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The global cropland footprint of the non-food bioeconomy

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Abstract

A rapidly growing share of global agricultural areas is devoted to the production of biomass for non-food purposes. The derived products include, for example, biofuels, textiles, detergents or cosmetics. Given the far-reaching global implications of an expanding non-food bioeconomy, an assessment of the bioeconomy's resource use from a footprint perspective is urgently needed. We determine the global cropland footprint of non-food products with a hybrid land flow accounting model combining data from the Food and Agriculture Organization and the multi-regional input-output model EXIOBASE. The globally interlinked model covers all cropland areas used for the production of crop- and animal-based non-food commodities for the years from 1995 to 2010. We analyse global patterns of raw material producers, processers and consumers of bio-based non-food products, with a particular focus on the European Union. Results illustrate that the EU is a major processer and the number one consumer region of non-food cropland, despite being only the fifth largest producing region. Two thirds of the cropland required to satisfy EU non-food consumption are located in other world regions, giving rise to a significant dependency on imported products and to potential impacts on distant ecosystems. With almost 29% in 2010, oilseed production, used to produce, for example, biofuels, detergents and polymers, represents the dominant share in the EU's non-food cropland footprint. There is also a significant contribution of more traditional non-food biomass uses such as fibre crops (for textiles) and animal hides and skins (for leather products). Our study emphasises the importance of comprehensively assessing the implications of the non-food bioeconomy expansion as envisaged in various policy strategies, such as the Bioeconomy Strategy of the European Commission.

Keywords: Bioeconomy, land footprint, non-food products, multi-regional input-output analysis, hybrid land flow accounting

JEL codes: Q56, Q57

1 Introduction

Land is vital to our economy and livelihoods. It provides humanity with food, feed, fuel, fibre, and areas for buildings and infrastructure. In addition, land has a high recreational and aesthetic value for humans and is essential for regulating ecosystem services and for maintaining plant and animal biodiversity. However, there is only a limited amount of bioproductive land available on the planet and human pressure on this land is steadily increasing[1,2]. Three main reasons can be identified.

1. The land demand in industrialised countries continues to be very high. With around 3,000 m² per capita in 2010, the EU-28 had a per capita cropland footprint that was more than 40% above the global average[3-5]. Only industrialised countries with large land areas and low population densities, such as the USA, Canada or Australia, have higher per-capita cropland footprints.
2. Middle classes are rapidly growing in several world regions, most notably in emerging economies such as China. Increasing incomes change consumption behaviours, lifestyles and diets, with a general increase in the consumption of animal-based products. For example, in East Asia, changes in diets were by far surpassing population growth as the main driver for increasing food-related land demand in the past 30 years[6].
3. The third reason, and the one on which this article will focus, is the rise in pressures on global land resources due to increasing demand for non-food biomass products, i.e. biomass for energy or material uses (for example, biofuels and bioplastics). We will show that these non-food uses of cropland have been a fast growing share of the EU cropland footprint, largely in response to strategies aimed at reducing fossil fuel dependence. Low oil prices, concerns about food security and the extent of achieved greenhouse gas savings have hampered this trend in recent years. However, in the medium and long-term the trend is towards a more bio-based economy.

Biomass from agriculture, forestry, and aquatic sources is a key commodity in the bioeconomy. In 2008, 4% of harvested biomass worldwide was used each for material and energy purposes[7]. Currently, about 10% of the feedstock base of the global chemical industry consists of renewable materials such as oils, fats, sugar, starch, and cellulose, and demand is constantly growing[8,9].

Over the past 15 years, international organizations and governments have increasingly developed strategies and initiatives with the aim of designing and fostering bioeconomic growth[10-12]. These efforts are driven by the expectation that a bio-based economic transformation will contribute to economic growth, generation of employment both in urban and rural regions, and a reduction of greenhouse gas emissions due to a lower fossil fuel dependence[13]. A critical view is that a growing bioeconomy could lead to adverse environmental impacts by increasing demand for land and water in ecologically sensitive regions[14]. The economic and environmental benefits and costs of a global bioeconomic transformation are likely to be unevenly distributed in space as countries have largely varying competitive advantages for the production and processing of bio-based materials.

Europe stands out as the only world region that is a net-importer of the four major natural resource categories: materials, water, carbon and land[15]. Imports of feedstock for the EU bioeconomy can have negative consequences for land use and ecosystems in distant places. These impacts tend to be less well studied than the economic benefits of trade. Hence, this article quantifies the global land demand for non-food products manufactured by the European bioeconomy and those consumed in Europe. It analyses the historical development of Europe's global land demand over the period of 1995 to 2010 from three – equally important – perspectives: a) the land use perspective (cropland use for non-food purposes), b) the industry perspective (cropland embodied in agricultural products used in non-food manufacturing industries) and c) the consumer perspective (cropland embodied in final consumption of non-food products).

The bioeconomy is often defined as 'an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources, such as plant and animal sources'[13]. The study results presented here narrow the focus to industrial activities using biomass from cropland for non-food purposes, including both products from plant and animal sources. This article thereby aims to complement available studies related to the land footprint of food consumption and of different dietary patterns[6,16-20] as well as land footprint assessments not further distinguishing food and non-food uses[4,21]. The scope of this study is confined on the cropland footprint and thus excludes land areas related to the production of wood and wood products. Although timber is a key resource in the bioeconomy context, the calculation of land demand related to timber consumption is challenged by limited data availability regarding actual harvested forest areas – in contrast to overall forest areas[5,22].

