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Linking global crop and livestock consumption to local production hotspots

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ABSTRACT

International trade plays a critical role in global food security, with global consumption having highly localized environmental impacts. It has been difficult to gain insights into these effects due to the diversity of food production, and complexity of supply chains in international trade. We present a Spatially-explicit Multi-Regional Input-Output (SMRIO) model which couples primary crops and livestock at a high spatial resolution with a global Multi-Regional Input-Output (MRIO) model. We then identify hotspots (the most significant production regions) for primary crops and livestock driven by international consumption. We present the method and data behind this approach, and provide illustrative case studies for Indonesian palm oil and Brazilian soy and beef production. Regionally, China is the largest primary crop consumer, while the EU28 is the largest livestock consumer. Primary crops and livestock hotspots are highly unequal, and the embodied primary crops and livestock for high-income countries are distributed over larger areas when compared to lower-income countries since high-income countries have more numerous trade links. Identified hotspots could allow for increased cooperation between consumers (high-income countries) and producers (lower-income countries) to improve sustainability programs for global food security.

1. Introduction

Global food security is fundamental for human development with 12 of 17 Sustainable Development Goals (SDGs) having direct relationships with food systems (Meyfroidt, 2018). However, global food security is challenged by increasing global food demand due to both population growth and potential dietary shifts to higher calorie intake and a greater proportion of animal products (Godfray et al., 2010). Global population doubled from 1950 (2.5 billion) to 1987 (5.1 billion), and tripled by 2018 (7.6 billion) (Fig. S1) (UN, 2019). Although population growth is slowing, estimates suggest a global population of almost 10 billion by 2050 at a medium variant scenario (UN, 2019). To meet this growth, the FAO suggests that cereal, meat, fruit and vegetables, and oil supply need to increase by ~39%–56%, ~29%–55%, ~48%–54%, and ~40%–51% respectively (between 2012 and 2050) (FAO, 2018). Since the green revolution, increases in crop yield and cropland area have kept pace with increases in global food demand (Pellegrini and Fernández, 2018); however, food supply is unevenly distributed (Wood et al., 2018), and yields have stagnated in recent years (Alston et al., 2009). Between 2008 and 2050, four staple crops – wheat, rice, soybean, and maize – are estimated to have annual yield growths of 0.9%, 1.0%, 1.3% and 1.6% respectively (Ray et al., 2013), half the rate needed to satisfy demand while keeping prices stable (Ray et al., 2013). In some regions, yield growth may even stagnate entirely (Ray et al., 2012). The projected demand growth may exceed yield growth given these estimations. Following current food production and consumption patterns, environmental impacts are estimated to increase by 50%–90% from 2010 to 2050 in the absence of technological progress and targeted mitigation measures (Springmann et al., 2018). To stay within a safe operating space for humanity, we must therefore limit both the inputs and space required for food production (Springmann et al., 2018). This is because agricultural production requires increasing areas of land (Bruckner et al., 2019) and freshwater (Wang and Zimmerman, 2016), causing serious environmental impacts, such as eutrophication, soil acidification, ecotoxicity, greenhouse gas emissions, and biodiversity loss (Mottet et al., 2017). While many studies only focus on crops, we also examine the spatial distribution of livestock. Feed contains a large amount of additives, antibiotics, and antimicrobials, but most of them are not degraded in the animal's body. Instead, they are excreted by the livestock and released to the environment (Steinfeld et al., 2006; Mottet et al., 2017). As the consequence, these compounds harm environmental and human health by accelerating eutrophication, deteriorating soil contamination, and promoting the spread of drug-resistant pathogens (Steinfeld et al.,

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2006; Mottet et al., 2017; Van Boeckel et al., 2015). Additionally, the fact that about one third of food is lost or wasted embodied in food supply chain from farm to fork exacerbates these burdens (Xue et al., 2017). Food loss and waste occurs at every phase from production to final consumption along the food supply chain, and varies for agricultural products at different regions (Xue et al., 2017). For example, fruits and vegetables are lost or wasted more than cereals, and lower-income countries have a higher ratio of food loss at the production stage, while higher-income countries have a higher rate of food waste at the consumption stage (Xue et al., 2017). On top of these significant challenges, climate change and the increasing frequency of extreme weather events further exacerbate the problems faced by agricultural production (Lesk et al., 2016).

Some countries have gradually given up expanding cropland (Green et al., 2005), and have spared cropland to preserve nature (Balmford et al., 2005). This can result in a shift of the environmental burden related to agricultural production from high-income nations to low- and middle-income nations through trade (Scherer et al., 2018). Although trade can globally increase resource use efficiency and reduce environmental impacts in some cases (Lambin and Meyfroidt, 2011), the externalities in producing countries are not accounted for in trade. Globalization has led to a spatial disconnect between production and consumption of agricultural products (Kissinger, 2012). Growing international trade provides exotic or seasonal agricultural products for consumers year-round (Fader et al., 2013), improving food supply. The amount of global food trade, as measured in caloric content, has doubled from 1986 to 2009, enough to feed more than 1 billion people. The global food trade as percentage of global food production increased from 15% to 23% (D'Odorico et al., 2014). Understanding the role of international trade in food systems is essential in understanding the environmental impacts of global food supply and demand. Previous studies have focused on embodied environmental pressures and impacts, such as land use, water use, greenhouse gas emissions, and biodiversity loss (Mottet et al., 2017). These studies attribute the environmental responsibility of this supply to the consumers of food (Wiedmann, 2009).

