

Linking responsible consumption and production: A global assessment of cropland use for agri-food production

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Abstract

Sustainable Development Goal 12 requires countries to achieve responsible consumption and production patterns without exceeding safe environmental limits for natural resource use. However, little is known about how cropland impacts from the agri-food sector contribute to the exceedance of national environmental limits for consumption and production. Using a multi-regional input-output model, we linked the cropland impacts of agri-food production to countries of consumption while considering the exceedance of production-based and consumption-based environmental limits. We defined national consumption-based environmental limits via the fair-share approach and quantified national production-based environmental limits according to the biophysical limit of available arable land. We then classified countries into quadrants according to their exceedance of consumption and/or production environmental limits. We found that the USA, Australia and other high-income countries were exceeding both consumption-based and production-based environmental limits. High-population but low-income countries such as India and China were within safe consumption-based environmental limits but exceeded production-based environmental limits. Brazil and other countries of the Americas incurred substantial environmental costs due to the conversion of forests into cropland to produce food for export. We identified patterns in international trade relationships that could inform national-level responsible agri-food consumption and production patterns across the global supply chain, thereby contributing to Sustainable Development Goal 12. More stringent regulations and commitments in national and international policies are required to reduce the exceedance of consumption-based and production-based environmental limits and avoid exceeding the global land-system change planetary boundary.

Keywords: Cropland, environmental limits, consumption, production, trade, Sustainable Development Goals.

1 Introduction

Agriculture and food trade are essential components of global food security and economic development. Countries meet their food requirements via the combination of domestic production and imports of agri-food commodities. For many countries, agri-food production is also an export industry (D'Odorico et al., 2014). Global agri-food production, consumption and trade generate environmental impacts for national and international land, water and other natural resources (Dalin and Rodríguez-Iturbe, 2016; Kastner et al., 2011; Laroche et al., 2020; Wu et al., 2018). Agri-food system sustainability depends on both consumption and production staying within safe environmental limits for natural resource use. Current trends in food

demand and productivity point to the real danger of exceeding multiple environmental limits (Bowles et al., 2019; Clark et al., 2020; Conijn et al., 2018; Springmann et al., 2018).

Environmental limits can be defined using the planetary boundaries framework, which delineates safe environmental limits for the human use of natural resources while ensuring the stability and resilience of the Earth system (Rockström et al., 2009; Steffen et al., 2015). National consumption-based environmental limits can be defined according to a fair-share approach, where each person is allocated an equal share of a global resource (Fang et al., 2015a; Häyhä et al., 2016; Lucas et al., 2020; O'Neill et al., 2018). Conversely, national production-based environmental limits can be defined according to biophysical measures of natural resource availability in each country (Li et al., 2019; Shaikh et al., 2021).

Given globalised agri-food trade and complex telecoupling among countries, explicitly linking the environmental impacts of agri-food consumption and production and assessing these against country-specific environmental limits is essential to achieve responsible consumption and production, as mandated by the United Nations Sustainable Development Goal (SDG) 12 (UN, 2015). Delineating national environmental limits for both consumption and production is therefore paramount, yet current research has typically assessed agri-food system sustainability from either a consumption or production perspective (Kastner et al., 2014b; Lucas et al., 2020; Mace et al., 2014; Nilsson and Persson, 2012; Nykvist et al., 2013; Osei-Owusu et al., 2019; Ryberg et al., 2020; Yu et al., 2013). For example, Gerten et al. (2020) assessed the environmental impacts of global food production against production-based environmental limits for biosphere integrity, land-system change, freshwater use and nitrogen flows. Huang et al. (2020) assessed the environmental impacts of food production in China against its production-based environmental limit for domestic freshwater. Li et al. (2020) recently assessed the environmental impacts of food and non-food consumption in China against consumption-based environmental limits for domestic and international freshwater use.

Achieving responsible agri-food consumption and production is the joint responsibility of consumers and producers (Kastner et al., 2012; Lenzen et al., 2007; Vanham et al., 2019). Therefore, assessments of responsible agri-food consumption and production need to take a more holistic view to consider virtual flows of natural resources embedded in traded commodities (Lucas et al., 2020). Responsible agri-food consumption needs to consider not only whether a country is within its safe consumption-based environmental limits, but also whether the production of consumed commodities contributes to the exceedance of production-based environmental limits in their country of origin. Likewise, responsible production should consider not only whether a country is within its safe production-based environmental limits, but whether the consumption of those commodities occurs in countries that are exceeding their consumption-based environmental limits. For instance, China's agri-food consumption is within its safe consumption-based environmental limits, yet China sources ~52% of its soybeans from Brazil, where 30% of soybean crop expansion between year 2000 and 2014 occurred at the expense of native vegetation in the Cerrado biome (Fearnside and Figueiredo, 2015; Soterroni et al., 2019).