2 Results

We first present the global land requirements for the production of non-food products. In the second part, we illustrate how these non-food products are traded on international markets, from agricultural production to processing industries and then to final consumers. The third section focuses on the role of the EU as a final consumer, investigating the geographical and product structure of its non-food cropland footprint.

2.1 Global cropland use for non-food purposes

With increasing material and energetic demand for non-food bio-based products, the land area to produce these has expanded significantly over the past 15 years. In 1995, more than 132 Mha arable land were required for producing biomass for non-food uses. This area increased to more than 178 Mha in 2010, a growth of 35% in only 15 years, faster than population growth in this period which was 20%. In the same period, global average yields for cereals and oil crops increased by 29% and 44%, respectively23. In the year 2010, non-food agricultural areas thus accounted for approximately 12% of the overall global cropland area.

With 81.8 Mha and a share of 46% in global non-food cropland in 2010, Asia-Pacific was by far the largest producing region of feedstocks for the non-food bioeconomy. China, India and Indonesia were major producers of non-food products, contributing 20.9 Mha, 12.4 Mha and 14.1 Mha, respectively, to the Asian total in 2010. Strong increases in land requirements were observed in China and Indonesia. Growth in China from 9% to 17% of the country's cropland area was mainly related to vegetable oils and oil crops, with soybean oil being the major commodity for the production of non-food products. To a lesser extent maize for ethanol production also expanded.

The expansion in Indonesia from 7.0 Mha to 14.1 Mha (or 31% of the available cropland) mostly focused on vegetable oils; Indonesia is the world's largest producer of palm oil and second for coconut oil, which together accounted for 39% of its non-food cropland areas in 2010. Indonesia is also a major producer of natural rubber (27% of the non-food area in 2010), a raw material mainly used to produce car tires and latex products, but also applied in the cement and chemical industry.

Production in the USA expanded by around 10 Mha between 1995 and 2010, mostly driven by increased maize production for ethanol. Maize held a share of 60% of all non-food agricultural areas in the year 2010, making the USA the number one ethanol producer world-wide. Also Brazil, the second largest ethanol producer after the USA, increased its cropland use for non-food purposes, used mainly for the cultivation of sugar cane (50%) and oilseeds (22%), significantly from 7.1 Mha in 1995 to 11.7 Mha in 2010.

Table 1 illustrates the cropland used in each modelled region between 1995 and 2010 to supply the global non-food bioeconomy with agricultural raw materials.

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Table 1. Global cropland use for the production of agricultural raw materials supplied to the non-food bioeconomy compared to the total available arable land (incl. land used for the cultivation of permanent crops), 1995 and 2010, in million hectares (Mha) and percentage shares, as well as the absolute and relative changes of non-food cropland use over the period.

Region	**1995**			**2010**			**Changes 1995 – 2010**	
	Non-food	**Total**	**Share**	**Non-food**	**Total**	**Share**	**Mha**	**%**
World	**132.2**	**1,535**	**9%**	**178.3**	**1,547**	**12%**	**46.1**	**35%**
Asia-Pacific	**63.5**	**608**	**10%**	**81.8**	**607**	**13%**	**18.3**	**29%**
China	12.0	130	9%	20.9	122	17%	8.9	75%
India	11.2	170	7%	12.4	169	7%	1.2	10%
Indonesia	7.0	31	23%	14.1	45	31%	7.1	102%
Australia	8.5	40	21%	6.0	43	14%	-2.5	-29%
Rest of Asia-Pacific	24.7	237	10%	28.3	228	12%	3.6	15%
Northern America	**20.0**	**236**	**8%**	**30.1**	**207**	**15%**	**10.1**	**51%**
United States of America	16.7	184	9%	26.0	159	16%	9.3	56%
Canada	3.3	52	6%	4.0	48	8%	0.7	24%
Latin America	**13.3**	**159**	**8%**	**21.6**	**185**	**12%**	**8.3**	**62%**
Mexico	1.3	25	5%	1.6	26	6%	0.3	24%
Brazil	7.1	66	11%	11.7	77	15%	4.6	66%
Rest of Latin America	5.0	68	7%	8.2	82	10%	3.2	66%
Europe	**21.2**	**311**	**7%**	**23.1**	**289**	**8%**	**1.9**	**9%**
EU-28	10.4	131	8%	14.6	120	12%	4.2	41%
Russian Federation	7.8	129	6%	5.5	121	5%	-2.3	-29%
Rest of Europe	2.9	51	6%	2.9	48	6%	0	-1%
Africa & Middle East	**14.3**	**222**	**6%**	**21.8**	**260**	**8%**	**7.5**	**52%**
Middle East	2.7	66	4%	2.8	61	5%	0.1	4%
Rest of Africa	11.6	155	7%	19.1	199	10%	7.5	64%

Within the EU, land areas for non-food production increased by around 4 Mha, reaching 14.6 Mha (12% of the EU's cropland area) in 2010. The product composition in the EU was dominated by oil crops (43%), with rapeseed and sunflower being the dominant seeds. Animal products, such as hides and skins, also play a notable role in the EU (31% of total non-food agricultural area in 2010).