Two prominent examples of shifting environmental burdens through international trade are the export of Brazilian soy and Indonesian palm oil. Increasing global demand for beef, soybean oil, and soybean meal used, to a large extent, to feed livestock and produce biofuels has promoted Brazil to a position as one of the largest exporters of soybean and beef in the world (Barona et al., 2010). Brazil is expected to have the largest potential for agricultural expansion within this century (Lapola et al., 2014). Another high-yielding oil crop, oil palm has been the fastest growing crop in the 21st century (Naylor, 2016), driven by increasing demand for high-yielding crops producing refined vegetable oil. Much of this growth has occurred in South Asia, mainly Indonesia, where ~55% of global palm oil production takes place (Barona et al., 2010). However, agricultural expansion in tropical regions often comes at the expense of deforestation and the destruction of associated ecosystem services, devastating biodiversity, emitting large amounts of greenhouse gases (GHGs), and disturbing hydrological regulation. In Brazil's case, even though deforestation has been decreasing since 2004, it has seen the largest deforestation of any country worldwide. This is mainly due to agroindustry clearing for pasture and soybeans (Lapola et al., 2014). Deforestation appears to be worsening in Indonesia, with oil palm expanding at an average rate of 4500 km^2 annually, resulting in an average 1700 km^2 of deforestation per year from 1995 to 2015 (Austin et al., 2017).

In the past decades, increasing global food consumption was partly achieved by international trade at the expense of the local environment. This led to the global food system losing its resilience by becoming too homogeneous and dependent on continued trade (Suweis et al., 2015). Therefore, identifying spatial heterogeneity of different consumption patterns and setting a safe target for primary crops and livestock consumption are helpful for guiding more sustainable practices and healthier diets. Consumption-based accounting of primary crops and livestock raises consumer awareness of the original sources of their food and this can facilitate global cooperation between production- and consumption-oriented countries (Wiedmann, 2009). For example, while impacts of food production are often outsourced from high-income to lower-income nations, high-income nations often have advanced technology and management experience that can be transferred to those lower-income, producing countries. According to our knowledge, there has been no comprehensive assessment of crops and livestock embodied in trade at a high spatial resolution. To fill this gap, we develop a spatially explicit multi-regional input-output model (SMRIO) based on the EXIOBASE input-output model (Stadler et al., 2017), and investigate case studies on Brazilian soybean and cattle, and Indonesian palm oil to show the utility of this approach. Additionally, our work facilitates a more accurate assessment of environmental impacts from agriculture driven by final demand of any region in EXIOBASE, as our spatially explicit primary embodied crops and livestock can easily be combined with environmental intensities.

2. Materials and methods

Here we use a global, environmentally-extended multi-regional input-output (MRIO) model, EXIOBASE, linked to crop and livestock data derived from FAOSTAT, to calculate the consumption of crops and livestock for countries and regions. To avoid double-accounting in the system, we remove primary crops fed to livestock. The choice of livestock over feed for the food-related material footprint is justified by livestock being closer to human food consumption. As such, the information is easier to understand for consumers who usually choose food based on simple and informationally frugal heuristics (Schulte-Mecklenbeck et al., 2013). We then spatially allocate the consumption-based result of crops and livestock to the grid-level. We do this by using crop and livestock maps (Table 1), and by using both road quality and density (Meijer et al., 2018) to distinguish between production likely for export and production for domestic consumption.

Compared with other global MRIOs, EXIOBASE 3 contains the most detailed sectoral and environmental information and covers a long period from 1995 to 2015 (Stadler et al., 2017). For a detailed comparison, see Tukker and Dietzenbacher (2013). EXIOBASE 3 includes 163 industries, 200 products, 28 EU countries, 16 other major countries (Table S3), and 5 regions for the rest of the world (Stadler et al., 2017). In order to construct EXIOBASE 3, a series of underlying databases are needed to estimate bilateral trade flows, including re-exports. Specifically, for re-exports, EXIOBASE 3 uses publicly available data from Comtrade on either re-exports or re-imports at the country level to estimate changes over time in the share of re-exports in total exports from the 2007 base year (Stadler et al., 2017). Since spatial databases for crops and livestock are available in 2006, we choose this year for EXIOBASE. The database includes 8 crop sectors linking 163 types of crop derived from FAOSTAT (domestic extraction of primary crops, cereals are based on the weight of dry grain, vegetable and fruits are based on the weight of fresh fruit of human consumption, treenuts are based on the weight of nut for sale) with input-output accounts (Table

Table 1
Spatial data employed in this paper.

Data	Data source	Resolution
Global distribution of crops (SPAM)	http://mapspam.info/	5 arc minutes
Global distribution of livestock (Robinson et al., 2014)	http://www.livestock.geo-wiki.org	30 arc seconds
Global administrative areas	https://gadm.org/data.html, Version 3.6	vector data
Global Roads Inventory Project (GRIP) (Meijer et al., 2018)	http://www.globio.info/download-grip-dataset	5 arc minutes

S1). This forms the foundation for analyzing the distribution of crops driven by consumption.

To keep the livestock data consistent with that of spatial databases and comparable between different types of animal, we select related data from FAOSTAT to create 6 livestock satellite accounts to match with EXIOBASE, including cattle, pig, chicken, duck, goat, and sheep (Table S2). In addition, we use primary livestock products instead of live animals to keep them comparable. The mapping relationship between FAO countries and EXIOBASE countries and regions is shown in Table S3. Even though aquaculture is becoming more and more important (Naylor, 2016), we do not consider it in this paper because of a lack of spatially explicit data for aquaculture.

