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Quantifying the global cropland footprint of the European Union's non-food bioeconomy

Martin Bruckner*[1], Tiina Häyhä[2,3], Stefan Giljum[1], Victor Maus[1,3], Günther Fischer[3], Sylvia Tramberend[3], Jan Börner[4]

[1] Institute for Ecological Economics, Vienna University of Economics and Business, Vienna, Austria
[2] Stockholm Resilience Centre, Stockholm University, Sweden
[3] International Institute for Applied Systems Analysis, Laxenburg, Austria
[4] Institute for Food and Resource Economics, and Center for Development Research, University of Bonn, Germany

* Welthandelsplatz 1, 1020 Vienna, Austria, +43 1 31336 5756, martin.bruckner@wu.ac.at

Abstract

A rapidly growing share of global agricultural areas is devoted to the production of biomass for non-food purposes. The expanding non-food bioeconomy can have far-reaching social and ecological implications; yet, the non-food sector has attained little attention in land footprint studies. This paper provides the first assessment of the global cropland footprint of non-food products of the European Union (EU), a globally important region regarding its expanding bio-based economy. We apply a novel hybrid land flow accounting model, combining the biophysical trade model LANDFLOW with the multi-regional input-output model EXIOBASE. The developed hybrid approach improves the level of product and country detail, while comprehensively covering all global supply chains from agricultural production to final consumption, including highly-processed products, such as many non-food products. The results highlight the EU's role as a major processing and the biggest consuming region of cropland-based non-food products while at the same time relying heavily on imports. Two thirds of the cropland required to satisfy the EU's non-food biomass consumption are located in other world regions, particularly in China, the US and Indonesia, giving rise to potential impacts on distant ecosystems. With almost 39% in 2010, oilseeds used to produce for example biofuels, detergents and polymers represented the dominant share of the EU's non-food cropland demand. Traditional non-food biomass uses, such as fibre crops for textiles and animal hides and skins for leather products, also contributed notably (22%). Our findings suggest that if the EU Bioeconomy Strategy is to support global sustainable development, a detailed monitoring of land use displacement and spillover effects is decisive for targeted and effective EU policy making.

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

1 Introduction

Over the past 15 years, many governments and international organizations have developed strategies and initiatives to design and foster an economy that increasingly uses bio-based materials, chemicals, and renewable energy sources (European Commission, 2012a; Meyer, 2017; OECD, 2009; Staffas et al., 2013; White House, 2012). These efforts are driven by the need to reduce greenhouse gas emissions and fossil fuel dependence, with the expectation that a bio-based economic transformation will contribute to economic development and employment both in urban and rural regions (McCormick and Kautto, 2013).

The European Union (EU) is particularly active in promoting bio-based transformations and seeks to respond to global social-environmental challenges through its Bioeconomy Strategy (European Commission, 2012a). The bioeconomy has been envisioned as an important component for smart and green growth while simultaneously achieving the EU's climate and other environmental targets and the 2030 Agenda (Bell et al., 2018; McCormick and Kautto, 2013; Scarlat et al., 2015). EU action towards increasing bio-based resource use, bioenergy in particular, has earlier roots, however. In 2003, it established the Biofuel Directive (2003/96/EC) to promote the use of biofuels and other renewable fuels for transport. The Renewable Energy Directive (2009/28/EC) followed in 2009 and provided the policy framework for the production and use of domestically produced and imported energy from renewable sources in the EU, including an EU-wide 20% renewable energy target as well as a 10% renewable transport fuel target for individual member countries by 2020.

The sustainability of the EU's expanding bioeconomy has also been questioned (O'Brien et al., 2015; O'Brien et al., 2017; Pfau et al., 2014; Ramcilovic-Suominen and Pülzl, 2018). Evidence is rising that an expanding industrial bioeconomy, for example, causes direct and indirect land use change, thereby generating greenhouse gas emissions (Searchinger et al., 2008), and has implications for water quality and quantity (Thomas et al., 2009). Imports of feedstock for the EU bioeconomy can thus have negative consequences for ecosystems in distant places (Deininger, 2013). Based on a systematic review, Pfau et al. (2014) found that bioeconomy should not be considered as self-evidently sustainable. They concluded that further research and policy development should pay attention to how the bioeconomy could contribute to sustainable development. Ramcilovic-Suominen and Pülzl (2018) argued that sustainability is not a core motivation of the EU Bioeconomy Strategy, in which the main emphasis is on biotechnology, eco-efficiency, competitiveness, innovation, economic output and industry, while the strategy is ambiguous about how it will contribute to sustainability. O'Brien et al. (2017) also stressed that the sustainability of the EU's bioeconomy depends on how it is being implemented, with a particular risk being increased global land use requirements of the economy. This risk is illustrated by the fact that 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 (Häyhä et al., 2018; Tukker et al., 2016). 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 (Tramberend et al., 2019).

Various EU policy documents acknowledge that European production and consumption patterns cause land use-related impacts beyond Europe's borders. For example, in its Resource Efficiency Roadmap (European Commission, 2011), the EU states that "by 2020, EU policies take into account their direct and indirect impact on land use in the EU and globally" (p. 15). In its 7th Environmental Action Programme (European Commission, 2012b), 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. Directive (EU) 2015/1513 targets indirect land use change of biofuels production, aiming at a drastic reduction of unintended consequences of the EU's biofuel use on the earth's climate (Council Directive, 2015/1513/EU). Despite these policy objectives, the EU's Bioeconomy Strategy does not explicitly address resource use displacement. Moreover, 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 (EUROSTAT, 2015) thus focus on territorial indicators only and fail to take into account the international teleconnections (Yu et al., 2013).

The importance of footprinting approaches has been widely acknowledged in national and regional sustainability assessments to account for possible land use displacement and leakage effects (Liu et al., 2018; O'Brien et al., 2015; Wiedmann and Lenzen, 2018). Research so far focused on the land footprint of food consumption and of different dietary patterns (FoEE, 2016; Giljum et al., 2013; Kastner et al., 2011; Kastner et al., 2012; Meier and Christen, 2012; Meier et al., 2014). Some assessments of the overall land footprint of countries were also presented (Bringezu et al., 2012; O'Brien et al., 2015; Weinzettel et al., 2013; Yu et al., 2013).