Land areas devoted to the cultivation of non-food products also grew in Africa, to more than 19 Mha in 2010, while decreasing in Oceania and the Russian Federation. Note that because of low yields in Africa, the physical quantity of non-food commodities produced from crop-land is lower compared to similar area extents in other parts of the world.

2.2 From land use to consumption

The previous section provided an overview of the primary production perspective, i.e. quantifying those land areas in producing countries and regions where crops are cultivated that are directly or indirectly used for non-food purposes. The harvested biomass is then further processed by industries, such as producers of biofuels or bioplastics, or the rubber or textile industries. These industries may be located in the same country, or may import feedstock from other countries. After processing, bioeconomy end-products are consumed by individuals, governments, businesses, or are put on stock for use in the following years. Consumption and changes in stock constitute the so-called final demand of an economy. Again, consumers may be located in the country of production or processing, or the final products may be exported to be consumed in other world regions.

Figure 1 illustrates the land embodied in international flows of non-food biomass products. It shows on the left side where the cropland for the production of non-food products is used, in the middle part where the industries are located that process the respective biomass products, and on the right side where the final products are consumed. Note that the aggregated totals of embodied land are identical in all three parts of the flow diagram.

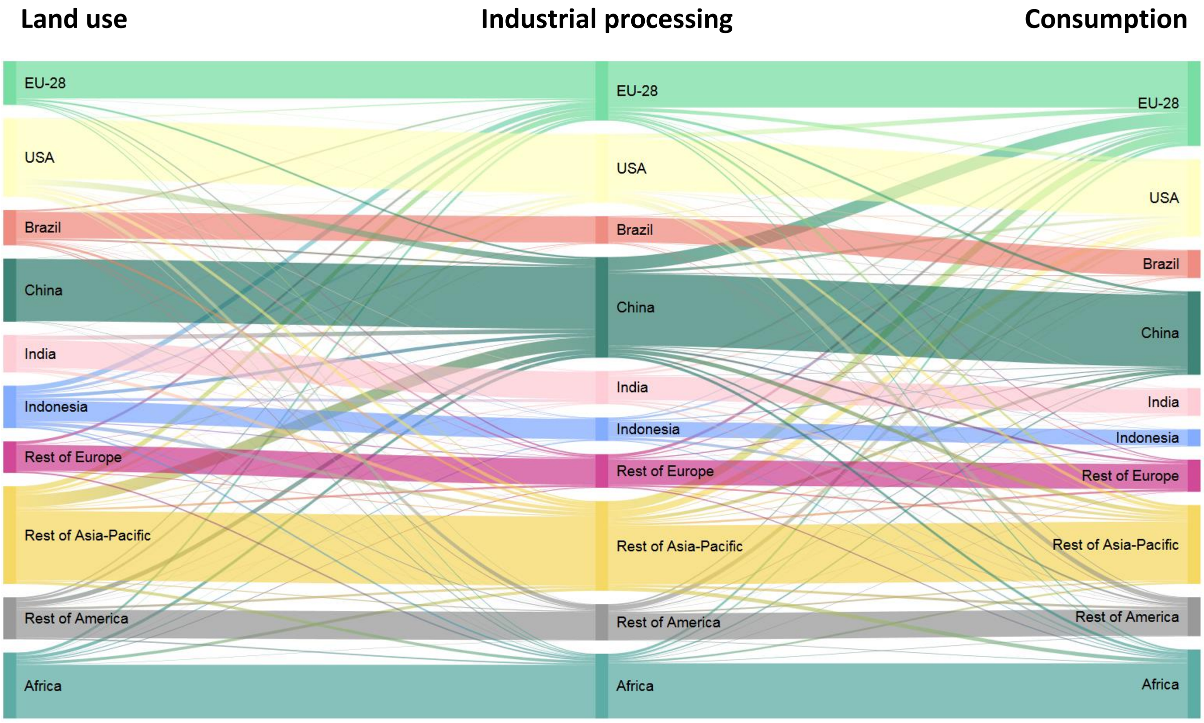

Figure 1: Global flows of embodied land associated with non-food products, 2010.

On the left side, the producing countries and regions are illustrated, as they have been analysed in the previous section. It can be seen that, at the current level of model's geographical aggregation, most countries and world regions are net-exporters of biomass for non-food use and related land areas between the steps of primary production and processing, implying that a part of the involved manufacturing processes (and related value added) do not take place in the producer country of the raw material. For example, in 2010, Brazil produced crops destined for non-food uses on around 11.7 Mha. However, Brazilian industries only processed crops equivalent to around 9.2 Mha. This means that products equivalent to an area of around 2.5 Mha were exported to processing industries in other countries and regions. This pattern is even more pronounced in Indonesia, where the domestic industry processed only around half of the primary products produced within Indonesia (7.8 Mha compared to 14 Mha). Indonesia is a major exporter of palm oil and other non-food products, most notably to the EU and the region 'Rest of Asia-Pacific'.

The column in the middle of Figure 1 illustrates the geographical location of the industries that further process the biotic raw materials into products, i.e. the industry perspective. It can be seen that large processing industries are located in China, where crop and livestock products produced on more than 33 Mha of cropland were processed into non-food commodities in 2010. Only around 21 Mha have been cultivated for non-food purposes in China itself. From a processing perspective, China is thus a net-importer of embodied land from other world regions. With 19.8 Mha, the EU also had a significant processing industry with around a quarter of the required raw materials being imported from other world regions.

