

Our Common Cropland: Quantifying Global Agricultural Land Use from a Consumption Perspective

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Published in:
Ecological Economics

DOI:
[10.1016/j.ecolecon.2018.12.005](https://doi.org/10.1016/j.ecolecon.2018.12.005)

Published: 01/01/2019

Document Version:
Early version, also known as preprint

Document License:
Other

[Link to publication](#)

Citation for published version (APA):
Tramberend, S., Fischer, G., Bruckner, M., & van Velthuisen, H. (2019). Our Common Cropland: Quantifying Global Agricultural Land Use from a Consumption Perspective. *Ecological Economics*, 157, 332 - 341. <https://doi.org/10.1016/j.ecolecon.2018.12.005>

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

3

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13

14 **Abstract**

15 Understanding teleconnections of regional consumption patterns and global land use supports policy
16 making towards achieving sustainable land use. We present an innovative globally consistent hybrid
17 land-flow accounting method to track biomass flows and embodied land along global supply chains. It
18 uses the large FAOSTAT database, which is, for non-food commodities, complemented with a multi-
19 regional input-output model. We employ the hybrid model globally between 1995 and 2010 and present
20 results for 21 regional markets. Results highlight the growing integration in international markets. In
21 2010, 31% of cropland cultivation was for export markets compared to 16% in 1995. The higher land
22 demand of livestock-based diets, which account for one third of global cropland use, and differences in
23 land use intensities cause large regional variations in extents and composition of land footprints. The
24 utilization of cropland changed towards a growing importance of the non-food sector accounting for
25 12% in 2010. Comparing land quality weighted cropland footprints across regions further reveals large
26 differences in the appropriation of available global cropland productivity. Because of large uncertainties
27 and quality differences in the actual use of grassland for feeding ruminants, we propose land quality
28 weighted grassland footprints to discuss the additional land use for ruminant livestock products.

29

30 **Highlights**

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

36 **Keywords**

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

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42 **1. Introduction**

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

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

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

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

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

80 Consumption-based accounting or ‘footprint’ analysis (Hoekstra and Wiedmann, 2014; Wiedmann and
81 Lenzen, 2018) aims to understand complex supply chains, ‘tele-connect’ production and consumption,
82 and evaluate respective resource use and environmental or social impacts vis-à-vis defined sustainability
83 goals or planetary boundaries (O’Neill et al., 2018). Footprints will play an increasing role in helping
84 governments, businesses, and consumers understand their true resource dependencies (Moran et al.,
85 2013). This study contributes with a quantitative analysis of agricultural consumption and land resource
86 use, which is a prerequisite for designing effective policy instruments in a globalized world economy.
87 The research focus here is on agricultural ‘land footprints’ in terms of appropriate resource allocation to
88 final consumers including the effects of international trade. Because of large differences in biophysical
89 productivity across global agricultural areas, we will highlight the importance and effect of including land
90 quality in an area-based land footprint.

91 A recent review (Bruckner et al., 2015) of existing concepts for measuring tele-couplings in the global
92 land system identified three main approaches: (i) environmental-economic accounting approaches
93 applying input-output analysis and tracking supply chains in monetary values; (ii) physical accounting
94 approaches using an accounting framework based on data in physical units, and (iii) hybrid accounting
95 combining elements from both environmental-economic and physical accounting. Prior studies using
96 hybrid accounting at different regional scales include Vringer et al. (2010), Steen-Olsen et al. (2012),
97 Weinzettel et al. (2013) and Weinzettel et al. (2014). Consistent global statistics comprising physical data
98 on inter-sectoral flows, such as physical input-output tables (PIOT), are lacking (Giljum and Hubacek,
99 2004; Hubacek and Giljum, 2003) and theoretical discussions and practical applications are needed for
100 further development (Suh, 2004). Further, Life Cycle assessments (LCA) (Antón et al., 2007; Wagendorp
101 et al., 2006) and Life Cycle Impact Assessments (De Haes, 2006; Milà i Canals et al., 2007) have evaluated
102 land use along supply chains. LCA studies are technically detailed, but based on assumptions and data

103 from regionally representative industries. Hence, consistency with national and global land use statistics
104 is usually impaired (Bruckner et al., 2015).