However, existing studies do not further distinguish food from non-food uses and are therefore unable to assess this important part of the bioeconomy transformation. In this paper, we fill this research gap for the European Union by analysing its role in the global non-food bioeconomy with a novel hybrid method, linking biophysical and monetary accounting models for assessing the non-food sector's land requirements. We include both products from plant and animal sources and apply three perspectives to assess the EU's non-food cropland footprint between 1995 and 2010: 1) the land use perspective (cropland use for non-food purposes), 2) the industry perspective (cropland embodied in agricultural products used in non-food manufacturing industries) and 3) the consumer perspective (cropland embodied in final consumption of non-food products).

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 (Bruckner et al., 2015; Fischer et al., 2017).

2 Methods: hybrid land flow accounting

Land footprint studies either use biophysical or monetary accounting models applying top-down or bottom-up methods to attribute land use to final consumers (for a detailed review see Bruckner et al., 2015). The present study implements a hybrid top-down accounting approach to track the demand for cropland embodied in biomass flows along global supply chains by linking the biophysical LANDFLOW model (European Commission, 2013; Fischer et al., 2017) with the multi-regional input-output (MRIO) model EXIOBASE 3 (Stadler et al., 2018). This hybrid method was described in detail and applied previously by Tramberend et al. (2019).

Hybrid models are argued to *"provide more accurate results than the standard MRIO method"* (Weinzettel et al., 2014, p.115). Using the physical accounting model LANDFLOW in combination with an MRIO model substantially increases the product detail of the results, while ensuring the comprehensive coverage of all economic activities worldwide. A particular strength of the LANDFLOW model is that it specifies non-food uses of each agricultural product, which was a prerequisite for this study. By linking EXIOBASE to a biophysical accounting model, non-food flows can be traced to the final consumer, instead of being truncated and allocated to those countries, where the industrial processing takes place.

To grant full access and foster transparency, all data, R scripts, and supplementary files to reproduce this study as well as all presented maps and figures can be found on GitHub: https://github.com/fineprint-global/eu_bioeconomy_footprint/.

The applied models: LANDFLOW and EXIOBASE

LANDFLOW is a global physical biomass trade accounting model based on data from the UN Food and Agriculture Organization (FAOSTAT, 2017). It follows the approach of Kastner et al. (2014) and uses detailed and comprehensive agricultural supply and use data (covering production, stock changes, international trade and utilization) measured in physical volumes (i.e. tons) from the FAOSTAT's Commodity Balance Sheets 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.

The method not only covers crops and derived crop products, but also animal products such as milk, meat, fats and hides, among others (Table S.1 in the Supplementary Material). 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.

The land embodied in products is tracked to final utilization, differentiated into food, 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 (FAO, 2001). 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 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 trade of detergents or textiles is not recorded in the FAO data.

Therefore, we allocated the results of the LANDLFOW model for the category of other uses, representing the land embodied in agricultural commodities when entering non-food manufacturing industries, to the respective industries of the MRIO model EXIOBASE 3 (Stadler et al., 2018). This allowed further tracing upstream flows of non-food biomass commodities from processing industries through the global economy along monetary supply chains to the final consumers. EXIOBASE is an environmentally extended multi-regional input-output database ranging from 1995 to 2011 for 44 countries and five continental rest regions. Its symmetric product-by-product MRIO tables reflect the input structure for the production of 9800 products (200 products per country) and their domestic and bilateral interlinkages. MRIO models, and particularly EXIOBASE, are widely used in footprinting (see, for example, Giljum et al., 2016; Moran and Wood, 2014; Tisserant et al., 2017; Tukker et al., 2016; Wiedmann and Lenzen, 2018). In this study, the MRIO model was used to complement the limited information on non-food supply chains in the LANDFLOW model, in order to identify the final consumer of crop-based products manufactured in industrial processes.

Linking LANDFLOW and EXIOBASE

The decisive step in linking the two models was the mapping of the non-food commodity supply from the LANDFLOW model to the using industries in the EXIOBASE MRIO model. We defined a corresponding EXIOBASE sector for each LANDFLOW commodity, e.g. the EXIOBASE sector 'Products of vegetable oils and fats' corresponds to the LANDFLOW commodity 'vegetable oils'. We then masked the uses of the outputs of this sector in the MRIO entering (domestic and foreign) non-food manufacturing industries, i.e. by removing any uses by the food industry or the service sectors. The resulting correspondence table then delivered the monetary value of the vegetable oil uses by non-food industry (see Table S.3 for a summarized representation of the correspondence tables). Based on this information, we derived industry shares and allocate the land inputs proportionally. As a result, we obtained a land use matrix $\mathbf{P}$, with elements p_{ij} containing information on the land embodied in each agricultural product i further processed for non-food purposes by manufacturing industry j. For more details see Tramberend et al. (2019).

The consumption footprint of cropland embodied in non-food products $\mathbf{F}$ was then calculated straight-forward by using the environmentally extended demand-driven Leontief model (Miller and Blair, 2009) 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 in each region. The environmental extension matrix $\mathbf{E}$ for the MRIO model was derived by dividing absolute input quantities by the respective output value of each industry: $\mathbf{E} = \mathbf{P}\,\hat{\mathbf{x}}^{-1}$.

Limitations of the methodology

There are some important limitations of the presented data and methods. Even though the data available from FAOSTAT provide full country detail for all UN member states, we run the LANDFLOW model at a more aggregated level (see Table S.2). Geographical detail should therefore be improved for assessing region-specific impacts from agricultural production. Some authors even argue that an accurate assessment of impact footprints requires a trade model operating at the subnational level, particularly for big and diverse countries such as Brazil (Flach et al., 2016; Godar et al., 2016).

Moreover, the model currently does not allow separately reporting of final bio-based products such as biofuels, cosmetics, detergents, lubricants or biopolymers, but rather aggregated product groups such as vegetable oils, covering all products derived thereof.

Grid cell level results

We downscaled the national results for some major crops to the level of 5 arc minute grid cells (around 10 km x 10 km at the equator) using the spatial distribution of 42 crops provided by the Spatial Production Allocation Model (SPAM) v3.2 (You et al., 2017). In the first step, we aggregated the SPAM maps to three crop groups: 1) maize and sugarcane, 2) oil crops, and 3) fibre crops. We then allocated the EU footprint in each region to the geographically corresponding cells within that region, using the harvested area reported by SPAM to weight the allocation of the EU footprint into the SPAM grid cells. The weight ω_i^g to allocate a crop group g to a cell i is given by $\omega_i^g = a_i^g / s_r^g$, where a_i^g is the harvested area of the crop group g in the grid cell i and s_r^g is the sum of the harvested area of the crop group g for all cells within region r. The weight in a region sums up to one. This approach does not consider sub-national differences in the export shares and structure, which obviously biases the results. The downscaled results presented in this article thus should be interpreted as a probability distribution of the EU's footprint, rather than an exact localization. The detailed R codes and data used for this downscaling approach can be found in the previously indicated GitHub repository.