Moving to the right side of Figure 1, the flows of embodied cropland from the processing industries to the countries and regions of final consumption are illustrated, i.e. the consumer perspective. The EU was the largest consuming region with more than 28 Mha, followed by China, Rest of Asia-Pacific and the USA, also illustrated by Figure 2a. The dependence of EU consumption on foreign land areas is striking. In 2010, less than half of the land required to produce these non-food products (around 12.5 Mha) was located in the EU itself. Large amounts of embodied land (7.3 Mha) were imported to serve the further processing of these non-food products in the EU, most notably vegetable oils, e.g. for biofuel, polymer and detergent production, from Indonesia and other Asian countries. Most of the processing output (equalling 19.8 Mha of embodied land) served consumption within the EU itself. In addition, processed products were imported from all other world regions, including China (4.4 Mha; primarily embodied in oleochemical products), Rest of Asia-Pacific (3 Mha; vegetable oils and rubber) and the USA (1.6 Mha; primarily maize and ethanol).

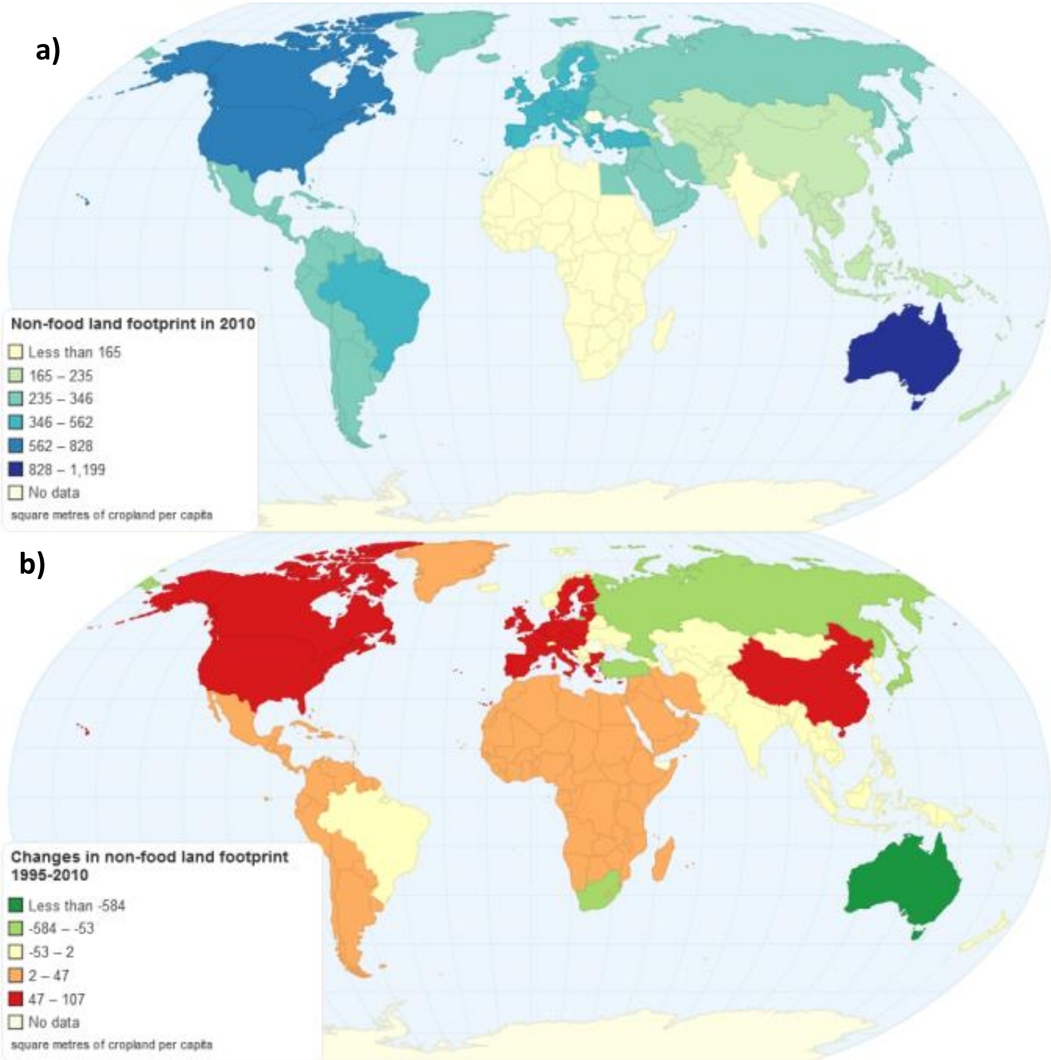

Figure 2: a) The cropland footprint of the consumption of bio-based non-food products in square metres per capita in 2010, by country. b) Changes in the non-food cropland footprint of nations 1995-2010 in square metres per capita.