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

117 **2. Methods and data**

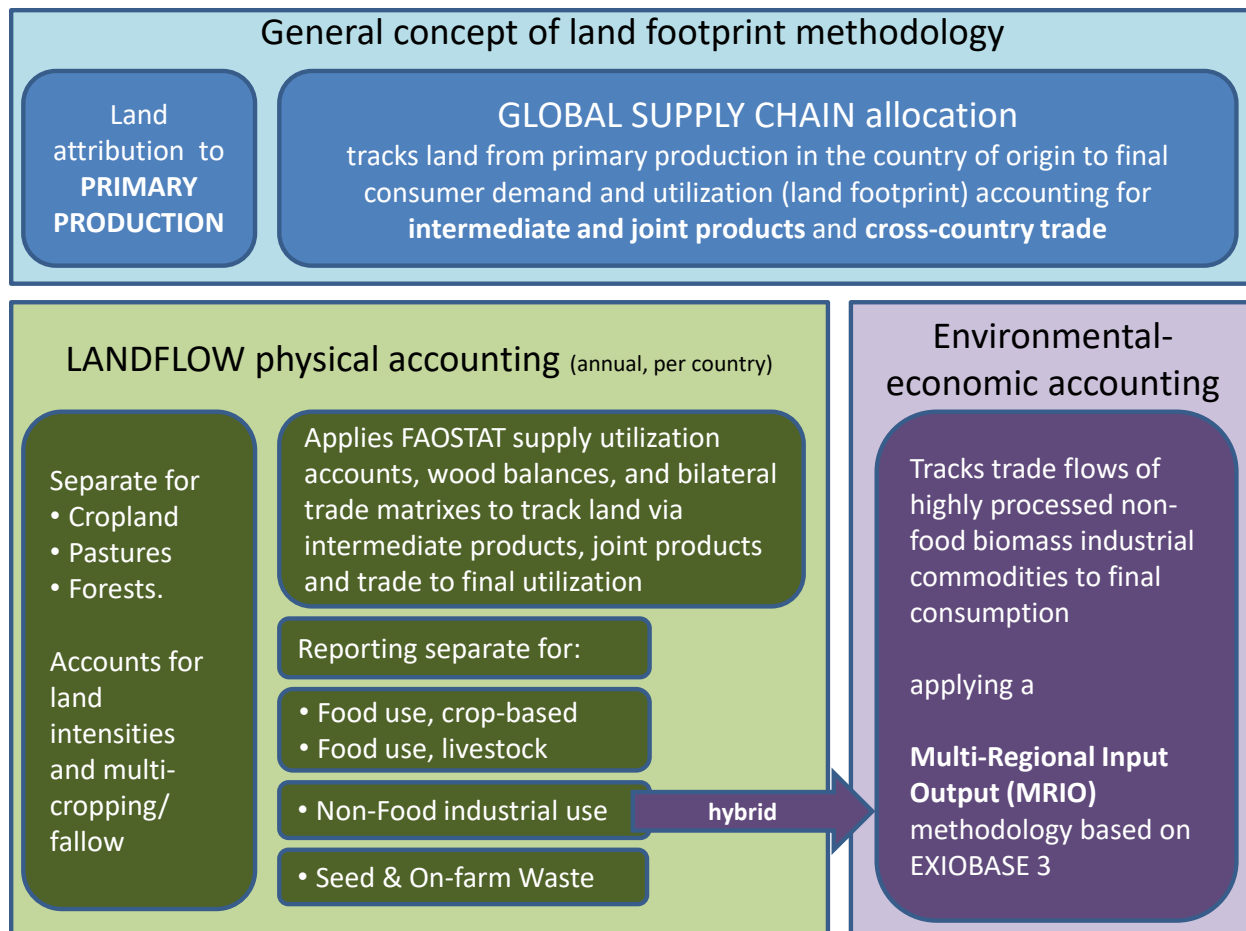
118 Figure 1 summarizes the concepts and integration of data flows implemented in the hybrid approach,
119 which combines physical and environmental-economic land flow accounting. Land footprint calculations
120 start from land attribution to primary production in the countries of origin, followed by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

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

132 of Environmental-Economic Accounting. This is stated, e.g., in the most recent publication of EXIOBASE
 133 v3 (Stadler et al., 2018).

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

136



137
 138 **Figure 1: Land footprint methodology, general concept and hybrid approach combining physical and**
 139 **environmental-economic accounting**
 140

141 Tracking land along global supply chains requires global land-use data and land intensities¹. Agriculture
142 utilizes arable land for the production of food, feed and fiber from annual and permanent crops
143 (*cropland*), and uses grassland and permanent pastures for grazing and the production of feed for
144 ruminant livestock herds (*grassland*). The productivity of cropland (yields) varies widely among crops
145 and across countries. The methodology of the applied land accounting model therefore retains, to the
146 extent possible, both the commodity type and geographical details of the supply chains. This is
147 implemented by using data from the Food and Agriculture Organization of the United Nations (FAO),
148 that is, annual land use and agricultural and forestry production statistics (FAOSTAT, 2016). The
149 LANDFLOW physical accounting model applies country- and crop-specific yields and accounts for
150 multiple cropping in the attribution of physical cropland to primary crop production.