3 Results: European Union's non-food cropland footprint

We analysed global patterns of raw material producers, processors and consumers of bio-based non-food products. Here we describe the results for the development of the EU's cropland footprint of non-food products between 1995 and 2010 as well as its geographical and product composition. Further results and illustrations, illustrating for example changes over time , can be found in the Supplementary Material, including the global cropland requirements for non-food products in different world regions (Table S.4 and Figure S.2) and the changes over time of the non-food cropland footprint of the EU (Figure S.1) and other world regions (Figure S.3).

Global flows of embodied non-food cropland

The primary production perspective on the left side of Figure 1 shows the land areas used for production of crops and livestock for non-food purposes. The harvested biomass is then further processed by industries, such as the chemical, the rubber or the textile industries. These processing steps may be located in the same country, or may import feedstock from other countries. The processing phase can have many steps. Figure 1 shows the amounts of embodied cropland requirements when the products first enter the processing phase in non-food manufacturing industries. Finally, the end-products are consumed by individuals or governments, or are put on stock for use in the following years. 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. Note that the aggregated totals of embodied land are identical in all three parts of the Sankey diagram.

The EU-28 is a major processor and the biggest consumer region of non-food cropland, but ranks only fifth among the largest crop producing regions. Consequently, the EU is a major net importer of embodied cropland (Figure S.4).

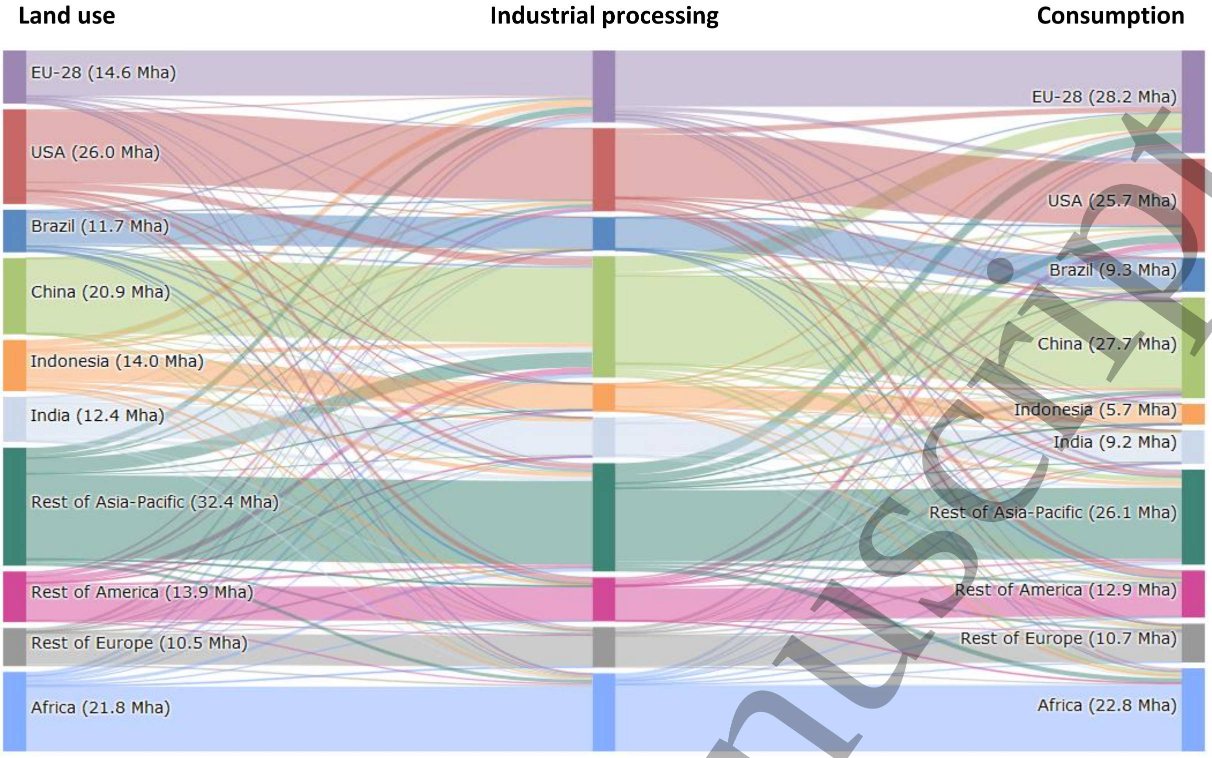

Figure 1. Global flows of embodied cropland associated with the international trade with non-food products in 2010. The left hand side of the Sankey diagram shows the cropland use in each region for the cultivation of crops later on used for non-food purposes. In the middle, we see the land embodied in crops and derived products used in industrial manufacturing processes. Finally, the right hand side of the graph depicts the land embodied in the final consumption of non-food products such as textiles or biofuels in each region.

The cropland area within the EU used for non-food purposes increased from 10.4 Mha to 14.6 Mha between 1995 and 2010 (Table S.4). The latter accounted for about 8% of the global non-food agricultural area in 2010. Oil crops were the most dominant crop type (43%), with rapeseed and sunflower being the most dominant plants. Animal products, such as hides and skins, also played a notable role reaching 31% of total non-food cropland area in the EU in 2010.

The EU also has a significant processing industry with around a quarter of the required raw materials and related land use being imported from other world regions. In particular, vegetable oils for biofuel, polymer and detergent production were imported from Indonesia and other Asian countries. In 2010, the EU's processing industry required 19.8 Mha of cropland. Most of the processing output 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).

The EU was the largest consuming region in absolute terms with 28.2 Mha in 2010 followed by China (27.7 Mha). In relation to population, Australia leads the ranking (1199 m²/capita) followed by the USA (828 m²/capita), Canada (807 m²/capita), the EU (562 m²/capita) and Brazil (468 m²/capita). In comparison, the average non-food cropland demand in India was only 75 m²/capita (see Figure S.2 and Table S.6). From 1995 to 2010, the overall cropland footprint of the EU's consumption of non-food products increased by 23% from around 23 Mha to 28 Mha, after reaching a peak in the year 2007 with 31.5 Mha (see Figure S.3).