Cropland use for agri-food production is a widely used indicator (or *control variable*) to represent the environmental limits of the land-system change planetary boundary in agri-food system studies (Chaudhary and Krishna, 2019; McLaughlin, 2018; Rockstrom et al., 2009; Springmann et al., 2018; Usubiaga-Liaño et al., 2019). To assess responsible agri-food consumption and production amid complex telecoupled linkages of cropland impacts embedded in trade, simultaneous assessment of national-level cropland impacts of agri-food consumption and production is needed against national consumption-based and production-

based environmental limits. Studies have assessed the production-based aspect at the global level (Conijn et al., 2018; Gerten et al., 2020; Hillebrand et al., 2020; Springmann et al., 2018), the consumption-based or production-based aspect at the national level (Hu et al., 2020; Huang et al., 2020; Li et al., 2020; Sala et al., 2020; Sun et al., 2019), and the consumption-based aspect but not using the planetary boundaries framework (Fang et al., 2021; Laroche et al., 2020; Osei-Owusu et al., 2019; Tramberend et al., 2019; Yang et al., 2020).

To provide a more comprehensive view of agri-food system sustainability, this study explicitly links the cropland impacts of agri-food consumption and production in the context of national consumption-based and production-based environmental limits and international trade. We first defined national consumption-based environmental limits via the fair-share approach and quantified national production-based environmental limits based on the biophysical limit of available arable land. We then performed a national-level multi-regional input-output (MRIO) assessment of responsible agri-food consumption and production against consumption-based and production-based environmental limits for cropland. We defined national consumption-based environmental limits via the fair-share approach and quantified national production-based environmental limits based on the biophysical limit of available arable land. To bridge the consumption and production perspectives, we classified countries into four quadrants according to their exceedance of consumption-based and/or production-based environmental limits. We also unpack the major traded crops affecting the responsible consumption and production of global cropland. We discuss the implications of the results on responsible consumption and production and propose measures to achieve SDG 12 to ensure global food security, economic development and prevent the overexploitation of cropland resources.

2 Methods

2.1 Cropland impacts of agri-food consumption and production

MRIO models use economic input-output tables to capture production, consumption, global trade flows and interdependencies among economic sectors (Leontief, 1970; Wiedmann et al., 2011). The environmental satellite accounts in MRIO databases allow the incorporation of resource use and emissions in physical units (such as Mkm² of cropland), enabling quantitative estimates of the full supply chain of domestic and international impacts of national consumption and production (Kissinger and Rees, 2010; Weinzettel et al., 2013).

Cropland impacts are embedded in agri-food commodities and flow from production to consumption countries via trade. We used Exiobase 3.0 for the year 2011 to calculate national cropland impacts embedded in the production of agri-food commodities (e.g. oilseeds, wheat, vegetables and fruits) and trace international virtual cropland flows (Stadler et al., 2018). For example, we quantified the virtual cropland flows embedded in the production of oilseeds (e.g. corn, soybeans, mustard and sesame) in a country (e.g. Brazil) and consumed as agri-food products (e.g. vegetable, fat, meat and other products) in consumption countries (e.g. China). Thus, we quantified telecoupled cropland impacts of domestic consumption, imports and exports of agri-food commodities.

The national cropland impact of the consumption (C) of agri-food commodities is the sum of domestic cropland impacts due to consumption of domestic production (D) and virtual flows of cropland impacts embedded in imports (I). Likewise, the national cropland impact of production (P) is the sum of the domestic cropland impacts of production for domestic consumption (D) and cropland impacts of exported agri-food commodities (E).