2.1. The spatial distribution of crops and livestock

We use spatial crop production data from the Spatial Production Allocation Model (SPAM) version 3.2. SPAM depicts the spatial distribution of 42 types of crop, including variables on production, yield, physical area, and harvest area (You et al., 2014). SPAM uses the average value of statistical data from 2004 to 2006. In order to match these data with the crop categories available in FAOSTAT, we aggregate *Millet Pearl* and *Millet Small* into *Millet*, and we aggregate *Coffee Arabica* and *Coffee Robusta* into *Coffee* (see Supplementary material).

For livestock data, we use a high-resolution livestock density dataset at 30 × 30 s for 2006, including cattle, goat, sheep, pig, chicken, and part of duck (Robinson et al., 2014). In order to keep the same spatial resolution with road density as described below, we scale this down to 5 × 5 min.

2.2. Global Roads Inventory Project (GRIP)

Previous studies using SMRIO approaches assume proportionality between production volumes and locations (Kanemoto et al., 2016). This proportionality means there is no ability to distinguish between regions that produce food for export and regions that consume this food locally. This can be important in regions with both subsistence farming and industrial production in low- and middle-income nations (consider the Indonesian case with a high amount of subsistence consumption yet producing large amounts of palm oil for international markets). To address this and take the literature a step forward, we start from the assumption that agricultural products have better access to markets if there are better transportation services (Meijer et al., 2018; Verburg et al., 2011). We use data from the Global Roads Inventory Project (GRIP) (Meijer et al., 2018) to allocate the spatial distribution of primary crops and livestock for export. We regard regions where road density is higher than 100 m/km^2 as the first-priority for export, and the remaining area as the first-priority for domestic consumption. We allocate exported primary crops and livestock into the first-priority region for export. If the ratio of actual exports to the production in this region is above one (implying that more is produced for export than currently produced in this region), we allocate the rest of primary crops and livestock for export into the lower-priority region for export (first-priority region for domestic consumption). Similarly, we allocate primary crops and livestock into first-priority regions for domestic consumption, and the rest for domestic consumption is allocated into the second-priority region for domestic consumption (Canada is a special case, please see explanatory note 1 *Special solution for Canada* in the Supplementary material).

2.3. SMRIO analysis

We use spatial distributions as spatial weights, and allocate consumption-based primary crops and livestock into grid cells with the same proportion of each grid cell accounting for the total amount in a country or region, according to equations (1) and (2), which have been used to allocate carbon emissions (Kanemoto et al., 2016). By doing so, we trace the spatial distribution of the production source for crops and livestock to the consumption destination.

$$\boldsymbol{F}^s = \sum_r R^r \frac{\sum_i \boldsymbol{e}_i^r \sum_{jt} \boldsymbol{L}_{ij}^{rt} \boldsymbol{y}_j^{ts}}{\sum_i d_i^r} \tag{1}$$

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \tag{2}$$

where $\boldsymbol{F}^s$ is the spatial distribution of the total consumption of country *s; R^r* is the distribution map of crops or livestock in absolute values in country ***r*** that produces crops or livestock; e_i^r is the crop or livestock intensity for sector *i* in country *r;* ***L*** is the Leontief inverse matrix; ***I*** is the identity matrix, and ***A*** is the technical coefficient matrix to describe input output relationships between sectors and countries; y_j^{ts} is the final consumption of sector *j* of the country *t* with the last sale to the destination country *s*. d_i^r is the share of sector *i* in country *r.*

2.4. Comparison with tentative targets

A safe operating space typically relates to environmental impacts (e.g., biodiversity loss) or to emissions as outputs from the anthroposphere (e.g., greenhouse gas emissions) (Steffen et al., 2015), especially from food production (Campbell et al., 2017). Operationalizing such planetary boundaries is complicated and has not yet been done for most environmental impacts. The most comprehensive assessments exist for carbon emission targets (IPCC, 2018; UNEP, 2014). Further tentative boundaries for water and land use have been suggested based on limits of physical availability (Hoekstra and Wiedmann, 2014; Tukker et al., 2016). Bringezu suggested halving (agricultural) resource use compared to the 2000 level to reduce environmental pressures, as human impacts on the planet were already too high in 2000 (Bringezu, 2015). These suggested targets for resource use have not been unanimously accepted for several reasons (Tukker et al., 2016). Most importantly, these targets are not based on an actual assessment of physical limits or levels of unacceptable environmental damage, but are simply based on the assumption that any further increase implies the risk to further aggravate environmental impact beyond acceptable limits. While this objection is undoubtedly true, this approach offers a heuristic for understanding the increasing environmental pressures triggered by food consumption through supply chains. In this case, and in the absence of any updated alternative, we will use the target of keeping the use of primary crops and livestock at the 2000 level for illustrative purposes.