Non-food cropland footprint of the EU

While the vast majority (86%) of cropland embodied in the EU's food consumption in 2010 stemmed from the EU itself (Fischer et al., 2017), for the case of non-food products only 35% (9.9 Mha) were based on domestic land resources (Table S.5). The remaining 65% of the cropland (18.3 Mha) was imported from outside the EU-28 (Figure 2). Large amounts of embodied land (7.3 Mha) were also imported to serve manufacturing processes in the EU.

With 2.7 Mha of embodied land, China was a major supplying country for the EU, 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 (Figure 2 and Table S.5). 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).

In 2010, more than one third of the EU's cropland footprint for non-food products was related to vegetable oils and oil crops, which are mainly consumed in the form of biofuels, detergents, lubricants and polymers (FNR, 2014). This is more than double the embodied land of this category in 1995. Increasing consumption of vegetable oils was a main determinant for the overall growth of the EU non-food cropland footprint.

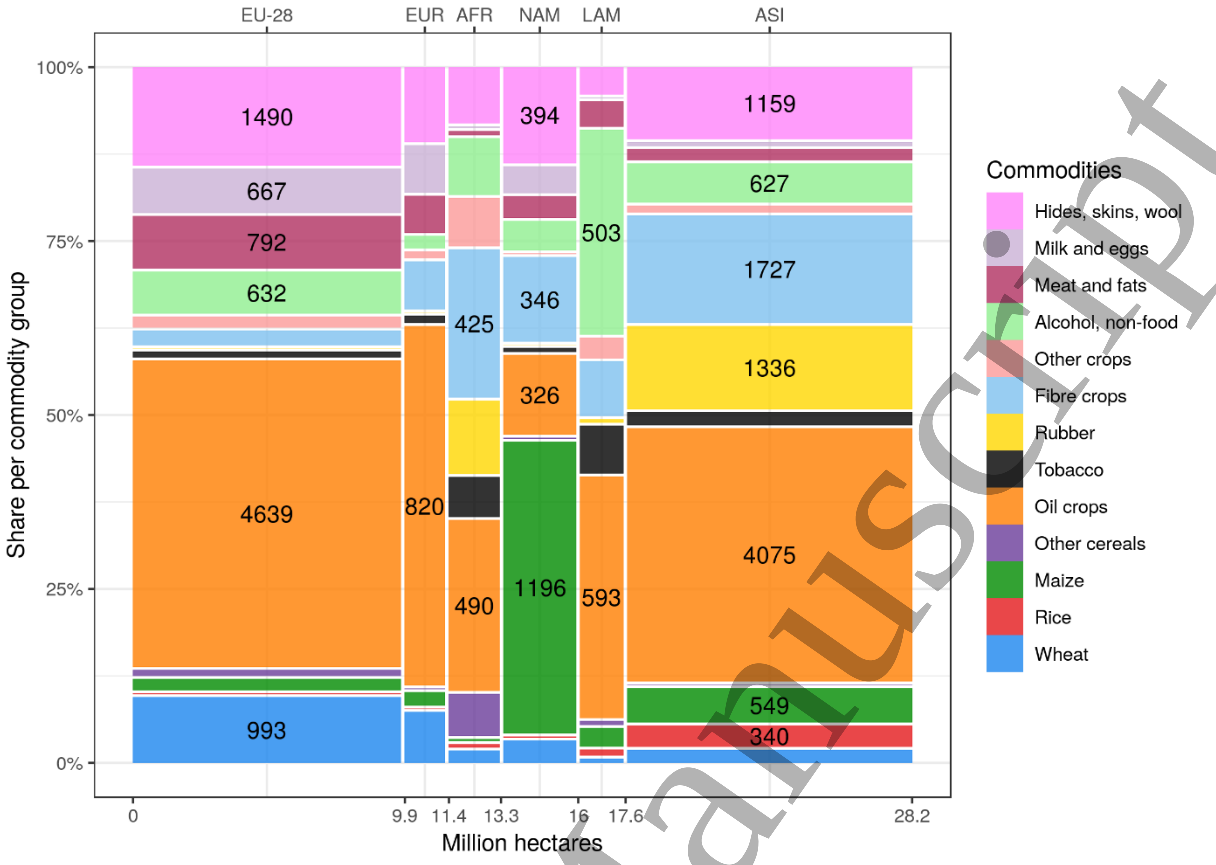

Figure 2. Global cropland footprint of the EU's *consumption of non-food products* in 2010, by producing region and commodity, x-label in million hectares, y-label in percentage shares, values inside the figure in thousand hectares. EU-28 = European Union, EUR = Rest of Europe, AFR = Africa, NAM = Northern America, LAM = Latin America, ASI = Asia

Spatially explicit footprint maps

Figure 3 provides a probability distribution of the EU's footprint over a 5 arcminute grid for selected crops: a) maize and sugarcane, which together represent more than 90% of the global ethanol feedstock and in addition are used for material purposes e.g. in the production of adhesives or bioplastics; b) oil crops, which is the biggest crop category in the EU's non-food cropland footprint; and c) fibre crops, mainly represented by cotton used in the textile industry.

Spatially explicit footprint maps allow identifying regional hotspots, such as the maize plantations in the Great Plains of the US, sugarcane in south-central Brazil, or cotton in the big river basins of Pakistan. Consistent spatially explicit supply chain and footprint assessments are essential to fully capture the spatiotemporal heterogeneity of biomass production and related impacts, such as deforestation, biodiversity loss or water scarcity, which differ greatly between production regions.

Another noticeable aspect is the change in composition of the EU non-food cropland footprint between 1995 and 2010 (Figure S.1). While in 1995, crop products contributed 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 and material use. In contrast, the cropland area related to the consumption of animal products, such as hides and skins, showed a declining trend.