151 The global supply chain allocation in hybrid accounting combines physical and environmental-economic
152 accounting. For physical accounting, LANDFLOW tracks the flow of cropland and grassland along supply
153 chains using the high level of commodity detail reported in the FAO land use data and physical volumes
154 (tons) of agricultural production and bilateral trade. Domain boundaries of the FAOSTAT databases
155 restrict the tracking of highly processed non-food agricultural products to final utilization. For instance,
156 once animal fats enter the industrial sector to produce cosmetics, or tanned leather from skins and
157 hides are turned into leatherwear or shoes, the trade of cosmetics or shoes respectively is not recorded
158 in the FAOSTAT data. Other examples of trade that cannot be tracked with FAOSTAT data include
159 biofuels produced from vegetable oils or clothes produced from fibers (e.g. cotton).

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

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.

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

172 Calculations operate on an annual basis for the period 1995 to 2010 for pre-defined 28 (LANDFLOW) and
173 21 (MRIO) markets globally (Table 3 in SI1). The markets were selected to: (i) ensure consistent linkage
174 between the LANDFLOW and MRIO modelling systems; (ii) represent major national economies (e.g.
175 Brazil, China, India, USA), and (iii) allow a logical hierarchy of regions and national economies. Results
176 are presented as three-year moving averages (i.e. 2010 represents 2009-2011) to smoothen short-term
177 fluctuations and noise caused by random outliers, and to accentuate longer-term trends.

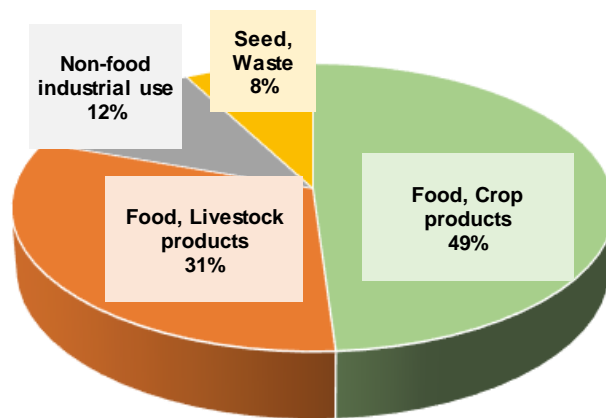
178 **3. Results**

179 With the newly developed hybrid accounting model, we established a database that connects globally
180 national cropland production with consumption presented in terms of 21 markets between 1995 and
181 2010. Cropland in supply versus cropland in utilization is presented for 17 crops and 8 livestock
182 commodity groups listed in A-1.1.2. Extents of cultivated cropland (“Production”) and cropland
183 embedded in imported commodities (“Imports”) represent a market’s total cropland in supply.
184 Utilization consists of cropland in consumption, reported separately for crop-based food use (“Food,
185 crops”), livestock food use (“Food, livestock”) and non-food products (“Non-food”, e.g., biofuels, oleo-
186 chemicals from vegetable oil, textiles from cotton or wool, tobacco, and tires from natural rubber), and
187 cropland embedded in exported commodities (“Exports”). We allocate land equivalents of seed
188 production and on-farm waste, such as harvest loss, to the utilization item “Seed/On-farm waste”. Crops
189 may be taken from stock (“From stock”, included in cropland in supply) or put on stock (“To stock”,
190 included in cropland in utilization). We use the term cropland footprint for the total area of cropland
191 embedded in a country’s consumption including indirect consumption (e.g. feed use) and the land
192 allocated to seed production and on-farm waste. In each year, and globally by market cropland in the
193 supply of agricultural products equals cropland in utilization, thereby presenting a comprehensive
194 picture of area extents embedded in production, trade, intermediate use and consumption.

195 **3.1 Global cropland footprint developments and trade**

196 In 2010, some 1.5 billion hectares were cultivated for crop production. Half of these cropland extents
197 were used for the cultivation of crops directly consumed in human diets. About one third were used for

198 the cultivation of feed crops, indirectly providing animal proteins and fats for human consumption (e.g.,
199 meat, milk, eggs). Some 12% were cultivated for the non-food sector including specialized industrial
200 crops (e.g. cotton, tobacco, natural rubber), as well as other crops and livestock products intended for
201 industrial use (e.g., biofuels, biopolymers, textiles, leather, and oleo-chemicals). The remaining 8% of
202 cropland represents the land equivalents associated with seed production and on-farm waste (Figure 2).