In 2000, primary crops, excluding feed crops, totaled 5.9 Gt, and livestock totaled 0.8 Gt, based on EXIOBASE 3 and FAOSTAT (FAOSTAT, 2019; Stadler et al., 2017). Based on this, we obtain per-capita targets for embodied primary crops and livestock of 0.90 t/capita and 0.12 t/capita in 2006, our year of analysis. These targets are roughly in line with the latest food-specific healthy diet recommendation (Willett et al., 2019). The EAT-Lancet Commission recommends 0.4 t/capita/year of plant-based food, and 0.1 t/capita of animal-based food (except for fish) for human direct consumption. If we assume one third of primary crops are consumed directly by humans, one third of primary crops are used to feed livestock (Mottet et al., 2017), and one third of primary crops are wasted, while also one third of livestock are wasted (Xue et al., 2017), and two thirds of livestock are consumed by humans directly, it requires additional production of 0.4 t/capita/year for primary crops (excluding feed), and 0.05 t/capita/year for livestock. This sums up to almost 0.8 t/capita for primary crops and 0.15 t/capita for livestock, which is similar to 0.9 t/capita for primary crops and 0.12 t/capita used in our study. To investigate the variation of per-capita mass for different nations regarding primary crops, we set 0 to 0.45 t/capita as far below the target, 0.45 t/capita to 0.9 t/capita as below the safe target, 0.9 to 1.8 t/capita as exceeding the target, and > 1.8 t/capita as far exceeding the target. For livestock, we set 0 to 0.06 t/capita as far below the target, 0.06 t/capita to 0.12 t/capita as below the safe target, 0.12 to 0.24 t/capita as exceeding the target,

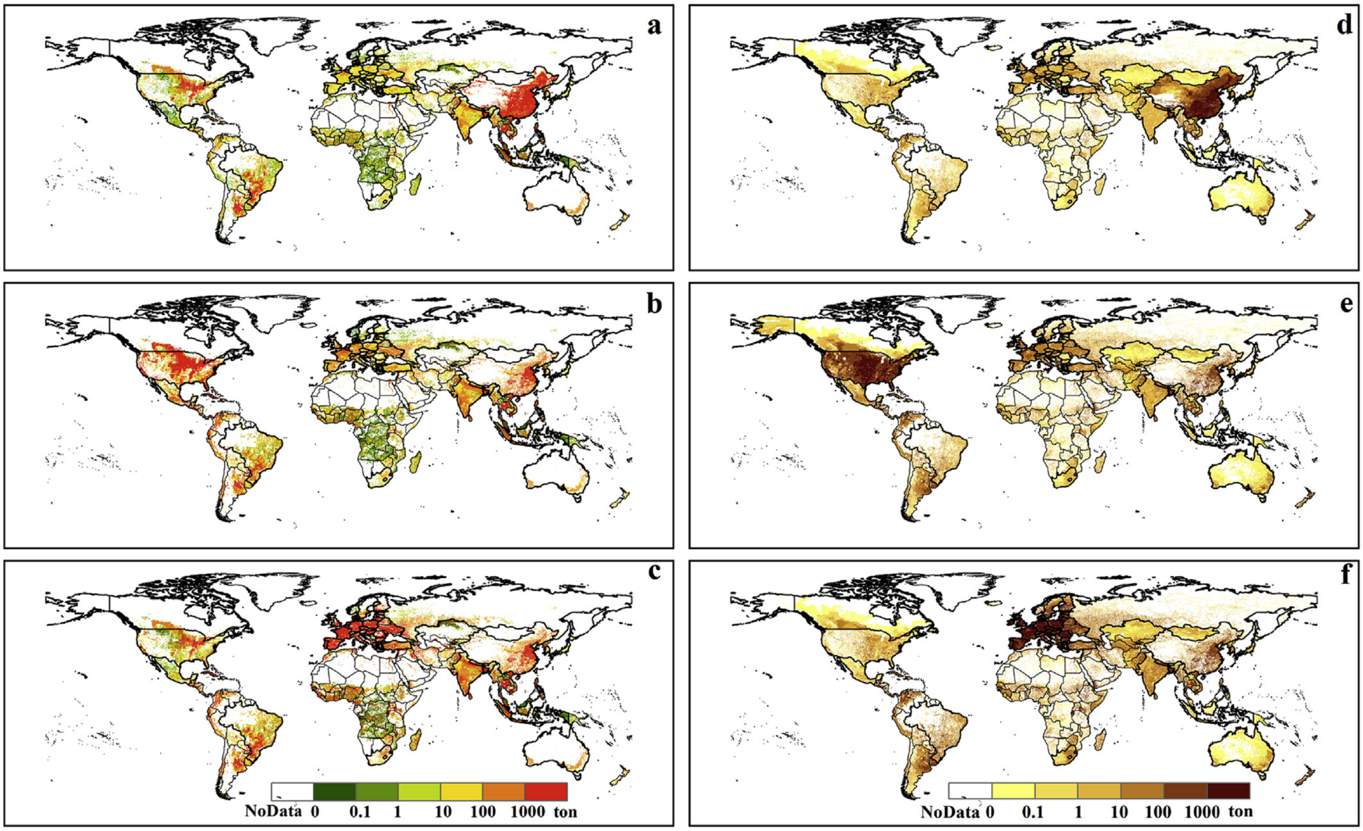

Fig. 1. Spatial distribution of the primary crop hotspots driven by consumption of China (a), the US (b), and the EU28 (c), and the livestock hotspots driven by consumption of China (d), the US (e) and the EU28 (f).

and > 0.24 t/capita as far exceeding the target.

