minute grid cell) of attainable net primary production (NPP). Note that we aim for an index of biophysical potentials of land and therefore we do not consider actual productivity in 2010 obtained due to agricultural inputs (fertilizer and pesticides) and crop management (seed quality). We distinguish irrigated areas, because in some regions current intense crop production is only possible with irrigation (e.g., Egypt).

We estimate for each country average land quality based on the biophysical productivity summed by 5 arc-minute grid-cell over all rain-fed and irrigated cropland extents in 2010. The reference point for normalization was defined as the global median productivity of current rain-fed and irrigated cropland. China (55 % irrigated cropland) emerges as a country with an average productivity near the global median of about 20 tons dry biomass per hectare (or about 10 tons cereal equivalent). In this way, we can express statistically reported physical cropland extents in terms of more closely comparable cropland extents weighted by land quality (A-2.3). For instance, cropland in sub-humid tropical climates has a higher land productivity compared to cropland in temperate seasonal climates, and irrigated cropland potential generally exceeds the rain-fed potential. In India, where 39 % of cropland is equipped for irrigation, for example, the share in global (unweighted) cropland is 11.1 % compared to 14.6 % for land quality weighted cropland. Land quality weights below 1 are found in countries with temperate seasonal climates at higher altitudes (Canada, Central Europe, Russia) or some water-limited areas of the sub-tropics. For instance, Russia's 122 Mha cropland (8 % of global cropland) equates to 82 Mha land quality weighted cropland (5.5 % of global bio-productivity).

Finally, hybrid land flow accounting was used to track productivity-weighted cropland extents through supply chains from production to final consumption. We emphasize once again that the quality-adjustment of cropland relates to the biophysical potential and does not consider actual production performance in 2010.

Land quality weighted cropland footprints comparable across countries provide important information for a discussion on the global use of cropland resources from a distribution and fairness perspective. Distribution aspects are formulated in SDG 10, which calls for 'reducing inequality within and among countries'. The focus of SDG 10 is on increasing economic equity. The goal of achieving universal access to natural resources is not explicitly mentioned. However, we believe that effective use, sustainability and a fair sharing of the limited global cropland resources is pivotal to achieving SDG 1 (food security, sustainable agriculture) that is closely linked to SDG 10.

The bio-productivity weighted cropland footprint provides a metric for the magnitude and distribution of human consumption in terms of the solar, terrain, soil and water resources of global cropland. Table 6 presents a comprehensive summary of quality weighted cropland extents by broad regions. It compares regional shares of population, cropland in production and in consumption (footprint), and shows implied cropland self-reliance and the composition of the cropland footprint by broad use categories. Note, all variables were calculated using productivity-weighted cropland extents.

In addition, Figure 6 shows a scatterplot of regional shares in cropland resources embedded in consumption (x-axis; third column in Table 6) against regional shares in global population (y-axis; first column in Table 6). The diagonal line in the scatter-plot represents a theoretical equal distribution of the available cropland productivity across the global population. For regions below the diagonal their share in consumption of global quality-adjusted cropland resources exceeds their share in global population. Note, this can be due to resource demanding consumption patterns (e.g. most developed regions) or due to low actual resource productivity (e.g. Africa) relative to biophysical cropland potential. Green indicates that the region is a net cropland exporter, red that it is a net cropland importer, and no color that it is 95–105 % self-reliant in cropland use.

	Share in global total			Self-reliance ratio	Composition of footprint			
	Population	Cropland in production	Footprint		Seed & Waste	Food Crops	Food Livestock	Non-food use
Net exporters of cropland								
AUS	0.3%	1.9%	1.2%	159%	4%	16%	64%	16%
NAM	5.0%	13.6%	10.5%	129%	3%	26%	53%	19%
LAM	8.6%	13.7%	10.6%	129%	10%	30%	54%	6%
OEUR	3.4%	8.1%	7.3%	110%	10%	47%	30%	13%
Cropland self-sufficient								
IND	17.4%	14.5%	13.8%	105%	8%	76%	11%	5%
RASI	17.2%	14.6%	14.2%	103%	8%	59%	20%	13%
AFR	14.1%	14.8%	15.1%	98%	11%	68%	14%	7%
Net importers of cropland								
CHN	19.8%	8.1%	10.4%	78%	6%	47%	29%	18%
EU28	7.3%	6.6%	9.2%	72%	4%	31%	45%	20%
MEA	5.0%	3.7%	6.0%	62%	8%	51%	29%	12%
JPN	1.8%	0.3%	1.4%	18%	2%	44%	41%	16%

All data are based on calculations using land quality weighted cropland area equivalents.