203

204 *Figure 2: Global cropland footprint, 2010*

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

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

216

217

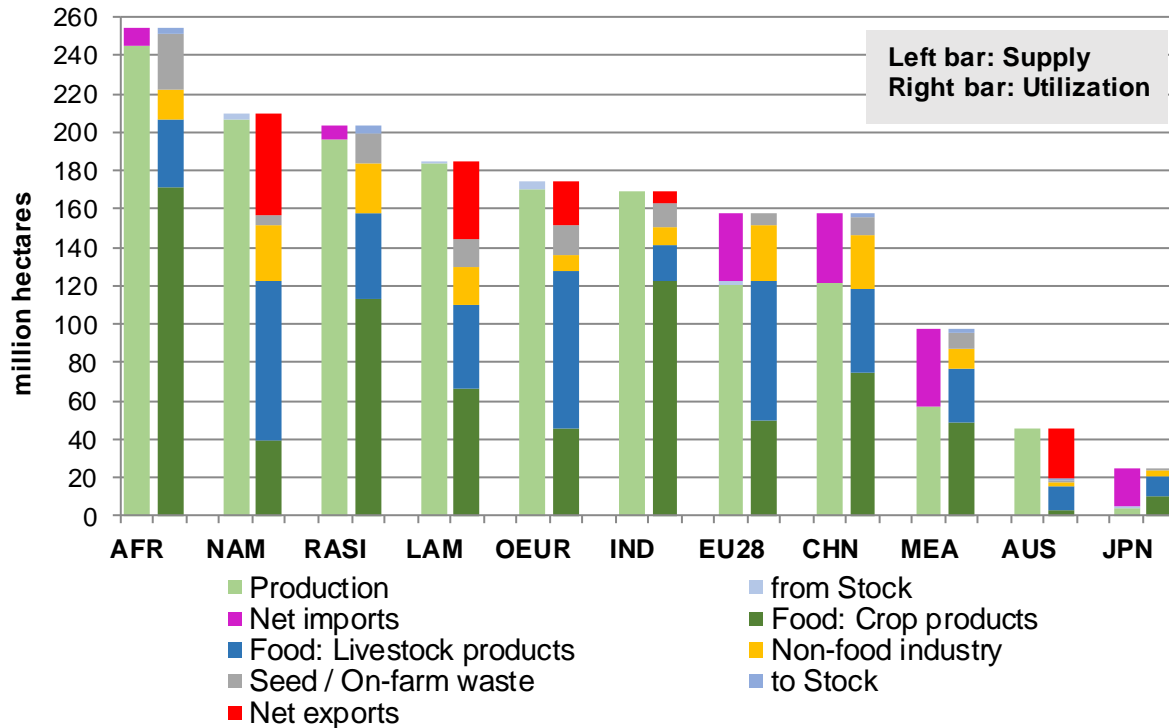
<i>Million hectares</i>	1995		2000		2005		2010		Growth 1995 – 2010
Food, Crops	756	49.8 %	763	50.6%	755	50.1%	744	49.0%	-12 (- 2 %)
Food, Livestock	500	33.0 %	488	32.4%	487	32.3%	477	31.4%	-23 (- 5 %)
Non-Food	132	8.7 %	134	8.9%	147	9.8%	178	11.7%	+46 (+ 35 %)
Seed & Waste	130	8.5 %	121	8.1%	119	7.9%	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 %)

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

219 In SI2-2.1, we present a summary of net trade patterns by main commodity groups and regions for 2010.
220 Large quantities of wheat, maize, oil crops, and meat products were exported from the USA and Canada
221 (53 Mha), making Northern America the largest net exporting region. Oil crops, derived vegetable oil,
222 oilseed cakes, and stimulants, were the main export commodities of Latin America, the second largest
223 net exporting region (41 Mha). Non-EU Europe (including Russia) was a significant net exporter of
224 cereals, vegetable oils, and to a lesser extent, oil crops. The largest net importing regions were the
225 Middle East (40 Mha), China (36 Mha), and the EU (35 Mha). The Middle East is a net importer of almost
226 all agricultural commodities, but above all wheat. China and the EU are net importers of especially oil
227 crop products. Northern America, the EU, Australia and Japan import significant amounts of stimulants
228 (11 Mha).

229 3.2 Regional cropland in supply, utilization and trade

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



237

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

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

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

245 3.3 Cropland self-reliance

246 The cropland self-reliance ratio (SRR), that is a country's ratio of cropland in production to cropland in
 247 consumption, varies widely. Table 2 lists the main regions by descending levels of SRR of the year 2010.
 248 In Australia, national consumption uses one-third of the cultivated cropland in the country, the
 249 remainder going to exports. At the other end of the scale, consumers in Japan require five times more
 250 land than the domestically cultivated cropland area. Compared to 2000, cropland used in 2010 increased
 251 in Latin America, Africa and the region 'Rest of Asia'. In the other regions, cropland extents were almost
 252 stable or decreased by small amounts. In Latin America cropland use increased foremost in response to

253 demand from export markets. In contrast, cropland expansion in Africa and 'Rest of Asia' resulted from
 254 higher domestic demand, which was mainly driven by population growth.