3. Results

3.1. Hotspots of primary crops and livestock

As expected, per-capita primary crop and livestock consumption is positively correlated with the per-capita GDP (Fig. S2). For example, the highest per-capita crop consumption is found in Luxembourg (8423 kg/capita), 12 times higher than in Indonesia (643 kg/capita). This phenomenon is more significant for livestock with a factor of 30 difference among per-capita total livestock weight, at 845 kg/capita in Ireland compared to 26 kg/capita in Indonesia (Fig. S2). In addition, high-income nations have more significant overseas primary crop and livestock hotspots than that of low-income nations (Fig. 1), because they have a comparative advantage in capital while having more expensive labor and land (Fig. S3). This is consistent with previous studies (Behrens et al., 2017; Suweis et al., 2015). Fig. 1 depicts primary crop and livestock hotspots driven by the three largest economies: the EU28, the United States (US), and China. The spatial distribution of primary crop and livestock hotspots generally matches.

China is the largest consumer of primary crops, accounting for 18.4% of global primary crop consumption (Fig. S4). Fig. 1 (a) reveals the spatial distribution of primary crops driven by China's consumption. The most significant primary crop hotspots are located in East China, following the so-called 'Hu-line' closely (a geographical line South to North between Heihe in Heilongjiang Province and Tengchong in Yunnan Province). More than 90% of Chinese people live in the east of the "Hu line", an area home to the most intensive cropland in China, including the three great plains of China: the Northeast China Plain, the North China Plain, and the Yangtze Plain.

International crop hotspots driven by Chinese consumption include the Corn Belt in the US, and the Cerrado biome of Brazil, which are a major source of China's soybeans. China is the largest consumer of soybean in the world, accounting for 28.7% of total production. To a large extent this is possible with large amounts of imports, at 32.6% of the global total soybeans imports in the supply chain. The US and Brazil are the largest two contributors to China's soybean consumption with 20.4 Mt and 17.9 Mt, respectively. China is also the largest importer of palm oil with hotspots in Sumatera in Indonesia (the largest exporter of palm oil).

For many other products, the US has larger trade flows. Domestic primary crop hotspots are centered on the well-known Corn Belt. Although it is the largest producer and exporter of cereals, it is the largest importer of global vegetables, tropical fruits, and temperate fruits, accounting for 15.2%, 19.4%, and 13.7% of global imports, respectively. In addition, 43.6% of vegetables, 57.0% of tropical fruits, and 35. 2% of temperate fruits consumed in the US come from abroad. An estimated 15.1% of vegetables and 6.6% of temperate fruits for US final consumption import from China, mainly from the east of China. The US imports 15.3% of its tropical fruit from Mexico, mainly surrounding the Gulf of Mexico; and 7.6% of tropical fruit from Brazil, mainly the Upper Paraná Basin.

Turning to the EU28, large amounts of domestic production of primary crops translates into limited imports. Where imports arise they are generally from the Corn Belt of the US; the Cerrado biome of Brazil; Sumatra and Kalimantan in Indonesia; the east of China; and the Indo-Gangetic Plain in India. The result is consistent with previous studies that the spatial distribution of land and water use for crop production driven by EU consumption (Bruckner et al., 2019; Lutter et al., 2016).

Compared with primary crop hotspots, livestock production is driven by domestic rather than foreign consumption. Domestic livestock makes up 88% of EU28 livestock consumption (it is also the largest consumer of livestock at 23.5% of global consumption) (Fig. S5).

Overseas livestock hotspots of the EU28 are scattered in the east of China,; the south of India, the southeast and southwest of Australia, and the Pampa in South America.

The US imports the largest percentage of livestock, accounting for 12.8%–15.8% of global animal trade flows (all animals summed together). Since the US produces mainly pig, cattle, and chicken, other animals are generally imported. As such 96.2% of goats, 91.9% of sheep, 59.4% of ducks, 28.6% of pigs, 14.7% of cattle, and 11.6% of chickens originate from abroad. A significant pig hotspot is located in the Interior Plains since a large amount of maize and soybean produced in the area provides feed for rearing. Other hotspots are scattered in the east of China, such as the North China Plain, the south of Canada, the southeast of Mexico, the west and north of the Netherlands, the west of the United Kingdom, the south of India, the southeast and southwest of Australia, and the northeast of Spain.

China is the largest consumer of primary crops, it is the third largest consumer of livestock, accounting for 11.0% of global consumption. The livestock hotspot for China is also east of the “Hu-Line”, which provides feed for livestock. Other significant hotspots are located in the west of the “Hu-line” and distributed in the top four prairies, namely Hulunbeier Prairie, Xilin Gol Prairie, Erie Prairie, and Nagga Alpine Steppe, which suit the grazing of ruminant animals.

3.2. Consumption of brazilian soybean and beef and Indonesian palm oil

To reveal specific issues for regions under pressure, we provide case studies on the role of beef and soybean production in Brazil and palm oil production in Indonesia through international supply chains.

Brazil is a dominant producer of soybeans, accounting for 23.4% of the global production and 30.6% of global exports respectively. Only 4.7% of Brazil's soybean production is used domestically, with 35.7% exported to China, 22.5% exported to the EU28, and 6.0% exported to the USA (Fig. 2 a, c), both directly and indirectly. Because most of soybeans are consumed by foreign countries, the spatial distribution of soybeans for domestic and overseas consumption is almost identical, and concentrates on its producing regions–the South Atlantic Forest biome, the Cerrado biome, and the South Amazon biome. The result is similar to previous analysis (Godar et al., 2015). In contrast, most of cattle is consumed domestically, even though Brazil was the second largest producer of cattle in 2006, exporting 1.23 Mt of beef to the EU28, 0.2 Mt to the US, and 0.1 Mt to China. The major regions for domestic beef consumption concentrate on the Paraná River basin, the Tocantins basin, and along the Atlantic coast in the Atlantic Forest biome, which covers a large amount of pasture suitable for grazing. However, major regions for beef consumption abroad mainly gather in the South of the Paraná River basin and the Atlantic coast in the Atlantic Forest biome, which are the major cattle feeding areas, have a developed transportation network, and are near the Brazilian ports (Google Map, 2018).