Figure 2a reveals the global consumption hotspots for cropland embodied in bio-based non-food products. In 2010, Australia showed by far the biggest level of consumption with 1200 square metres per capita, followed by the USA and Canada with slightly more than 800 square meters. Consumption in Australia is particularly high for hides & skins, while for the USA and Canada it's dominated by maize and products derived therefrom. In the EU-28, consumption of bio-based non-food products required 560 square metres per capita, while an Indian only demanded 75 square metres on average. Footprints increased for almost all countries between 1995 and 2010 (Figure 2b), particularly in China, where it more than doubled from 100 to almost 210 square metres per capita. Also North America showed a growth by more than 100 square metres per capita, followed by an 84 square metres increase in the EU-28. Australia and to a lesser extent also the Russian Federation, South Africa, Japan, Turkey and Brazil experienced reductions in their non-food cropland footprints by between 6% (for Brazil) and 44% (for South Africa). This stark decline in South Africa was mainly caused by the product groups 'ruminant hides & skins' and 'other industrial crops', i.e. fibre crops and natural rubber. Besides a reduction in consumption, increased feed conversion efficiencies and crop yields may have contributed to this decrease.

2.3 The EU cropland footprint of non-food products: the consumer perspective

The previous section illustrated that the EU is a significant consumer of non-food products, with a significant share of required biomass – and related embodied land – being imported from other world regions. We now take a closer look at the development of the EU cropland footprint for non-food products over time as well as its geographical and product composition.

The overall cropland footprint of the EU's consumption of non-food products increased by 23% from around 23 Mha in 1995 to 28.2 Mha in 2010, after reaching a peak in the year 2007 (with 31.5 Mha). While with 86% the vast majority of cropland embodied in the EU's food consumption in 2010 stemmed from the EU itself[5], for the case of non-food products only 35% (9.9 Mha) were based on domestic land resources (see Table A 3). The remaining 65% of the cropland (18.3 Mha) was imported from outside the EU-28**.** With 2.7 Mha of embodied land, China was a major supplying country, accounting for almost 10% of the EU's non-food cropland footprint, mainly in the form of oil crops, maize, and fibre crops, or products derived therefrom. Indonesia, with 2 Mha, also provided large areas, largely related to palm and coconut oil. The group Rest of Asia-Pacific, including Malaysia, Bangladesh, the Philippines and Thailand, among others, supplied Europe particularly with vegetable oils, rubber, fibre crops and non-food alcohol. Northern America also played an important role as an exporter of maize for industrial uses (e.g. in the form of starch or ethanol).

Looking at the product composition of the EU's cropland footprint for non-food products in 2010, more than one third was related to vegetable oils and oil crops, mainly consumed in the form of biofuels, detergents, lubricants and polymers[24]. This is more than double the embodied land of this category in 1995. Increasing consumption of vegetable oils was therefore a main determinant for the overall growth of the EU non-food cropland footprint.

Another noticeble aspect is the change in composition of the EU non-food cropland footprint between 1995 and 2010. While in 1995, crop products contributed only 63% to the overall land footprint of the EU bioeconomy, this share increased to 80% in 2010. This includes increasing quantities of cereals, non-food alcohol (mainly from maize and sugar cane) and vegetable oils for fuel use. In contrast, the embodied land related to the consumption of animal products, such as hides and skins, showed a declining trend.

Table 2. Global cropland footprint of the EU's consumption of non-food products in 2010, by producing region and commodity, in thousand hectares and percentage shares.

	EU-28	Rest of Europe	Africa & Middle East	Northern America	Brazil	Rest of Latin America	Australia	China	India	Indonesia	Rest of Asia-Pacific	Total	%
Crop products	**6,990**	**1,134**	**1,709**	**2,102**	**787**	**696**	**89**	**2,496**	**989**	**2,015**	**3,587**	**22,594**	**80%**
Wheat	993	116	35	91	1	10	34	53	0	0	119	1,452	5%
Rice	9	0	9	3	0	14	0	36	2	93	209	376	1%
Maize	166	30	5	1,196	16	29	0	494	3	22	29	1,991	7%
Other cereals	86	1	120	3	0	9	0	0	0	0	4	225	1%
Roots & pulses	33	4	84	2	0	5	1	0	0	0	50	179	1%
Sugar & sweeteners	78	5	9	0	16	24	1	0	1	1	28	164	1%
Oil crops (incl. oils & cakes)	4,639	820	490	326	177	416	14	1,191	235	1,187	1,448	10,943	39%
Fruit, vegetables, spices	50	6	11	1	1	2	0	1	1	15	5	92	0%
Coffee, tea, cocoa	0	0	34	0	1	1	0	0	0	1	1	38	0%
Tobacco	84	16	114	15	92	25	0	155	29	12	9	551	2%
Rubber	0	0	210	0	2	6	0	61	18	550	707	1,554	6%
Fibre crops	219	109	425	346	81	53	30	442	672	7	576	2,959	10%
Alcohol, non-food	632	28	162	119	401	103	9	63	26	128	400	2,070	7%
Livestock products	**2,949**	**364**	**176**	**592**	**15**	**116**	**658**	**213**	**130**	**5**	**387**	**5,604**	**20%**
Meat and fats	792	84	11	88	8	54	63	39	2	2	70	1,215	4%
Milk and eggs	667	108	4	109	0	1	8	22	1	0	26	947	3%
Hides, skins, wool	1,490	171	161	394	6	61	587	152	127	2	291	3,442	12%
Total	**9,939**	**1,498**	**1,884**	**2,693**	**802**	**812**	**748**	**2,709**	**1,119**	**2,020**	**3,974**	**28,198**	**100%**
Percentage share	35%	5%	7%	10%	3%	3%	3%	10%	4%	7%	14%	100%	

3 Discussion

The increasing amount of land and biomass consumed by the bioeconomy adds to the already high land demand for food supply and indicates a growing pressure on planetary boundaries. It also closely relates to issues of global justice when it comes to a fair distribution of biophysical resources. Potential environmental impacts include, for example, increased water scarcity[25] and nutrient pollution[26], but also potential negative climate impacts, in particular due to deforestation in tropical regions[27,28], driven by a growing demand for raw materials for the bioeconomy[8]. Social impacts may arise due to the dislocation of vulnerable socio-demographic groups in developing countries, such as subsistence farmers with unclear land access rights[29], and the commodification of land and food crops[30]. Besides socio-ecological considerations, the vulnerability of export crop production to climate change in some major supplying countries[31,32] also puts highly import-dependent economies at risk of supply constraints.