<i>Million hectares</i>	2000				2010			
	Prod	Cons	SRR	Net EXP	Prod	Cons	SRR	Net EXP
<i>Net exporting region*</i>								
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
<i>Net importing region</i>								
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%	

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

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

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

266 3.4 Per capita cropland in production and consumption

267 The cultivation and usage of global cropland has intensified since 1995. In 2010, consumption of the
 268 global population of 6.9 billion required on average 2,196 m² of cropland per capita, almost one fifth
 269 lower than in 1995 when 5.7 billion relied on 2,645 m² per capita (Table 3). This trend can be explained
 270 by higher yields, abandoning of marginal cropland in some regions and changing of relative regional

271 population weights in the global food consumptions (i.e. increasing importance of less developed
 272 regions with lower average consumption levels). In contrast to food-related footprints, the non-food
 273 footprints increased from 230 to 258 m² per capita, indicating the growing importance of the non-food
 274 sector for cropland usage.

<i>Square meters per capita</i>	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 %)

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

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

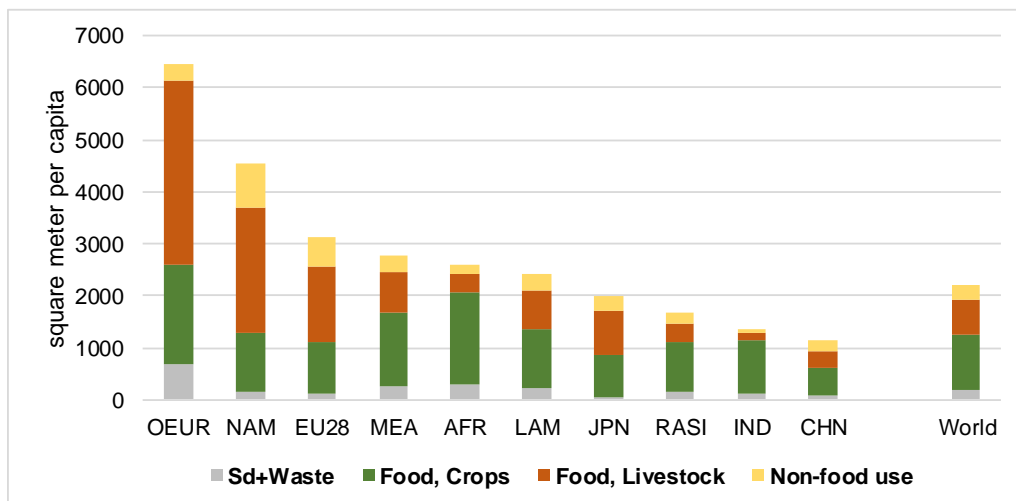
Region	2000			2010		
	POP	Consumption	Production	POP	Consumption	Production
	(10 ⁶)	square meters per capita		(10 ⁶)	square meters per capita	
AUS	19	8,659	25,180	22	8,506	20,766
OEUR	242	7,227	7,259	235	6,456	7,255
NAM	315	5,739	7,310	346	4,526	5,981
LAM	526	2,711	3,062	596	2,416	3,084
AFR	758	3,002	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

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

282 Except for Latin America, per capita cropland in production has decreased in all world regions. The
 283 largest relative decreases of almost 20 % occurred in Australia, Northern America, the Middle East and
 284 Western Asia. Per capita cropland in consumption (land footprints) decreased globally, especially in
 285 Northern America (-21 %) and Japan (-17 %). The exception is China, where strong income growth and a
 286 shift towards a livestock intensive diet, has resulted in a small increase (+4 %) of the per capita cropland

287 footprint. This was also caused by rising imports, which shifted the country from 92 % SRR in 2000 to
 288 78 % in 2010.

289 Extents and composition of per capita cropland use varies widely across countries and regions (Figure 4).
 290 The largest cropland footprints of over 4,000 m² per capita, currently occur in countries where cropland
 291 resources are abundant (Australia, Russia, Canada, and the USA). Except for Russia, these countries are
 292 also major net exporters of cropland embedded in agricultural products, thus using their ample
 293 domestic cropland resources to supply other countries. In Latin America, which is also a main exporter,
 294 the per capita cropland footprint is only marginally above the world average. The European Union, the
 295 Middle East and Japan, are net importers with per capita cropland use between 2,000 and 3,000 m². The
 296 lowest per capita footprints occur in highly populated Asian countries including China and India with
 297 1,139 and 1,350 m², which is significantly less than the global average of about 2,200 m².