Indonesia, the largest exporter of palm oil, contributes 49.8% to the global exports embodied in the supply chain. However, only 27.6% of palm oil is used for domestic consumption, 13.1% is exported to the EU28, 10.5% is exported to China, and 7.4% is exported to the US (Fig. 3), both directly and indirectly. Regions for domestic palm oil consumption in Indonesia range from Sumatra to Papua, covering almost all of Indonesia's territory, even though the intensity, palm oil mass per grid cell, gradually decreases. In contrast, regions for overseas palm oil consumption mainly gather in Sumatera and the South of Kalimantan, because most of Indonesian ports locate at the coast around these two islands (Google Map, 2018). In addition, one of the most important transportation hubs– Strait of Malacca settles between Sumatra and Malay Peninsula, and it provides a transportation advantage for these two islands.

3.3. Comparison with tentative targets

We find that primary crop and livestock consumption in almost all high-income countries (some of them, for example, New Zealand are included in rest-of-the-world regions) is beyond the illustrative target in 2006 (Fig. 4). Especially some of them, such as Australia, the US, Canada, the United Kingdom, and France, consume more than double the safe threshold. In contrast, the consumption of most low- and middle

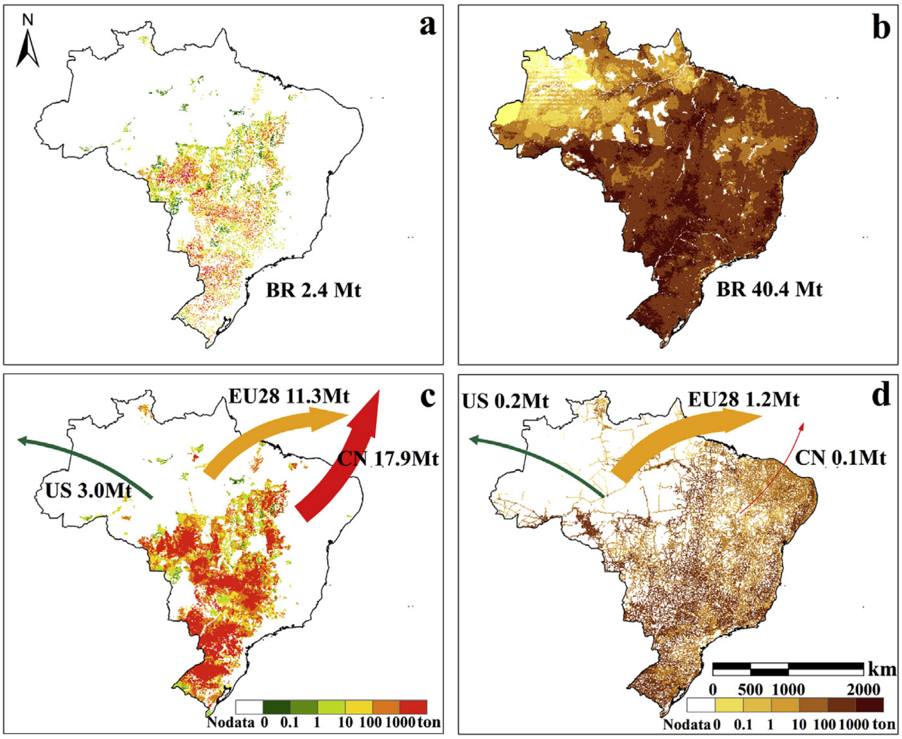

Fig. 2. Brazilian soybeans and beef for domestic consumption (a, b) and consumption in foreign countries (c, d).

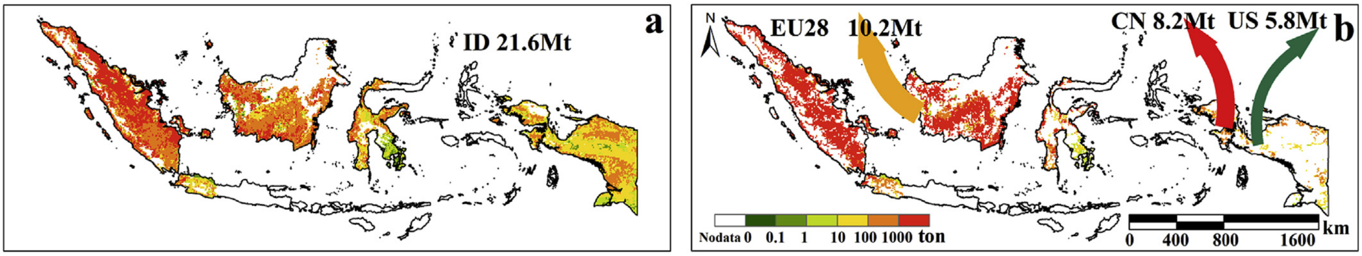

Fig. 3. Indonesian palm oil for domestic (a) and foreign consumption (b).

countries, mainly in Asia, the Middle East, and Africa, which constitute 75% of the global population (including China, India, Indonesia, South Africa, rest of Asia and Oceania, rest of America, rest of Africa, rest of Middle East) is within the safe operating space. The consumption in the rest of Africa and rest of Asia regions, making up 25% of the global population, is even far below the indicative target.