$$C = D + I \quad (1)$$

$$P = D + E \quad (2)$$

2.2 Environmental limits for consumption and production

Estimates of the global cropland area available for human use range from 19.5 Mkm² (Nykqvist et al., 2013) to 1.98 billion ha (Rockstrom et al., 2009) and 20.1 Mkm² (Henry et al., 2018). These estimates consider the available cropland area as 15% of the world's ice-free land area of ~132 Mkm² (UNCCD, 2017), which, according to Biermann and Kim (2020), is an overestimate. UNEP (2014) proposed a lower estimate of 16.4 Mkm² of cropland area for human use based on the precautionary principle (Van Vuuren and Faber, 2009). Springmann et al. (2018) adapted the global environmental limits for cropland use and proposed a global cropland limit of 12.6 Mkm² (10.6–14.6 Mkm²). Following Springmann et al. (2018)'s modelling approach and using UNEP (2014)'s cropland estimate based on the precautionary principle, we adopted the estimates of 10.6 Mkm², 12.6 Mkm² and 16.4 Mkm² and as low, best and high estimates of global cropland limit (L_G).

The consumption-based environmental limit (L_C) was allocated to countries based on the fair-share principle, where each country was assigned a share of the global cropland limit (L_G) based on the ratio of its population (P_N) to the global population (P_G) obtained from the UN (2017).

$$L_C = L_G * \frac{P_N}{P_G} \quad (3)$$

The production-based environmental limit (L_P) was allocated to countries based on their biophysical cropland resource, where each country was assigned a share of the global cropland limit (L_G) based on the ratio of nationally available cropland area (A_N) to the globally available cropland area (A_G). National (A_N) and global (A_G) available cropland areas were calculated using Eitelberg et al. (2015)'s spatially resolved estimates, which derived available cropland area in countries while maintaining sustainable amounts of land for natural ecosystems to support biodiversity and other natural resources.

$$L_P = L_G * \frac{A_N}{A_G} \quad (4)$$

A detailed explanation of the national allocation of consumption-based and production-based environmental limits is provided in Shaikh et al. (2021).

2.3 Environmental limit exceedance

Exceedance of the consumption-based environmental limit (E_C) occurs when the cropland impacts of agri-food consumption (from domestic production and imports) exceed the nationally defined safe consumption-based environmental limit. Likewise, the exceedance of production-based environmental limit (E_P) occurs when the cropland impacts of agri-food production (for domestic consumption and exports) exceed the national safe production-based environmental limit.

$$E_C = \left(\frac{D+I}{L_C} - 1 \right) \times 100\% \quad (5)$$

$$E_p = \left(\frac{D + E}{L_p} - 1 \right) \times 100\% \quad (6)$$

A positive value of exceedance indicates national transgression of environmental limits, while a negative value indicates that environmental impacts are within safe limits.

2.4 Analysis and visualisation

2.4.1 Quadrant classification

We developed a quadrant classification (Q1–Q4), where Q1 contained regions or countries that were within safe consumption-based and production-based environmental limits; Q2 contained regions that exceeded consumption-based environmental limits but were within safe production-based environmental limits; Q3 contained regions that were within safe consumption-based environmental limits but exceeded production-based environmental limits; and Q4 contained regions that exceeded both consumption-based and production-based environmental limits. We present results for 10 major national economies and aggregated other countries as regions: Asia (others), Europe, the Americas (others) and Africa. Detailed country-level classifications are presented in the supporting information (Figure S1).

2.4.2 Linking consumption and production

Using equations (1) and (6), we linked the cropland impacts of national agri-food consumption to production countries, allowing us to assess responsible agri-food consumption in the context of corresponding production-based environmental limit exceedance. Likewise, using equations (2) and (5), we linked the cropland impacts of national agri-food production to consumption countries, allowing us to assess responsible agri-food production in the context of consumption. We quantified the virtual cropland flows embedded in the production of major agri-food commodities consumed as different agri-food products. For example, virtual cropland flows occurred when cropland impacts of oilseeds (corn, soybeans, mustard, sesame, etc.) produced in Brazil and consumed in China as animal vegetable and fat products, when cropland impacts of cereals (e.g. maize and barley, but excluding wheat and rice) produced in Africa were consumed in Europe as animal products, or when cropland impacts of wheat produced in Australia were consumed in Asia as cattle and fish products.

3 Results

3.1 National environmental limit exceedance and cropland impacts

Regions were classified in quadrants (Q1–Q4) according to their exceedance of consumption-based and production-based environmental limits (Figure 1). Many countries were located in Q4 because they exceeded both environmental limits (e.g. Australia, Canada, Mexico, Turkey and the USA). China, India, Asia (others) and Indonesia were located in Q3 because they only exceeded production-based environmental limits. Brazil was located in Q2 because it exceeded its consumption-based environmental limit but not its production-based environmental limit. In contrast, the Americas (others) were located in Q4 as they did not exceed either environmental limit.