Despite sluggish demand for biofuels in recent years, global production is expected to further increase by 11% for ethanol and 32% for biodiesel from 2015 to 2025[33]. Moreover, material uses particularly of starch and oil crops to produce, for example, detergents, lubricants and polymers will continue growing with estimated growth rates around 25% between 2011 and 2020 in the case of Germany[24].

Our results have implications for both future research and strategies or initiatives aimed at limiting the potential negative social and environmental impacts of an expanding bioeconomy. First, growing demand for non-food bio-based products means that demand for global cropland is increasingly driven by other than traditional food value chains, including completely new value chains, that emerge as a result of value chain conversion processes or in response to new biomass applications[34]. To accommodate these trends, existing governance regimes may have to be adapted to account for greater value chain complexity including a larger number of downstream intermediaries.

Second, although still to a limited extent in our period of study, biomass production may gradually shift from traditional sources in the Americas and South East Asia to new agricultural frontiers with lower governance capacities in Africa[35]. Such a shift represents a challenge for value chain governance mechanisms, including some certification schemes, that rely on social and environmental monitoring or law enforcement mechanisms at national level.

Third, land footprints are only a part of a much larger puzzle that involves the quantification and equitable sharing of the costs and benefits associated to the production and consumption of biomass-based commodities. Recent work on identifying the origin of such commodities at higher spatial resolution increases our ability to associate product sourcing with actual impacts on the ground[36]. However, the origins and destinations of global biomass flows are not stable over time and as responsible consumers pull out of producer regions with questionable impacts, voids will eventually be filled by others, if incentives prevail.

Our study also has implications for the further expansion of the European non-food bioeconomy as envisaged in the Bioeconomy Strategy of the European Commission[10]. The mismatch between domestic production on the one hand and industry demand for crops for further processing to non-food commodities on the other hand will likely grow. Given the far-reaching global implications of an expanding European bioeconomy, robust methods and indicators need to be developed and applied, in order to properly assess Europe's resource use as well as the related environmental and social impacts from a consumer (or footprint) perspective. But also the industry perspective can be expected to further gain importance, considering the fact that the share of agriculture on the value added of food supply chains is decreasing while the share of processing industries continues growing, as documented in a publication by the European Commission[37].

The fact that European production and consumption patterns cause land use-related impacts beyond Europe's borders has been acknowledged in various EU policy documents. For example, in its Resource Efficiency Roadmap[38], the EU states that "*by 2020, EU policies take into account their direct and indirect impact on land use in the EU and globally, and the rate of land take is on track with an aim to achieve no net land take by 2050*" (p. 15). In its 7th Environmental Action Programme[39], the EU also committed to support a "*land degradation neutral world in the context of sustainable development*" (p. 3) and calls for targets to be set to limit land take. However, despite these policy objectives, the EU has so far not agreed on a common methodology to assess distant land use-related impacts of EU policies. Key indicator systems with high relevance for land, such as the Resource Efficiency Scoreboard[40] thus focus on territorial indicators only and fail to take into account the international teleconnections.

There are also important links of our assessments to the climate policy field. In November 2016, the threshold for entry into force of the Paris Agreement to limit global temperature rise during this century well below 2 degree Celsius above pre-industrial levels was achieved. To achieve this goal, bioenergy will need to play a vital role, at minimum in the medium term. In the beginning of the 2000s, the use of global cropland for the non-food sector began to increase, mainly driven by increasing amounts of vegetable oil, alcohol, and sugar used to produce non-food commodities, including biofuels. Global biofuel production increased rapidly from 10 Mtoe in 2000 to almost 60 Mtoe in 2010[41]. Around 2010, cropland use for biofuel feedstock production has been estimated to require 25 Mha globally[41,42]. This suggests that a significant share of the increase in non-food cropland equalling 46 Mha results from the expansion of biofuel production.

Environmental governance in a globalized bioeconomy thus requires instruments that operate across multiple administrative levels and stakeholder groups. Robust quantitative information at high temporal and spatial resolution is needed to inform such a coordinated governance regime on the dynamics of material flows and the associated costs and benefits of impacts on the ground. Our findings suggest that there is scope for reducing negative impacts by optimizing feedstock composition or sourcing from world regions with favourable social and environmental production conditions, including the partial substitution of globally sourced biomass by local or regionally produced alternatives[43,44].