298

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

300 **3.5 Livestock cropland footprint**

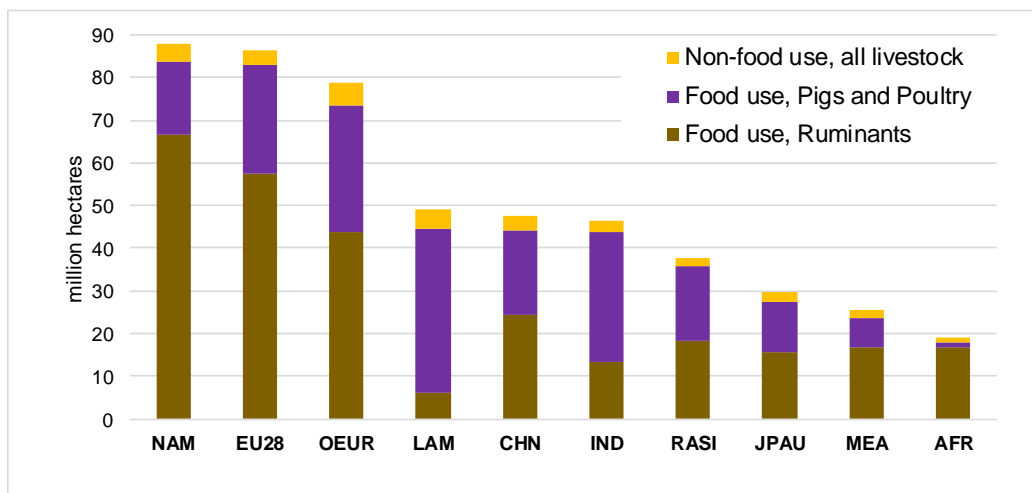
301 Our results show that one third of global cropland or 509 Mha (2010), are used for the production of
 302 feed and fodder crops to raise livestock herds. Some 60 % (304 Mha) of the livestock cropland footprint
 303 relate to ruminant livestock products (bovine meat, milk), and 40% (205 Mha) to products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

306 The vast majority (94%) of livestock consumption is for food use (meat, dairy products, eggs), and the
 307 remainder for non-food products (mainly products from wool, hides and skins). There are large regional
 308 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 %

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

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



316

317 *Figure 5: Composition of livestock cropland footprint, 2010*

318 **4. Discussion**

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

330 **4.1 Grassland use for ruminant livestock products**

331 In contrast to cropland, definitions of grassland differ across countries, in particular in semi-arid climates
332 or mixed grassland-shrub-forest ecosystems. Moreover, extents of grassland actually used for grazing
333 and the intensity or duration of use are not recorded in most countries and not included in FAO land use
334 data. This requires additional assumptions for land footprint calculations, which introduce an additional
335 source of uncertainty. At the same time, grazing areas constitute a huge fraction of human land
336 appropriation, its expansion has been a major driver of deforestation (Boucher et al., 2011; Rudel et al.,
337 2009), and ruminant livestock systems have often been associated with detrimental impacts on natural
338 ecosystems (Steinfeld et al., 2006). Reliable accounting of grassland footprints is hence desirable but
339 somewhat uncertain. Below, we make an attempt to put the grassland use for ruminant livestock into
340 perspective.

341 FAOSTAT reports “permanent meadows and pastures” covering some 3,360 Mha of widely varying
342 quality and productivity globally. These range from marginal qualities in the Northern Sahel or Central
343 Asia, to highly productive grassland in large parts of Europe and South America. Spatially detailed
344 grassland productivity data obtained from the Global Agro-Ecological Zones database (FAO and IIASA,
345 2012; Fischer et al., 2012) show a wide range in productivity from over 8 t/ha (dry weight) in lush
346 tropical grasslands to less than 1 t/ha in arid regions. Statistical data on extents of grassland actually
347 used for grazing is lacking. As working hypothesis we assumed that all statistically reported grassland is

348 attributed to ruminant livestock herds—a common approach that has been applied in other footprint
349 studies (Bruckner et al., 2014; Yu et al., 2013) as well.

350 Furthermore, because of wide grassland productivity ranges, we define normalized (reference) grassland
351 extents by weighting according to land productivity. For instance, by selecting a reference biomass yield
352 of 5 t/ha (dry weight) (reflecting an above global average productive grassland as is typical in Central-
353 Europe and Southern America), the reported global permanent meadows and pastures extent of
354 3,400 Mha when normalized is equivalent to 1,400 Mha of the reference pasture with a total annual
355 production of about seven billion tons biomass. A-2.2 presents the grassland production for reported
356 and normalized grassland areas for selected countries. For 2010, applying such a land productivity
357 weighted normalized grassland in footprint calculations, reveals that 16 % of normalized grassland
358 extents (or available grassland biomass) were used for ruminant livestock commodities entering
359 international trade, which is significantly less than the 31 % share in the case of cropland (see Table 1).