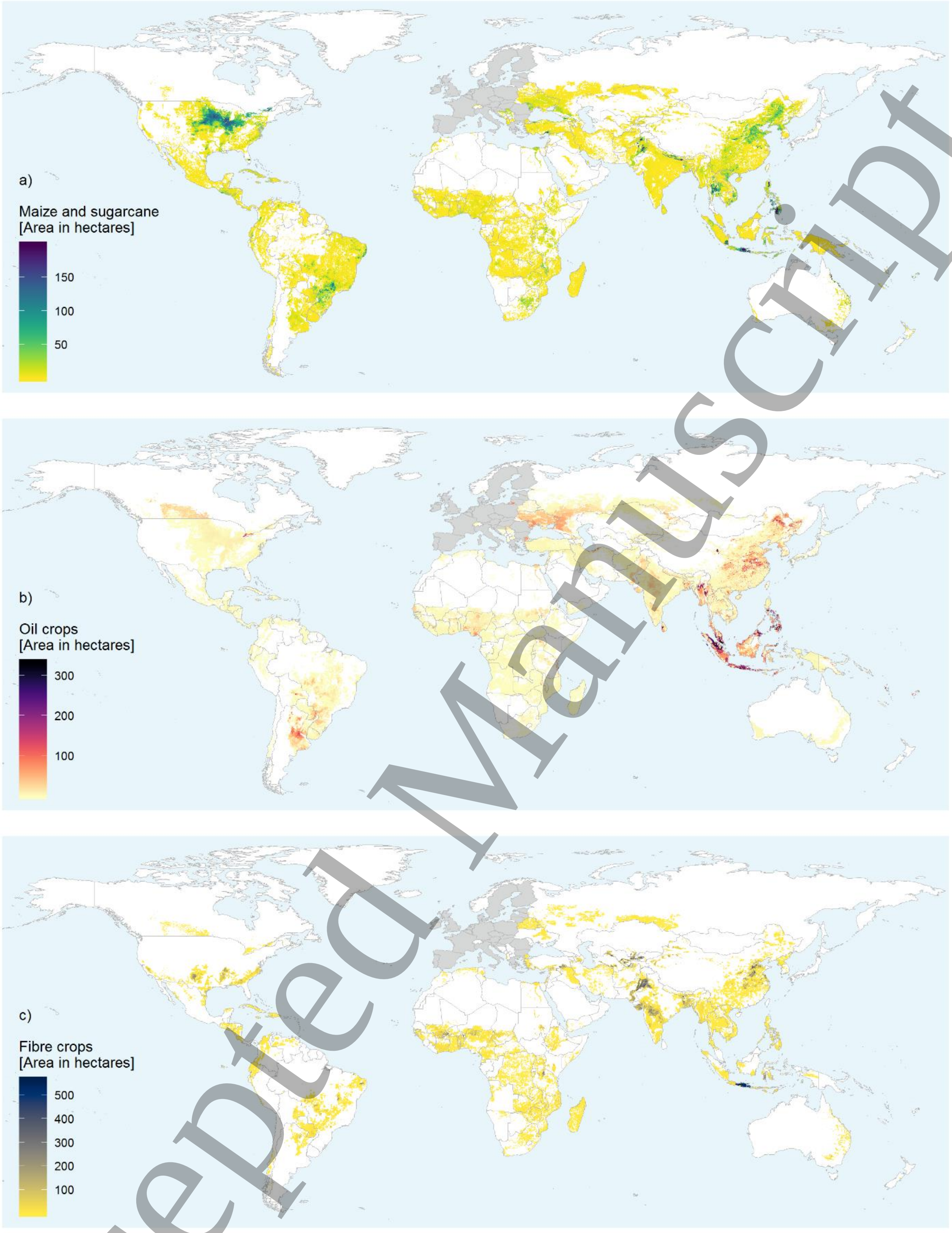

Figure 3. European Union's non-food related cropland use outside the EU in hectares per grid cell for a) maize and sugarcane, b) oil crops, and c) fibre crops. The colour scale indicates the number of hectares of cropland used by the EU in each grid-cell (5 arcminutes).

4 Discussion

Social and environmental implications

Our results emphasise that a particular attention should be given to the non-food sector, as it is the main driver of growing biomass demand, in recent years particularly due to increasing vegetable oil demand for fuel use. The EU's high external non-food land footprint indicates that a big part of the environmental impacts related with the EU's consumption occur in other world regions. Our findings show that the EU increasingly sources non-food biomass feedstocks from tropical regions, which have been identified as hotspots of both deforestation and biodiversity loss (Koh and Wilcove, 2008; Sodhi et al., 2004).

While the production-based approach measures territorial land use, the consumption perspective brings in the global socio-economic dynamics. Literature indicates that the European Union's consumption-based cropland use is already beyond a globally equitable limit (Bringezu et al., 2012; Häyhä et al., 2018; O'Neill, 2015; O'Brien et al., 2015; Tukker et al., 2016). Anthropogenic land modification, in particular deforestation, has already transgressed the planetary boundary for land system change, causing increasing pressure on climate and biodiversity (Campbell et al., 2017; Steffen et al., 2015). Many global energy and land use scenarios envision that the systemic change towards a bio-based economy will be more heavily reliant on terrestrial ecosystems and land resources (e.g. Di Fulvio et al., 2019; Lotze-Campen et al., 2010; Popp et al., 2014; Schipfer et al., 2017). The expanding bioeconomy will then add to the already high land demand for food supply, resulting in growing pressure on planetary boundaries. This relates closely to issues of global justice when it comes to a fair distribution of biophysical resources (Häyhä et al., 2016).

Assessments of social and environmental impacts related to the consumption of bio-based commodities are usually focussing on certain products or regions. Only few studies conducted comprehensive consumption-based assessments of certain impacts with global coverage of all traded products. The model approach presented in this article facilitates the analysis of impacts from a consumption perspective. Potential environmental impacts to be studied include, for example, increased water scarcity (Mekonnen and Hoekstra, 2016) and nutrient pollution (Zhang et al., 2014), but also potential negative climate impacts, in particular due to deforestation in tropical regions (Achard et al., 2014; Lawrence and Vandecar, 2015), driven by a growing demand for raw materials for the bioeconomy (Sheppard et al., 2011). 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 (McMichael, 2012), and the commodification of land and food crops (Birch et al., 2010).

There is a need to analyse pathways for reducing negative impacts of the bioeconomy, for example 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 (Kpdonou and Barbier, 2012; Priefer et al., 2017). However, as responsible consumers pull out of producer regions with questionable impacts, voids will eventually be filled by others, if incentives prevail.

Economic implications

At the current level of the 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) does 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'. These results have implications for ongoing debates about the economic benefits of developing and emerging economies engaging in global value chains (GVCs). Studies have illustrated that participation of these countries in GVCs can have positive economic impacts, e.g. through dissemination and uptake of new technologies, but results are particularly positive when combined with an upgrading of exports (UNCTAD, 2013). The adoption of bioeconomy strategies in an increasing number of countries, including import-dependent regions, such as the EU, offers new options for value creation in developing countries (Dietz et al., 2018). However, the key challenge will be to ensure that value addition through processing will take place in the countries of production (Virchow et al., 2016). The results illustrated above suggest that – from the perspective of biomass producer countries – there is still significant room for increasing domestic upgrading of biomass exports and develop a biomass export portfolio oriented towards higher value-added products.