4 Conclusions

In this paper, we have assessed global patterns of land demand for non-food products from a production, processing and consumption perspective, with a focus on Europe's role in the global non-food land system. The assessment highlighted the increasing importance of non-food products, being the fastest growing source of demand for agricultural land globally. Europe plays a crucial role in determining global developments, being the biggest consumer region of non-food biomass products (measured in terms of cropland area), but only the fifth largest producer. 86% of the land used to satisfy European food demand is located in Europe, whereas 65% of the land providing non-food products to the region is cultivated elsewhere. The expanding European bioeconomy is thus highly dependent on agricultural areas in other world regions, most notably in Asia.

There is still significant room and need to expand the presented method in terms of including other commodities of key importance (e.g. timber and forest areas) as well as updating the calculations to the most recent years. Furthermore, current statistics from the FAO and EXIOBASE do not allow to explicitly separate bioenergy (e.g. biodiesel and ethanol) from biomaterial uses (e.g. detergents, adhesives, textiles, polymers). Industry data could help refining the model for addressing more detailed research questions.

Assessments of the environmental and social impacts related to the European consumption of non-food bio-based products in regions all over the world are almost entirely missing in the literature. In order to take into account the regional differences in environmental and social conditions within producing countries, footprint methods need to move from the aggregated national to a spatially detailed level[36,45-49].

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Appendix I – Methods

Land footprint studies use physical or monetary production and trade data and apply top-down or bottom-up methods to connect land use with final consumption[22]. The present study uses a hybrid (mixed-unit) top-down accounting approach to track the demand for cropland embodied in biomass flows along global supply chains. The advantage of applying a global top-down approach is that it avoids double-counting and tracks all global flows comprehensively and consistently[22,50]. At the same time, it is limited in detail, as it operates on globally available agricultural and economic statistics. As a consequence, while all kinds of products from biological sources are covered (e.g. textiles, leather products, lubricants, bioplastics, etc.), the model does not allow reporting all these products separately, but rather aggregated product groups such as vegetable oils, covering all products derived from vegetable oils including, for example, biofuels, cosmetics, detergents and lubricants.

In this paper, the cropland footprint of non-food products will be approached in two ways. First, quantifying the cropland footprint of the raw material inputs required by the manufacturing industries of a country to produce bio-based materials and fuels ("industry perspective"); and second of the bio-based products consumed in a country ("consumer perspective").

The industry perspective

First, we calculated the cropland footprint of non-food products from the industry perspective using the global physical biomass trade accounting model LANDFLOW[5,51], which is based on data from the Food and Agriculture Organization (FAO) of the United Nations[23]. We calculated the product-related cropland footprints disaggregated into 25 different product groups (see Table A 1).

Table A 1: List of commodities covered by the biomass trade accounting model

No.	Crop commodity	No.	Livestock commodity
1	Wheat	**18**	Ruminants, meat and offal
2	Rice	**19**	Ruminants, dairy products
3	Maize	**20**	Ruminants, fats and meals
4	Other cereals	**21**	Ruminants, hides and skins
5	Roots & pulses	**22**	Monogastrics, meat and offal
6	Sugar crops (primary)	**23**	Monogastrics, eggs
7	Sugar, sweetener, molasses	**24**	Monogastrics, fats and meals
8	Oil crops (primary)	**25**	Monogastrics, hides and skins
9	Vegetable oil		
10	Oil cakes		
11	Fruit, vegetables, spices		
12	Stimulants		
13	Tobacco		
14	Rubber		
15	Other industrial crops		
16	Alcohol, non-food		
17	Fodder crops		

The calculation model also specifies 14 countries and 6 aggregate regions, including the EU-28 (see Table A 2).

Table A 2: List of countries and regions covered by the biomass trade accounting model

No.	ID	Regions	No.	ID	Regions
1	AUT	Austria	**11**	RUS	Russian Federation
2	DEU	Germany	**12**	AUS	Australia
3	EU28	Rest of EU-28*	**13**	TUR	Turkey
4	USA	United States of America	**14**	IDN	Indonesia
5	JPN	Japan	**15**	ZAF	South Africa
6	CHN	China	**16**	RAFR	Rest of Africa
7	CAN	Canada	**17**	RASI	Rest of Asia-Pacific
8	BRA	Brazil	**18**	REUR	Rest of Europe
9	IND	India	**19**	RSAM	Rest of Latin America
10	MEX	Mexico	**20**	RMIE	Rest of Middle East

* excluding Austria and Germany

Using a physical accounting model instead of a monetary model substantially increases the detail and robustness of the results[22]. A particular strength of the physical accounting model LANDFLOW is that it specifies the category of 'other use' (i.e. non-food-feed use) of each agricultural product, which is a precondition to quantify the footprint of the non-food bioeconomy.

The applied model uses detailed and comprehensive supply and use data (covering production, stock changes, international trade and utilization) measured in physical volumes (i.e. tons) from the FAO Supply Utilization Accounts[1] to set up a global tree structure for all commodity flows and tracks embodied cropland along these supply chains. For example, land used to produce soybeans is tracked from harvest via processing to final utilization. In the case of co-production, such as soybean oil and cake, land areas are split and allocated to the derived products in relation to their economic value, i.e. using price allocation. Specifically, for each joint product value shares are calculated from physical quantity using published technical extraction rates and a price of the sub-product.

The method not only covers crops and derived crop products, but also animal products such as milk, meat, fats and hides. Feed balances are estimated for ruminants and monogastrics respectively and available feed crops are allocated according to dietary and energy requirements of the two livestock groups. Once cropland areas are allocated to the two livestock groups, embodied land areas are attributed to multiple derived products (e.g. milk, meat and hides from ruminant livestock) using value shares as described for the case of soybean oil and cake[5].