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

368 Furthermore, the grassland area embedded in consumption depends on the assumptions regarding
369 grassland actually used for grazing. Assuming all reported permanent grassland to be used for grazing
370 may overestimate actual use and provides only a first rough estimate. As a possible improvement, we
371 suggest that actual use of grassland areas could be estimated based on national ruminant livestock feed
372 balances, that is, amounts of grassland biomass required in each country for meeting the feed
373 requirements of ruminant livestock herds in addition to recorded crop fed (see e.g. (Bouwman et al.,
374 2013; Herrero et al., 2013)). Such estimates combined with grassland productivity data, can provide a
375 better understanding of required grassland area use. For example, the LANDFLOW livestock module
376 calculates feed balances for the allocation of recorded food items to the two livestock groups
377 (ruminants, pigs and poultry), which can for ruminant animals be compared with estimated biomass

378 supply from permanent meadows and pastures. Still, some uncertainty of the actual grassland use
379 remains and only improved monitoring of grassland use can provide reliable data on biomass
380 appropriation.

381 4.2 Land quality weighted cropland footprints

382 The importance of differences in biophysical characteristics for the comparability of grassland footprints
383 across countries also applies to cropland, albeit to a somewhat lesser extent, as cropland has historically
384 developed in the most fertile regions of the world. Cropland productivity depends on many factors
385 including the quality of climate, soil, and terrain resources, farmers' access to technology and expertise,
386 land management (especially irrigation and availability of agro-inputs), and socio-economic
387 circumstances. Similar to the concept of the Human Appropriation of Net Primary Productivity (HANPP)
388 (Haberl et al., 2007) and its trade adjusted embodied HANPP (eHANPP) (Erb et al., 2009; Haberl et al.,
389 2012), we report in addition to area-based cropland footprints, a normalized land quality weighted
390 cropland footprint. Land quality weights were obtained from the Global Agro-Ecological Zones
391 assessment (FAO and IIASA, 2012; Fischer et al., 2012), which provides for current (year 2010) rain-fed
392 and irrigated cropland spatially detailed estimates (5 arc-minute grid cell) of attainable net primary
393 production (NPP). Note that we aim for an index of biophysical potentials of land and therefore we do
394 not consider actual productivity in 2010 obtained due to agricultural inputs (fertilizer and pesticides) and
395 crop management (seed quality). We distinguish irrigated areas, because in some regions current
396 intense crop production is only possible with irrigation (e.g., Egypt).

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

409 the sub-tropics. For instance, Russia's 122 Mha cropland (8 % of global cropland) equates to 82 Mha
410 land quality weighted cropland (5.5 % of global bio-productivity).

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

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

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

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

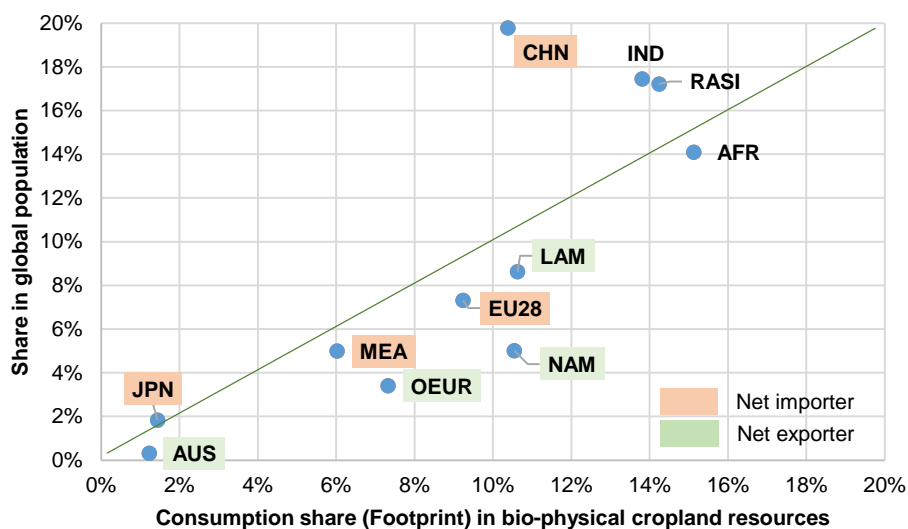
437

	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%

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

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

441



442

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

444

445 As can be expected, areas with abundant cropland in relation to their population size are net cropland
446 exporters, including Australia, Northern and Latin America and the region 'Other Europe and Russia'.
447 Some 37 % of global quality-adjusted cropland resources are located in these regions, which, together
448 are home to 1.2 billion people (17 % of global population). Except 'Other Europe and Russia' these areas
449 have a high livestock component in their consumption patterns. One third of the global population
450 (2.3 billion) lives in net importing regions (China, European Union, Middle East and Western Asia, Japan)
451 and rely on foreign cropland for a substantial share of their consumption. Among those, China's one fifth
452 of global population uses only just over 10 % of the global quality-adjusted cropland resources. It is
453 interesting to note that the remaining large population in Asia (India, Rest of Asia), like China, consumes
454 less of the global quality-adjusted cropland than their share in global population (above the green line).
455 However, unlike China, they are rather self-reliant or even minor exporters of embedded cropland,
456 partly because of trade restrictions and lack of financial resources may curtail demand and avoid
457 imports.