The mismatch between domestic production on the one hand and industry demand for crops for material and energy uses on the other hand will likely grow in the future. 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 by the European Commission (2009). The economic (and environmental) benefits and costs of a global bioeconomy transformation will therefore likely be geographically unevenly distributed as countries have largely varying competitive advantages for the production and processing of bio-based materials.

Besides socio-ecological considerations, the vulnerability of export crop production to climate change in some major supplying countries (McGregor et al., 2016; Vörösmarty et al., 2005) also puts highly import-dependent economies at risk of supply constraints.

Methodological considerations

Given the far-reaching global implications of an expanding European bioeconomy, robust methods and indicators need to be developed and applied, to comprehensively assess Europe's resource use as well as the related environmental and social impacts.

This paper contributes to advancing land footprint accounting and demonstrates a hybrid approach integrating the biophysical accounting method with the EXIOBASE MRIO model. As discussed extensively in the earlier literature (Bruckner et al., 2015; Liang and Zhang, 2013; Schoer et al., 2013; Vringer et al., 2010; Weinzettel et al., 2014), a hybrid footprint model allows to increase product and country detail, and (partially) avoids the assumption of unique sector prices. At the same time, the model keeps a comprehensive coverage of the entire economy including all manufacturing industries and service sectors, and considers non-market commodity flows. To exploit the full potential of hybrid methods, the highest possible level of country and commodity detail provided by FAO statistics should be used. Adding more spatial and product detail will be an important task for future modelling, as yields and environmental impacts may differ largely within product and country groups, thus introducing an avoidable aggregation error.

Moreover, there is still significant room and need to expand the presented method by including other biomass commodities of key importance (e.g. timber and forest areas). 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, polymers). Industry data could help refine the model for addressing more detailed research questions.

Alternative accounting approaches based on economy-wide material flow analysis (ew-MFA) can reach far greater level of product detail than the present study. O'Brien et al. (2015), for example, calculate the land footprint of the EU accounting for a list of 991 commodities, including both food and non-food products. The ew-MFA method basically accounts for imports and exports of all commodities and, in the case of the land footprint, converts them into land equivalents, i.e. the area required for their production. For this conversion, data from Life Cycle Assessment studies and process analyses are used to derive land use coefficients in hectares per ton of product. While being the most detailed method in terms of products, the regional resolution of ew-MFA studies is very limited, as it is not possible to specify the country of origin of the raw materials, consequently not being able to consider differences in yields or local environmental impacts.

Finally, cropland footprints are only a part of a much larger puzzle that involves the quantification and equitable sharing of the costs and benefits associated with the production and consumption of biomass-based commodities. Footprinting methods thus need to be downscaled from national to local levels to account for regional differences and dynamics in the socio-environmental conditions that determine biomass production and its impacts in producer regions (Flach et al., 2016; Godar et al., 2015; Godar et al., 2016; Kanemoto et al., 2016; Moran and Kanemoto, 2016; Moran and Kanemoto, 2017).

Governance implications

Our results clearly indicate a growing demand for non-food bio-based products. This means that cropland demand is increasingly driven by other than traditional food value chains, including more complex or completely new value chains that emerge in response to new biomass applications (Philp et al., 2013). Moreover, 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 (Gasparri et al., 2016). Hence, better information and transparency about the socio-economic and environmental benefits and costs associated with globally traded biomass will become key to inform the increasing number of value-chain based governance initiatives (Gardner et al., 2018). Key governance challenges include substitution effects between value chains with heterogeneous levels of regulation or regulatory enforcement that can lead to environmentally costly indirect land use change (Arima et al., 2011). Hybrid footprinting approaches with high spatial and temporal resolution can help to address this challenge by serving as early warning systems, when biomass sourcing patterns shift to regions or value chains that exhibit severe governance gaps.

5 Conclusions

To date the literature on land footprints has not separated food and non-food applications of crops and derived products. In this paper, we assessed, for the first time, 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 biomass trade. The analysis highlighted the increasing importance of non-food products, being the fastest growing source of direct and indirect demand for agricultural land in the EU, as well as globally. The dependence of EU consumption on foreign land areas for the non-food sector is striking. While 86% of the land used to satisfy European food demand is located in Europe, only 35% of the land providing non-food products to the region is cultivated within the EU, resulting in net imports of up to 18 Mha per year. The expanding European bioeconomy is thus highly dependent on agricultural areas in other world regions, most notably in Asia.

From the methodological perspective, this paper builds on the on-going discussion about the robustness of land footprints and potentials for further improving the currently used accounting methods. With the novel hybrid model, we were able to trace the non-food flows until the final consumer, without truncating these flows, as done in biophysical accounting models. Moreover, it allowed us to increase the level of product detail and to avoid the assumption of homogeneous prices as implicit in monetary MRIO models. At current data availability, only the hybrid accounting method is capable of combining high product detail with comprehensiveness of economic supply chains, particularly when it comes to manufacturing industries and service sectors. Therefore, we suggest that future studies aiming at quantifying land use related footprints, such as the biodiversity footprint, should use a hybrid accounting approach.

We argued that the EU's bioeconomy should be assessed not only territorially but from a global consumption-based perspective. Our findings showed that the non-food sector is attaining a growing importance in the EU's bioeconomy – as well as globally. Europe plays a crucial role in determining global developments as it is the biggest consuming region of non-food biomass products (measured in cropland area) and also the largest net-importer. If the European bioeconomy were to promote sustainable development at global scale, tools need to be in place that monitor trade-induced land use spillover and displacement effects that emanate from the region's energy, agricultural, and bioeconomy policy programs.

Environmental footprint measures, such as the land footprint, together with global environmental targets, can guide the EU in its process of implementing the Sustainable Development Goals, and provide the data basis to monitor and review progress.

References

Achard, F., et al., 2014. Determination of tropical deforestation rates and related carbon losses from 1990 to 2010. Global Change Biology. 20, 2540-2554.

Arima, E. Y., et al., 2011. Statistical confirmation of indirect land use change in the Brazilian Amazon. Environmental Research Letters. 6, 024010.

Bell, J., et al., 2018. EU ambition to build the world's leading bioeconomy—Uncertain times demand innovative and sustainable solutions. New Biotechnology. 40, 25-30.