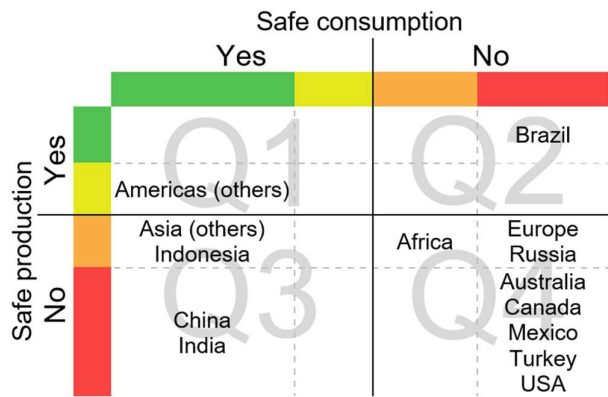


Figure 1. Classification of regions in four quadrants according to their exceedance of consumption-based and/or production-based environmental limits. Yellow and orange colours indicate potentially safe and unsafe uncertainty zones, respectively. See Figure S1 in the supporting information for detailed country-level classifications.

National consumption-based environmental limit exceedance was driven by cropland impacts of the consumption of agri-food products (Figure 2a). Australia showed the highest consumption-based environmental limit exceedance (+361%), mostly due to the consumption of wheat, cereals (excluding wheat and rice), and vegetables and fruits (Table 1). Exceedance of consumption-based environmental limits was also high in Russia (+223%), Canada (+188%), Turkey (+174%), USA (+147%), Mexico (+57%) and Europe (+46%) and mostly related to the consumption of cereals (excluding wheat and rice), wheat and oilseeds. In Brazil, the exceedance of consumption-based environmental limit (+32%) was mostly linked to the consumption of cereals (excluding wheat and rice), sugar cane, and vegetables and fruits. China, India, Asia (others), Indonesia and the Americas (others) were within their safe consumption-based environmental limits because of their high fair-share of global cropland use for consumption.

National production-based environmental limit exceedance was driven by the cropland impacts of agri-food production (Figure 2b). The environmental limit exceedance of the USA (+88%) and Canada (+79%) were mostly linked to the production of oilseeds, wheat and other cereals (Table 1). In Mexico, production-based environmental limit exceedance (+77%) was mainly due to the production of wheat, vegetables and fruits, and other crops. In India, production-based environmental limit exceedance (+65%) was linked to the production of vegetables and fruits, paddy rice and oilseeds. Environmental limit exceedance in Turkey (+63%) and Australia (+52%) were linked to the production of wheat, vegetables and fruits, and other cereals, while in China (+32%), exceedance was linked to the production of vegetables and fruits, wheat and paddy rice. Production of oilseeds, wheat, sugar cane, and vegetables and fruits explained most cropland impacts in Brazil and the Americas (others), which however remained under their environmental limits due to the region's high biophysical limit for cropland use.