4. Discussion

Some studies, for example, the well-known transparent supply chains for sustainable economies (TRASE) project (Godar et al., 2015), have been tracing global supply chains sub-nationally very well (Gardner et al., 2019). However, the TRASE project mainly focuses on the environmental and social risks of agricultural expansion of a few commodities (soy, palm oil, sugarcane, cocoa, coffee, timber, and beef) on tropical forest ecosystems, and the SEI-PCS model (Spatially Explicit Information on Production to Consumption Systems) mainly focuses on subnational administrative regions (Godar et al., 2015). In this paper, we trace the supply chain of more agricultural products, namely 40 crop categories (as available in SPAM except for 2 types due to aggregations) and 6 types of livestock. We identify spatially explicit hotspots at a higher resolution (5 arc min) driven by final consumption by tracing primary crops and livestock embodied in supply chains based on SMRIO analyses. We find that low- and middle-income countries, for example China, have a greater self-sufficiency (here defined as the ratio of production to demand (Coates, 2013)) as opposed to high-income countries, which are associated with larger trade flows. These results indicate that high-income countries outsource a significant amount of the burden from agricultural production, including large amounts of land and water use, to low-income countries with lower production cost. This is consistent with previous research (Chen et al., 2018; Chen and Han, 2015; Yu et al., 2013), where the EU28, the US, and Japan are the top outsourcers of cropland, grazing land, and agricultural freshwater. More than 40% of the trade volume of cropland is driven by the EU and the US. Cropland and animal stocks have been decreasing in high-income nations since 1960 (Fuglie, 2018), and in the future, agricultural production transfer to lower-income countries are expected to continue (Rulli et al., 2013). In addition, emerging giants, like China and India, will need more food from international markets, putting further pressure on food systems (Fukase and Martin, 2016). Most notably, more than 70% of global soybean exports are estimated to flow into China by 2023/2024 (Yao et al., 2018).

Primary crops and livestock in lower-productivity regions overseas are being consumed at a larger growth rate by richer countries, although the productivity gap between lower-income and high-income countries is shrinking (Fuglie, 2018). Regions with lower productivity have cheaper land and labor and have a competitive advantage in terms of low value-added production, especially primary crops. But these regions have less advanced agricultural technologies and lack capital to improve infrastructure (e.g., water efficiency and transportation

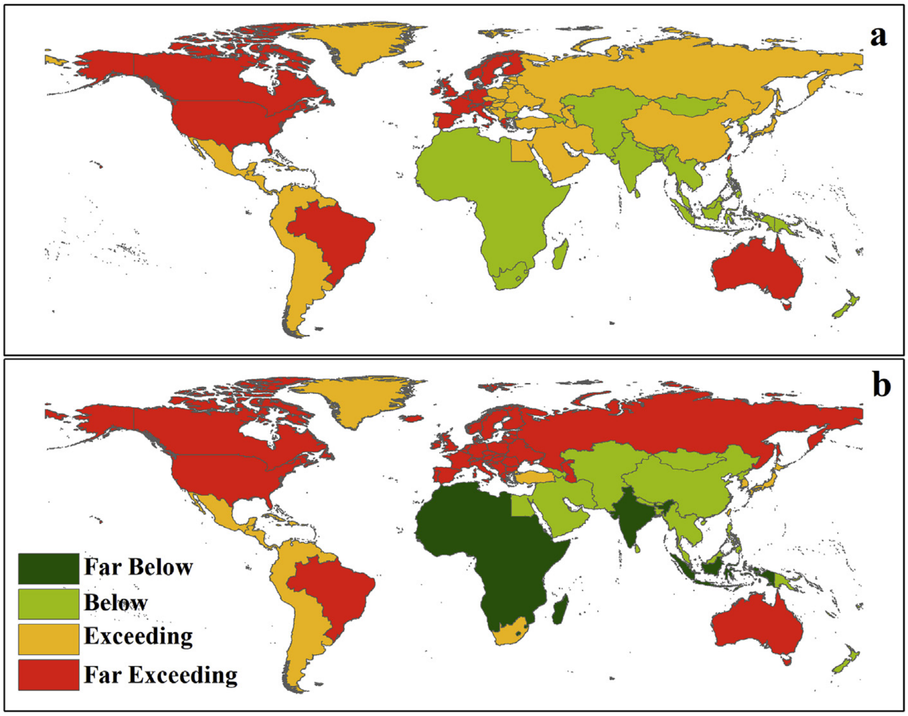

Fig. 4. Total primary crop (a) and livestock (b) consumption per-capita in comparison with the tentative target of 0.9 and 0.12 ton per-capita in 2006, respectively.

Table 2

Environmental impact research based on crop and livestock databases.