Birch, K., et al., 2010. Sustainable Capital? The Neoliberalization of Nature and Knowledge in the European "Knowledge-based Bio-economy". Sustainability. 2, 2898.

Bringezu, S., et al., 2012. Beyond biofuels: Assessing global land use for domestic consumption of biomass: A conceptual and empirical contribution to sustainable management of global resources. Land Use Policy. 29, 224-232.

Bringezu, S., et al., 2016. Multi-Scale Governance of Sustainable Natural Resource Use—Challenges and Opportunities for Monitoring and Institutional Development at the National and Global Level. Sustainability. 8, 778.

Bruckner, M., et al., 2015. Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods. Ecological Economics. 114, 11-21.

Campbell, B. M., et al., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecology and Society. 22.

Council Directive, Directive of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources. The European Parliament and the Council of the European Union, Brussels, 2015/1513/EU.

Deininger, K., 2013. Global land investments in the bio-economy: evidence and policy implications. Agricultural Economics. 44, 115-127.

Di Fulvio, F., et al., 2019. Spatially explicit LCA analysis of biodiversity losses due to different bioenergy policies in the European Union. Science of The Total Environment. 651, 1505-1516.

Dietz, T., et al., 2018. Governance of the Bioeconomy: A Global Comparative Study of National Bioeconomy Strategies. Sustainability. 10, 3190.

European Commission, A better functioning food supply chain in Europe. Vol. SEC(2009) 1445. SEC(2009) 1445, European Commission, Brussels, 2009.

European Commission, Roadmap to a Resource Efficient Europe. European Commission, Brussels, 2011.

European Commission, Innovating for Sustainable Growth: A Bioeconomy for Europe. Vol. COM(2012) 60. DG Research and Innovation, Brussels, 2012a.

European Commission, Living well, within the limits of our planet. 7th EAP — The new general Union Environment Action Programme to 2020. Brussels, 2012b.

European Commission, The impact of EU consumption on deforestation: Comprehensive analysis of the impact of EU consumption on deforestation. DG ENV Technical Report–2013–063. European Commission, Brussels, 2013.

EUROSTAT, EU Resource Efficiency Scoreboard 2015. Statistical Office of the European Communities, Luxembourg, 2015.

FAO, Food balance sheets. A handbook. Food and Agriculture Organisation of the United Nations, Rome, 2001.

FAOSTAT, FAO Statistical Databases: Agriculture, Fisheries, Forestry, Nutrition. Available at http://faostat.fao.org/. Statistics Division, Food and Agriculture Organization of the United Nations, Rome, 2017.

Fischer, G., et al., Quantifying the land footprint of Germany and the EU using a hybrid accounting model. UBA-FB-002497/2. German Federal Environment Agency, Dessau, 2017.

Flach, R., et al., 2016. Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities. Environmental Research Letters. 11, 075003.

FNR, Marktanalyse Nachwachsende Rohstoffe. Gülzow, available at: http://fnr.de/marktanalyse/marktanalyse.pdf, 2014.

FoEE, The true costs of consumption. The EU's land footprint. Friends of the Earth Europe, Brussels, 2016.

Gardner, T. A., et al., 2018. Transparency and sustainability in global commodity supply chains. World Development.

Gasparri, N. I., et al., 2016. The Emerging Soybean Production Frontier in Southern Africa: Conservation Challenges and the Role of South-South Telecouplings. Conservation Letters. 9, 21-31.

Giljum, S., et al., Land Footprint Scenarios. A literature review and scenario analysis on the land use related to changes in Europe's consumption patterns. Friends of the Earth, Brussels, 2013.

Giljum, S., et al., 2016. Identifying priority areas for European resource policies: a MRIO-based material footprint assessment. Journal of Economic Structures. 5.

Godar, J., et al., 2015. Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption. Ecological Economics. 112, 25-35.

Godar, J., et al., 2016. Balancing detail and scale in assessing transparency to improve the governance of agricultural commodity supply chains. Environmental Research Letters. 11, 035015.

Häyhä, T., et al., Operationalizing the concept of a safe operating space at the EU level – first steps and explorations. Stockholm Resilience Centre Technical Report, prepared in collaboration with Stockholm Environment Institute (SEI) and PBL Netherlands Environmental Assessment Agency. Stockholm Resilience Centre, Stockholm University, Sweden, 2018.