458 Livestock-based diets are an important component of the land footprints (above 40 %) for some
459 1.6 billion people living both in net exporting (Australia, Northern America, Latin America), and net
460 importing (EU28, Japan) regions. Diets in Africa, India and many other Asian countries (except China) still
461 only include a small share of livestock protein, accounting for less than one fifth of the cropland
462 footprint. Africa's availability of per capita cropland resources is less constraining compared to those in
463 India and the 'Rest of Asia'. However, Africa is also the region with the largest prevailing yield gaps, i.e.
464 the difference between the land potential and actual production (FAO, 2011). In this aspect, a critical
465 factor to improve the food supply while reducing land footprint is to increase yields towards the
466 agronomic potential of the land and in some regions to increase areas equipped for irrigation.

467 4.3 Uncertainties

468 The hybrid methodology for land footprint calculations presented here, makes best use of available
469 data, combining the high commodity detail and available technical information of the FAO production,
470 trade and consumption data for the food sector in physical volume, with the full coverage of all global
471 supply chains of industrial non-food commodities in environmental-economic accounting models.
472 Nevertheless, some uncertainties remain due to gaps and inconsistencies in the reporting of the input
473 data used. These include foremost the bilateral trade data provided by FAO, which are currently based
474 on country reports, but are not aligned across countries to ensure globally consistent bilateral trade
475 flows. The harmonization procedure used in this study has tried to fill data gaps and achieve

476 consistency. As a consequence we decided to limit the number of markets to minimize the need for
477 adaptation of the reported data. A harmonization of bilateral trade data undertaken centrally by the
478 FAO could improve the robustness of the results and would allow a higher level of regional detail. The
479 number of markets that can be modelled is also limited by the regional coverage of the monetary input-
480 output (IO) model. While some IO models with global coverage include a larger number of countries,
481 albeit at coarse sectoral resolution, we use EXIOBASE because of its high product detail.

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

493 4.4 Future research needs

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

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

516 **5. Conclusions**

517 Hybrid land footprints provide a consumption-based land use indicator with a high level of commodity
518 detail for food and non-food products. In fact, hybrid accounting methods are the only globally
519 consistent top-down accounting tool capable of capturing the increasingly important non-food sector.
520 The availability of cropland per capita is commonly reported in national statistics. We suggest
521 complementing the per capita availability of cropland (i.e., a production based view), with the per capita
522 cropland footprint (i.e., a consumption based perspective). The footprint analysis highlights the higher
523 land demand of livestock-based diets as compared to crop-based diets, and extends available knowledge
524 through information on the geographical location of the required land and the involved global supply
525 chains. Between 1995 and 2010, an obvious trend in cropland utilization was an increasing share of
526 agricultural commodities entering international trade and the growing importance of the non-food
527 sector. The magnitude and composition of regional per capita cropland footprints varies considerably
528 across regions ranging from 1,000 to 2,000 m² in Asia to over 6,000 m² in Eastern Europe, Russia and
529 Australia. Per capita footprints have been generally decreasing since 2000, except for China, where a
530 small increase occurred, yet amounting to only half of the global average in 2010.

531 In a globalized world, the land footprint of a country includes the cropland used both domestically and
532 abroad to satisfy national consumption patterns. This creates complex teleconnections and involves two
533 elements with distinctly different spheres of influence. On the one hand, the laws and incentives for
534 agricultural production of the respective country regulate domestic land use. On the other, the import
535 of agricultural products is based on the sustainability of cultivation of foreign agricultural land, and the
536 importing country has only limited influence on land use and agricultural production conditions in the

537 exporting countries. One third of the world's cropland is cultivated for export markets with an upward
538 trend. This requires transnational agreements on sustainability standards and traceability of agricultural
539 production chains. Continued population growth and likely further integration of the world economy,
540 necessitate a rational discussion of the sustainability, composition and global impacts of national
541 cropland footprints in the context of planetary boundaries, fairness and the resource needs of future
542 generations.

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

548

549 **Acknowledgements**

550 This work received funding from the German Federal Environment Agency under the Environmental
551 Research Plan (UFOPLAN, project number 3711 12 102 2). We thank anonymous reviewers for useful
552 comments and suggestions.

553

554 **Conflicts of interest:** None

555

556

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688 **ANNEX**

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

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

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