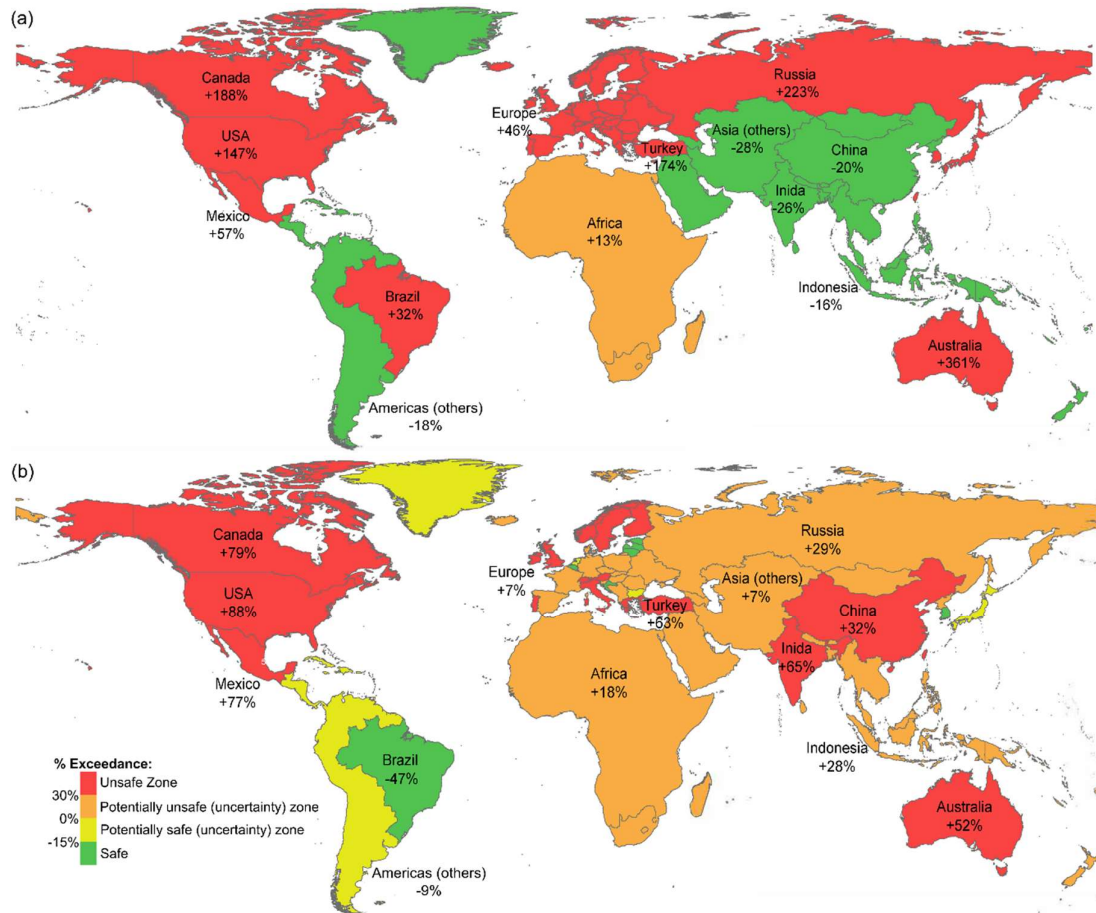


Figure 2. Maps of the percentage of national environmental limit exceedance for (a) consumption and (b) production of cropland. Positive numbers (red colour) indicate environmental limit exceedance while negative numbers (green colour) indicate the country is within its environmental limits. Yellow and orange colours indicate potentially safe and unsafe uncertainty zones, respectively.

Table 1. National environmental limit exceedance for consumption and production of cropland in 14 select countries and regions and the contributions of 4 product categories. The percentage contributions of all products (see Table S1 for additional products) sum up to all the consumption or production of regions or countries.

Country or region	Consumption					Production				
	Wheat	Other cereals	Vegetables & fruits	Oilseeds	Others	Wheat	Other cereals	Vegetables & fruits	Oilseeds	Others
Canada	28%	27%	15%	22%	8%	34%	19%	9%	37%	1%
USA	15%	38%	12%	13%	22%	17%	34%	4%	31%	14%
Mexico	9%	52%	8%	19%	12%	4%	21%	21%	38%	16%
Brazil	7%	30%	22%	6%	35%	3%	21%	14%	38%	24%
Americas (others)	15%	18%	17%	16%	34%	7%	19%	16%	35%	23%
Europe	21%	24%	17%	23%	15%	25%	31%	13%	18%	13%
Turkey	45%	15%	12%	19%	9%	42%	19%	20%	10%	9%
Russia	19%	32%	19%	19%	11%	42%	27%	9%	17%	5%
Africa	15%	40%	24%	10%	11%	5%	40%	29%	15%	11%
China	10%	16%	19%	38%	17%	14%	21%	28%	15%	22%
India	15%	13%	24%	17%	31%	14%	13%	22%	17%	34%
Indonesia	12%	17%	15%	10%	46%	-	9%	11%	26%	54%
Asia (others)	29%	19%	10%	21%	21%	28%	11%	17%	12%	32%
Australia	30%	22%	23%	14%	11%	54%	11%	22%	10%	3%

3.2 Linking cropland impacts among countries via trade

3.2.1 *Quadrant 1: Safe consumption-based and production-based environmental limits*

For the Americas (others), 68% of cropland impacts for the consumption of agri-food products originated from Q1 and Q2 regions that were within safe production-based environmental limits (64% from domestic production and 4% imported from Brazil; Figure 3, left column). On the production side, 62% of cropland impacts were due to production for Q1 and Q3 regions that were within safe consumption-based environmental limits (33% due to domestic consumption and 29% via exports to China, Indonesia, India and Asia; Figure 3, right column). The remaining cropland impacts were due to agri-food production for exports to Q4 and Q2 regions exceeding their consumption-based environmental limits such as the USA, Europe, Brazil and Africa.