Häyhä, T., et al., 2016. From Planetary Boundaries to national fair shares of the global safe operating space — How can the scales be bridged? Global Environmental Change. 40, 60-72.
Kanemoto, K., et al., 2016. Mapping the Carbon Footprint of Nations. Environmental Science & Technology. 50, 10512-10517.
Kastner, T., et al., 2014. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. Environmental Research Letters. 9, 034015.
Kastner, T., et al., 2011. Tracing distant environmental impacts of agricultural products from a consumer perspective. Ecological Economics. 70, 1032-1040.
Kastner, T., et al., 2012. Global changes in diets and the consequences for land requirements for food. Proceedings of the National Academy of Sciences. 109, 6868-6872.
Koh, L. P., Wilcove, D. S., 2008. Is oil palm agriculture really destroying tropical biodiversity? Conservation Letters. 1, 60-64.
Kpdonou, R., Barbier, B., The world towards bioeconomy, and Africa towards a reserve for biobased feedstock. In: t. E. A. o. A. E. S. J. R. I. th International Consortium on Applied Bioeconomy Research Conference, et al., Eds.), International Consortium on Applied Bioeconomy Research Conference. s.n., Ravello, Italie, 2012, pp. 19 p.
Lawrence, D., Vandecar, K., 2015. Effects of tropical deforestation on climate and agriculture. Nature Clim. Change. 5, 27-36.
Liang, S., Zhang, T., 2013. Investigating Reasons for Differences in the Results of Environmental, Physical, and Hybrid Input-Output Models. Journal of Industrial Ecology. 17, 432-439.
Liu, J., et al., 2018. Spillover systems in a telecoupled Anthropocene: typology, methods, and governance for global sustainability. Current Opinion in Environmental Sustainability. 33, 58-69.
Lotze-Campen, H., et al., 2010. Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. Ecological Modelling. 221, 2188-2196.
McCormick, K., Kautto, N., 2013. The bioeconomy in Europe: An overview. Sustainability. 5, 2589-2608.
McGregor, A., et al., Vulnerability of export commodities to climate change. In: M. Taylor, et al., Eds.), Vulnerability of Pacific Island agriculture and forestry to climate change. Secretariat of the Pacific Community, SPC, Auckland, 2016, pp. 239-293.
McMichael, P., 2012. The land grab and corporate food regime restructuring. The Journal of Peasant Studies. 39, 681-701.
Meier, T., Christen, O., 2012. Environmental Impacts of Dietary Recommendations and Dietary Styles: Germany As an Example. Environmental Science & Technology. 47, 877-888.
Meier, T., et al., 2014. Balancing virtual land imports by a shift in the diet. Using a land balance approach to assess the sustainability of food consumption. Germany as an example. Appetite. 74, 20-34.
Mekonnen, M. M., Hoekstra, A. Y., 2016. Four billion people facing severe water scarcity. Science Advances. 2.
Meyer, R., 2017. Bioeconomy Strategies: Contexts, Visions, Guiding Implementation Principles and Resulting Debates. Sustainability. 9, 1031.
Miller, R. E., Blair, P. D., 2009. Input-output analysis: foundations and extensions. Cambridge University Press.
Moran, D., Kanemoto, K., 2016. Tracing global supply chains to air pollution hotspots. Environmental Research Letters. 11, 094017.
Moran, D., Kanemoto, K., 2017. Identifying species threat hotspots from global supply chains. Nature Ecology & Evolution. 1, 0023.
Moran, D., Wood, R., 2014. Convergence Between the Eora, WIOD, EXIOBASE, and OpenEU's Consumption-Based Carbon Accounts. Economic Systems Research. 26, 245-261.
O'Neill, D. W., 2015. The proximity of nations to a socially sustainable steady-state economy. Journal of Cleaner Production. 108, 1213-1231.
O’Brien, M., et al., 2015. The land footprint of the EU bioeconomy: Monitoring tools, gaps and needs. Land Use Policy. 47, 235-246.
O’Brien, M., et al., 2017. Toward a systemic monitoring of the European bioeconomy: Gaps, needs and the integration of sustainability indicators and targets for global land use. Land Use Policy. 66, 162-171.
OECD, The Bioeconomy to 2030: Designing a Policy Agenda, Main Findings. Organisation for Economic Cooperation and Development, Paris, France, 2009.
Pfau, S., et al., 2014. Visions of Sustainability in Bioeconomy Research. Sustainability. 6, 1222.
Philp, J. C., et al., 2013. Biobased chemicals: the convergence of green chemistry with industrial biotechnology. Trends in Biotechnology. 31, 219-222.
Popp, A., et al., 2014. Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. Climatic Change. 123, 495-509.
Priefer, C., et al., 2017. Pathways to Shape the Bioeconomy. Resources. 6, 10.

Ramcilovic-Suominen, S., Pülzl, H., 2018. Sustainable development – A 'selling point' of the emerging EU bioeconomy policy framework? Journal of Cleaner Production. 172, 4170-4180.

Scarlat, N., et al., 2015. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development. 15, 3-34.

Schipfer, F., et al., 2017. Advanced biomaterials scenarios for the EU28 up to 2050 and their respective biomass demand. Biomass and Bioenergy. 96, 19-27.

Schoer, K., et al., 2013. Estimating Raw Material Equivalents on a Macro-Level: Comparison of Multi-Regional Input–Output Analysis and Hybrid LCI-IO. Environmental Science & Technology. 47, 14282-14289.

Searchinger, T., et al., 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science. 319, 1238-1240.

Sheppard, A. W., et al., 2011. Biosecurity and sustainability within the growing global bioeconomy. Current Opinion in Environmental Sustainability. 3, 4-10.

Sodhi, N. S., et al., 2004. Southeast Asian biodiversity: an impending disaster. Trends in Ecology & Evolution. 19, 654-660.

Stadler, K., et al., 2018. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. Journal of Industrial Ecology. 22, 502-515.

Staffas, L., et al., 2013. Strategies and Policies for the Bioeconomy and Bio-Based Economy: An Analysis of Official National Approaches. Sustainability. 5, 2751.

Steffen, W., et al., 2015. Planetary boundaries: Guiding human development on a changing planet. Science. 347, 1259855.

Thomas, M. A., et al., 2009. Water Quality Impacts of Corn Production to Meet Biofuel Demands. Journal of Environmental Engineering. 135, 1123-1135.

Tisserant, A., et al., 2017. Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and Waste Footprints. Journal of Industrial Ecology. 21, 628-640.

Tramberend, S., et al., 2019. Our Common Cropland: Quantifying Global Agricultural Land Use from a Consumption Perspective. Ecological Economics. 157, 332-341.

Tukker, A., et al., 2016. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. Global Environmental Change. 40, 171-181.

UNCTAD, Global value chains and development. Investment and value added trade in the global economy. UNCTAD, Geneva, 2013.

Virchow, D., et al., Biomass-based value webs: a novel perspective for emerging bioeconomies in Sub-Saharan Africa. Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development. Springer, 2016, pp. 225-238.

Vörösmarty, C. J., et al., 2005. Geospatial Indicators of Emerging Water Stress: An Application to Africa. AMBIO: A Journal of the Human Environment. 34, 230-236.

Vringer, K., et al., 2010. A hybrid multi-region method (HMR) for assessing the environmental impact of private consumption. Ecological Economics. 69, 2510-2516.

Weinzettel, J., et al., 2013. Affluence drives the global displacement of land use. Global Environmental Change. 23, 433–438.

Weinzettel, J., et al., 2014. Ecological footprint of nations: Comparison of process analysis, and standard and hybrid multiregional input–output analysis. Ecological Economics. 101, 115-126.

White House, National Bioeconomy Blueprint. White House, Washington, DC, USA, 2012.

Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nature Geoscience. 11, 314-321.

You, L., et al., Spatial Production Allocation Model (SPAM) 2005 v3.2. Accessed on June 10, 2018. Available from http://mapspam.info, 2017.

Yu, Y., et al., 2013. Tele-connecting local consumption to global land use. Global Environmental Change. 23, 1178-1186.

Zhang, Y., et al., 2014. Tracing nitrate pollution sources and transformation in surface- and ground-waters using environmental isotopes. Science of The Total Environment. 490, 213-222.

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ORCID IDs

Martin Bruckner https://orcid.org/0000-0002-1405-7951
Tiina Häyhä https://orcid.org/0000-0002-9462-0408
Stefan Giljum https://orcid.org/0000-0002-4719-5867
Victor Maus https://orcid.org/0000-0002-7385-4723
Guenther Fischer
Sylvia Tramberend
Jan Börner https://orcid.org/0000-0003-3034-5360