Table 6: Regional shares in population, cropland in production and consumption, cropland self-reliance ratio, and the composition of the cropland footprint, 2010

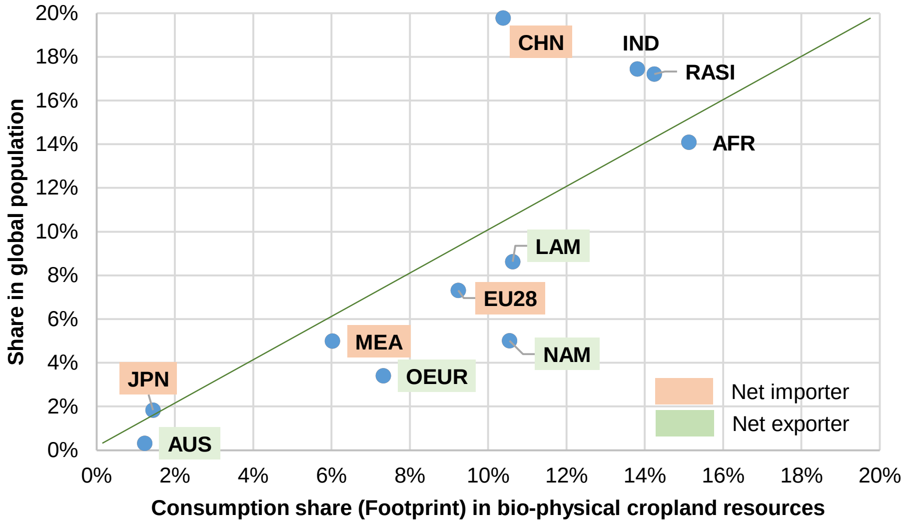

Figure 6: Regional shares of population and consumption (footprint) in global total, 2010

As can be expected, areas with abundant cropland in relation to their population size are net cropland exporters, including Australia, Northern and Latin America and the region ‘Other Europe and Russia’. Some 37 % of global quality-adjusted cropland resources are located in these regions, which, together are home to 1.2 billion people (17 % of global population). Except ‘Other Europe and Russia’ these areas have a high livestock component in their consumption patterns. One third of the global population (2.3 billion) lives in net importing regions (China, European Union, Middle East and Western Asia, Japan) and rely on foreign cropland for a substantial share of their consumption. Among those, China’s one fifth of global population uses only just over 10 % of the global quality-adjusted cropland resources. It is interesting to note that the remaining large population in Asia (India, Rest of Asia), like China, consumes less of the global quality-adjusted cropland than their share in global population (above the green line). However, unlike China, they are rather self-reliant or even minor exporters of embedded cropland, partly because of trade restrictions and lack of financial resources may curtail demand and avoid imports.

Livestock-based diets are an important component of the land footprints (above 40 %) for some 1.6 billion people living both in net exporting (Australia, Northern America, Latin America), and net importing (EU28, Japan) regions. Diets in Africa, India and many other Asian countries (except China) still only include a small share of livestock protein, accounting for less than one fifth of the cropland footprint. Africa’s availability of per capita cropland resources is less constraining compared to those in India and the ‘Rest of Asia’. However, Africa is also the region with the largest prevailing yield gaps, i.e. the difference between the land potential and actual production (FAO, 2011). In this aspect, a critical factor to improve the food supply while reducing land footprint is to increase yields towards the agronomic potential of the land and in some regions to increase areas equipped for irrigation.

4.3 Uncertainties

The hybrid methodology for land footprint calculations presented here, makes best use of available data, combining the high commodity detail and available technical information of the FAO production, trade and consumption data for the food sector in physical volume, with the full coverage of all global supply chains of industrial non-food commodities in environmental-economic accounting models. Nevertheless, some uncertainties remain due to gaps and inconsistencies in the reporting of the input data used. These include foremost the bilateral trade data provided by FAO, which are currently based on country reports, but are not aligned across countries to ensure globally consistent bilateral trade flows. The harmonization procedure used in this study has tried to fill data gaps and achieve consistency. As a consequence we decided to limit the number of markets to minimize the need for adaptation of the reported data. A harmonization of bilateral trade data undertaken centrally by the FAO could improve the robustness of the results and would allow a higher level of regional detail. The number of markets that can be modelled is also limited by the regional coverage of the monetary input-output (IO) model. While some IO models with global coverage include a larger number of countries, albeit at coarse sectoral resolution, we use EXIOBASE because of its high product detail.