Environmental impacts	Spatial resolution	Agricultural products	Sources of conversion factors	References
Greenhouse gas (GHG) emissions	national level	crops	International Fertilizer Association (IFA) survey	Sandström et al. (2018)
	national level	livestock	Meta-analysis	Sandström et al. (2018)
	5 arc min	crops	IPCC tier 1 method; International Fertilizer Association (IFA) survey	(Carlson et al., 2017; Zuo et al., 2018)
	21500 individuals	13 food groups	LCA and meta-analysis	He et al. (2018)
Nitrogen and Phosphorus	5 arc min	crops	International Fertilizer Association (IFA) survey	(Liu et al., 2010; Zuo et al., 2018)
Biodiversity	5 arc min	crops and livestock	Meta-analysis	Weinzettel et al. (2018)
Antimicrobials	5 arc min	livestock	Meta-analysis	Van Boeckel et al. (2015)
Water	5 arc min	crops	Hydrological model	(Pfister et al., 2011; Zuo et al., 2018)
	21500 individuals	13 food groups	Water Footprint Network survey	He et al. (2018)

services among many other improvements). In this paper, we identify spatially explicit hotspots driven by final consumption, which could help decision makers to provide targeted technical and financial support for countries from which they consume primary crops and livestock. This could narrow the yield gap of primary crops and livestock between countries to ensure global food security. This would help in achieving the UN's Sustainable Development Goals (SDGs), such as no poverty (SDG 1) and zero hunger, good health, and well-being (SDG 2). According to the latest published report on the *state of food security and nutrition in the world*, world hunger has started to increase since 2014 after a prolonged decrease, and about 1/9 of the global population (822 million) are undernourished in 2018 (FAO et al., 2019). Improving nutrition and providing healthy diets requires long-term efforts and needs global cooperation.

4.1. Limitations

There are several limitations to this approach. The first is sectoral and spatial homogeneity hypothesis. There are only 8 sectors for primary crops (Table S1) and 6 sectors for livestock (Table S2) for 44 individual countries and regions (Table S3), and remaining countries are aggregated into 5 rest of world regions in EXIOBASE.

However, FAOSTAT has the most detailed classification for primary crops (163 types) and livestock (6 types selected) for each country in the world. The sectoral and spatial aggregation leads to some loss of detail (Scherer and Pfister, 2016). For example, soybean, rapeseed, and palm oil share the same trade structure in EXIOBASE, which impacts the real distribution of soybeans and palm oil driven by final consumption in the EU28, the US, and China.

The second limitation is related to the quality of spatial databases. Robust and high-resolution spatial databases are essential to SMRIO (Moran and Kanemoto, 2017). These spatial databases are created by models, which might have biases. The most obvious is that there is no data on the spatial distribution of ducks in South America and Africa (Robinson et al., 2014). The situation has slightly improved in the recently updated spatial distribution of livestock (Gilbert et al., 2018), but due to the higher temporal mismatch we chose the previous version.

A third limitation relates to the allocation method. We use a road network to allocate the spatial distribution of primary crops and livestock to production for exports and for domestic consumption. While this approach seems to outperform previous analyses, for example of market access (Verburg et al., 2011), it still leads to some biases. Where there are large connected fields coupled with a low population density, and consequently fewer roads, such as in the Northeast China plain, exports might be underrepresented. However, linking trade with transportation is a widely accepted way in studying commodity supply chains at subnational scale. For example, some studies used a spatial cost minimization model (mainly including transportation cost) from production areas to consumption areas to estimate subnational commodity flows (Godar et al., 2015; Smith et al., 2017). Their results provide a good fit with results from this paper, as exemplified by soybeans in Brazil (Fig. 2, Fig. S6).

4.2. Future work

Agricultural production consumes the vast majority of land and freshwater, and leads to biodiversity loss and other environmental impacts. Identifying local environmental impact hotspots driven through global food consumption is the first step to mitigating local environmental impacts, to keep food production sustainable, and to guarantee global food security. Most present studies on estimating environmental impacts driven by agricultural production use a multiplication of environmental intensities or conversion factors (e.g. environmental impact per ton or ha of a specific crop) with crop-specific harvest areas or production amounts, and animal-specific production amounts (Table 2). The methods for getting conversion factors include meta-analyses, simulation models, and expert surveys. Such studies are promising sources for environmental conversion factors, which can be used in future research. By having spatially explicit embodied crops and livestock in combination with environmental conversion factors, we can obtain more accurate environmental impacts driven by final consumption of any given region within EXIOBASE.

4.3. Implications

Around 11% of the global population are still undernourished (habitual food consumption is insufficient to provide the dietary energy levels that are required to maintain a normal active and healthy life), mainly in Africa and Asia (FAO et al., 2019). If only eradicating poverty and other people keep their current consumption level, total primary crop and livestock consumption will exceed the safe operating space. Therefore, it is necessary to reduce consumption in high-income countries to offset the increase in lower-income countries. In addition, sustainable production and consumption of primary crops and livestock play a critical role in achieving other SDGs beyond the elimination of hunger (SDG 2) (Obersteiner et al., 2016). The large difference in final consumption of primary crops and livestock between high-income and lower-income countries also indicates social inequality among countries. Besides, agricultural technological changes and the reduction of food loss and waste are huge challenge to maintain sustainable consumption (Springmann et al., 2018). However, it is difficult to implement target policy, according to previous studies, because they trace food supply chains at the national level. In this paper, we use the SMRIO method to map the spatial relationship from production to consumption of primary crops and livestock. This can help to build targeted cooperation relationships between high-income and lower-income countries to keep agricultural production and consumption sustainable.

Data statement

Product-specific data and figures are available from the authors upon reasonable request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2019.09.008.

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