The land embodied in products is tracked to final utilization, differentiated into food, feed, seed, waste and other uses. The category of other uses comprises all non-food uses, including, for example, the quantities of vegetable oils used for the production of detergents, polymers and biodiesel, and meat and offal processed into pet food and pharmaceutical products[52]. In contrast to food use, the category of other uses, however, does not formally describe a final use but rather an industry use. LANDFLOW analysis thus tracks the supply chains of raw materials to the destination of industrial use (reported as 'other use') but cannot track the further trade of highly processed industrial commodities. For instance, once vegetable oils enter the industrial sector to produce detergents, or cotton enters the textile industry, the further use of detergents or textiles is not recorded in the FAO data. Therefore, the LANDLFOW model can be used for the study of industrial uses of biotic feedstocks by calculating the cropland footprint of the non-food bioeconomy from an industry perspective.

[1] Supply Utilization Accounts are distributed by FAOSTAT in the domain 'Food Balance'

The consumer perspective

Second, the cropland footprint of the EU's consumption of bio-based materials, products and fuels was calculated from a consumer's perspective. In order to achieve this, the physical flows of biomass that were previously tracked up to the processing industries are linked to the multi-regional input-output (MRIO) model EXIOBASE[53,54], which allows further tracing upstream flows of non-food biomass commodities from processing industries through the economy along monetary supply chains to the final consumers in different EU Member Countries.

The consumption footprint of cropland embodied in non-food products $\mathbf{F}$ is calculated using the environmentally extended demand-driven Leontief model[55] defined by the equation $\mathbf{F} = \mathbf{E} * (\mathbf{I} - \mathbf{A})^{-1} * \mathbf{Y}$, where $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse and $\mathbf{Y}$ is the final demand matrix showing the final demand for each product by each region. The LANDFLOW results for the category 'other uses' $\mathbf{P}$, with elements p_{ij}, contain information on the land embodied in each agricultural product i (see Table A 1) further processed for non-food purposes by manufacturing industry j. Table A 3 links the commodities of the LANDFLOW model shown in Table A 1 with the sectors of the MRIO model. Inputs are allocated according to the monetary inter-industry flows between supplying sector(s) and using sector(s) according to the year-specific information in the MRIO tables in EXIOBASE.

Table A 3: Supplying and using EXIOBASE sectors of the considered non-food commodities

Nr	LANDFLOW commodity	Supplying EXIOBASE sector(s)	Using EXIOBASE sector(s)
1	Wheat	Wheat	all non-food industries
2	Rice	Paddy rice; Processed rice	all non-food industries
3	Maize	Cereal grains nec	all non-food industries
4	Other cereals	Cereal grains nec	all non-food industries
5	Roots & pulses	Vegetables, fruit, nuts	all non-food industries
6	Sugar crops (primary)	Sugar cane, sugar beet	all non-food industries
7	Sugar, sweetener, molasses	Sugar	all non-food industries
8	Oil crops (primary)	Oil seeds	all non-food industries
9	Vegetable oil	Products of vegetable oils and fats	all non-food industries
10	Oil cakes	Products of vegetable oils and fats	all non-food industries
11	Fruit, vegetables, spices	Vegetables, fruit, nuts	all non-food industries
12	Stimulants	Crops nec	all non-food industries[1]
13	Tobacco	Crops nec	Tobacco products
14	Rubber	Crops nec	Rubber and plastic products
15	Other industrial crops	Plant-based fibers	Textiles
16	Alcohol, non-food	Additives/Blending Components; Biofuels; Chemicals nec	all industries
17	Fodder crops	Crops nec	all non-food industries[1]
18	Ruminants, meat and offal	Cattle; Meat animals nec; Products of meat cattle; Meat products nec;	all non-food industries[2]
19	Ruminants, dairy products	Raw milk; Dairy products	all non-food industries
20	Ruminants, fats and meals	Cattle; Meat animals nec; Products of meat cattle; Meat products nec;	all non-food industries[2]
21	Hides & Skins, Wool, ruminants	Cattle; Meat animals nec; Animal products nec; Products of meat cattle; Meat products nec; Food products nec	Textiles; Wearing apparel, furs; Leather and leather products; Wool, silk-worm cocoons
22	Meat, monogastrics	Pigs; Poultry; Products of meat pigs; Products of meat poultry	all non-food industries[2]
23	Eggs	Poultry; Animal products nec	all non-food industries
24	Monogastrics, fats and meals	Pigs; Poultry; Products of meat pigs; Products of meat poultry	all non-food industries[2]

Nr	LANDFLOW commodity	Supplying EXIOBASE sector(s)	Using EXIOBASE sector(s)
25	Monogastrics, hides and skins	Pigs; Products of meat pigs	Textiles; Wearing apparel, furs; Leather and leather products; Wool, silk-worm cocoons

Notes: 1) excluding those industries supplied with tobacco and rubber; 2) excluding those industries supplied with hides, skins and wool

The environmental extension matrix $\mathbf{E}$ for the MRIO model is derived by dividing absolute input quantities by the respective output value of each industry: $\mathbf{E} = \mathbf{P}\,\hat{\mathbf{x}}^{-1}$.