Further improvements in land footprint accounting methods could be achieved through more detailed reporting of livestock related data and more detailed information concerning non-food uses of agricultural production. In particular, reliable estimates of the extents and productivity of grassland actually used for grazing ruminants could significantly improve the reliability of grassland footprint results. In addition, more detailed reporting on the use of feed and forage for different animal groups could replace the current model based feed allocation method. Finally, the completeness and robustness of data reported to FAO on the production of fodder crops (e.g. grasses, forages and silages) should be scrutinized and requires consistent definitions of the physical resources involved (i.e., arable land or pasture land). National applications of the land footprint accounting method developed here, are facing the challenge to make use of available national statistical knowledge and expertise, while ensuring consistency of definitions and classifications.

4.4 Future research needs

Beyond the footprints featuring area extents and embedded bio-productivity presented here, additional information is needed to assess the sustainability of land use and inform consumers about the impacts of their consumption patterns domestically and abroad. The quest for sustainability in land use/management and land use change has a broad scope and encompasses interlinkages with biodiversity loss, hydrology, climate change, land degradation and soil conservation. It also cuts across several socio-economic dimensions (e.g., land governance and land tenure, achieving global food security, and the preservation of vital ecosystem services and land functions). We refer to a scoping study (Fischer et al., 2017b) and an example of linking European consumption to deforestation (Cuypers et al., 2013). A modification of the ecological footprint based on a weighting system that describes the degree of land disturbance (Graetz et al., 1995; Lenzen et al., 2007; Lenzen and Murray, 2001) (vis-à-vis an undisturbed natural state) has been an early attempt to include considerations of land sustainability into footprint accounting. Yet, a disturbance-based approach still cannot address whether land use is practiced sustainably (Lenzen and Murray, 2001).

Impact extended land footprints require an understanding of how sustainable land use and management is defined, and what is the underlying objective of a sustainable land use. A key challenge is to link the environmental pressure (e.g. deforestation, land degradation) to land use and primary production. The latter refers to the starting point of the supply chain including cultivation of crops on rain-fed or irrigated cropland and consumable biomass production of grassland for providing ruminant livestock feed. Further research is required on extending area-based and land quality weighted footprints to provide information beyond how much land is embedded in certain consumption patterns by also differentiating in terms of environmental (or social) impacts, i.e. how sustainable the land embodied in consumption was used.

5. Conclusions

Hybrid land footprints provide a consumption-based land use indicator with a high level of commodity detail for food and non-food products. In fact, hybrid accounting methods are the only globally consistent top-down accounting tool capable of capturing the increasingly important non-food sector. The availability of cropland per capita is commonly reported in national statistics. We suggest complementing the per capita availability of cropland (i.e., a production based view), with the per capita cropland footprint (i.e., a consumption based perspective). The footprint analysis highlights the higher land demand of livestock-based diets as compared to crop-based diets, and extends available knowledge through information on the geographical location of the required land and the involved global supply chains. Between 1995 and 2010, an obvious trend in cropland utilization was an increasing share of agricultural commodities entering international trade and the growing importance of the non-food sector. The magnitude and composition of regional per capita cropland footprints varies considerably across regions ranging from 1,000 to 2,000 m^2 in Asia to over 6,000 m^2 in Eastern Europe, Russia and Australia. Per capita footprints have been generally decreasing since 2000, except for China, where a small increase occurred, yet amounting to only half of the global average in 2010.

In a globalized world, the land footprint of a country includes the cropland used both domestically and abroad to satisfy national consumption patterns. This creates complex teleconnections and involves two elements with distinctly different spheres of influence. On the one hand, the laws and incentives for agricultural production of the respective country regulate domestic land use. On the other, the import of agricultural products is based on the sustainability of cultivation of foreign agricultural land, and the importing country has only limited influence on land use and agricultural production conditions in the exporting countries. One third of the world’s cropland is cultivated for export markets with an upward trend. This requires transnational agreements on sustainability standards and traceability of agricultural production chains. Continued population growth and likely further integration of the world economy, necessitate a rational discussion of the sustainability, composition and global impacts of national cropland footprints in the context of planetary boundaries, fairness and the resource needs of future generations.

Crop- and grassland footprints and their land quality and impact-oriented extensions provide a metric for the characterization of agricultural land use from a consumer perspective and attribute human consumption patterns to global land use extents and impacts. The increasing globalization of land use requires, in addition to national approaches, international policy responses to protect and strengthen the sustainability of global cropland.

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ANNEX

In addition to the methodology overview described in the main article, Supplementary Information SI1 provides a detailed description of the underlying accounting models used in the hybrid approach. This includes the physical accounting model LANDFLOW of IIASA (SI 1-1.1) and the environmental-economic accounting model, EXIOBASE, of the Vienna Economic University (SI 1-1.2). Finally, SI 1-1.3 describes the integration of both modelling frameworks into a hybrid land flow accounting model.

Supplementary Information SI2 includes selected additional results included in the sections 'Results' and 'Discussion' in the main manuscript.