3.2.2 *Quadrant 2: Exceeding consumption-based limits but within safe production-based environmental limits*

For Brazil, 89% of cropland impacts for the consumption of agri-food products originated from Q1 and Q2 regions that were within safe production-based environmental limits (81% from domestic production and 8% via imports from the Americas (others); Figure 3, left column). On the production side, 67% of cropland impacts were due to production for Q2 and Q4 regions that exceeded their consumption-based environmental limits (48% due to domestic consumption and 19% via exports; Figure 3, right column). In comparison, 33% were exported to Q3 regions, specifically to China and Asia (others).

3.2.3 *Q3: Safe consumption-based limits but exceeding production-based environmental limits*

For Asia (others), 93% of cropland impacts for the consumption of agri-food products originated from Q3 and Q4 regions that exceeded their production-based environmental limits (45% from domestic production and 48% via imports from the USA, Russia and Australia; Figure 3, left column). On the production side, 72% of cropland impacts were due to production for Q1 and Q3 regions that were within safe consumption-based environmental limits (62% due to domestic consumption and 10% due to exports to China, India and the Americas (others)), while 28% were due to exports to Q2 and Q4 regions exceeding their consumption-based environmental limits such as Africa, Europe and the USA (Figure 3, right column).

For China, 86% of cropland impacts for the consumption of agri-food products originated from Q3 and Q4 regions exceeding their production-based environmental limits (54% from domestic production and 32% via imports from the USA and Africa), while 14% of cropland impacts were from Brazil and the Americas (others) that were within safe production-based environmental limits (Figure 3, left column). On the production side, 91% of cropland impacts were due to production for Q1 and Q3 regions within safe consumption-based environmental limits (84% due to domestic consumption and 7% due to exports; Figure 3, right column). In comparison, 9% were exported to Q2 and Q4 regions exceeding their consumption-based environmental limits such as the USA, Europe and Australia.

For India, 89% of cropland impacts for the consumption of agri-food products were from domestic production, which exceeded the production-based environmental limit (Figure 3, left column). On the production side, 94% of cropland impacts were due to production for Q1 and Q3 regions within safe consumption-based environmental limits (88% due to domestic consumption and 6% via exports to Asia (others) and China; Figure 3, right column).

3.2.4 Q4: Exceeding both consumption-based and production-based environmental limits

For Europe, 93% of cropland impacts for the consumption of agri-food products originated from Q3 and Q4 regions exceeding their production-based environmental limits (52% from domestic consumption and 41% via agri-food imports from Australia, Russia, Africa, China, Asia (others), Indonesia and the USA; Figure 3, left column). On the production side, 89% of cropland impacts were due to agri-food production for Q2 and Q4 regions that exceeded their consumption-based environmental limits (79% domestic and 10% via export to countries such as Africa, Russia, Turkey and the USA), while 11% were due to export to Q1 and Q3 regions that were within safe consumption-based environmental limits, such as Asia (others), China and India (Figure 3, right column).

For the USA, 93% of cropland impacts for the consumption of agri-food products originated from Q3 and Q4 regions that exceeded their production-based environmental limits (57% from domestic production and 36% via agri-food imports from countries such as China, India and Mexico; Figure 3, left column). On the production side, 65% of cropland impacts were due to production for Q2 and Q4 regions exceeding their consumption-based environmental limits (49% due to domestic consumption and 16% via exports), while 35% were due to exports to Q1 and Q3 regions that were within safe consumption-based environmental limits, such as Asia (others), China and America (others) (Figure 3, right column).

For Australia, 97% of cropland impacts for the consumption of agri-food products originated from Q3 and Q4 regions exceeding their production-based environmental limits (67% from domestic production and 30% via imports from regions such as Africa, Asia (others), India and the USA; Figure 3, left column). On the production side, 48% of cropland impacts were due to production for Q2 and Q4 regions that exceeded their consumption-based environmental limits (26% due to domestic consumption and 18% via exports to regions such as the USA, Europe and Africa), while 52% were due to exports to Q1 and Q3 regions that were within safe consumption-based environmental limits such as Asia (others), China and Indonesia (Figure 3, right column).

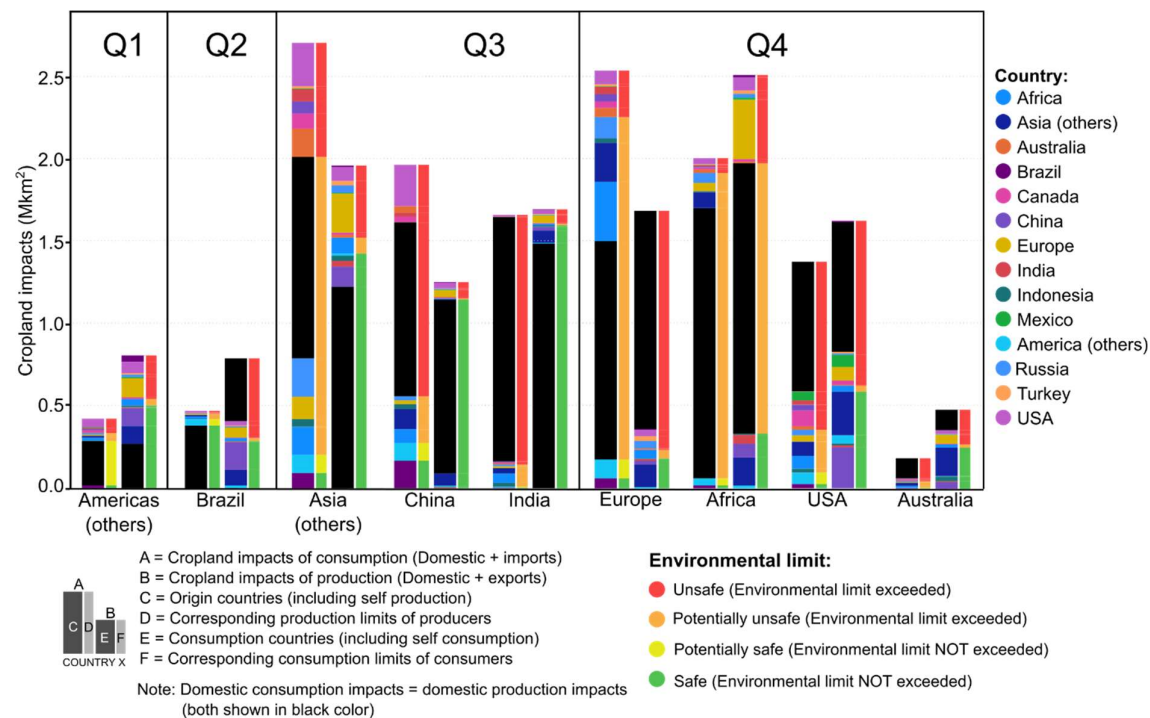


Figure 3. Domestic and imported cropland impacts of consumption on producers with corresponding production-based environmental limits of producers (left column for each region). Cropland impacts of production for domestic consumption and exports with corresponding consumption-based environmental limits of consumers (right column). See Figure S2 in the supporting information for all countries and regions.

3.3 Key global commodity flows and regional cropland exceedances

Globally, 80% of total cropland impacts were due to the consumption and production of oilseeds, cereals (excluding wheat and rice), wheat, and vegetables and fruits (Figure S3). Assessment of prominent cropland flows embedded in the trade of these commodities highlighted the role of individual trade relationships among countries (Figure 4). Virtual cropland flows embedded in agri-food commodities produced in safe production regions (Q1 and Q2) and consumed in safe consumption regions (Q1 and Q3) indicated responsible telecoupled agri-food production and consumption (Figure 4, yellow flows). For example, virtual cropland flows embedded in the production of oilseeds in Brazil (Q2) consumed as vegetable and fat products in China (Q3), Asia (Q3) and India (Q3) were within environmental limits of both production and consumption.

Virtual cropland flows embedded in agri-food commodities produced in safe production regions (Q1 and Q2) and consumed in unsafe consumption regions (Q2 and Q4) are shown in Figure 4 with pink flows. For example, virtual cropland flows embedded in the production of oilseeds in Brazil (Q2) were produced within safe environmental limits but consumed outside of safe environmental limits as vegetable and fat products in Europe (Q4) and Mexico (Q4).

Virtual cropland flows embedded in agri-food commodities produced in unsafe production regions (Q3 and Q4) and consumed in safe consumption regions (Q1 and Q3) are shown in Figure 4 with cyan flows. For example, virtual cropland flows embedded in the production of oilseeds in Africa (Q4), India (Q3) and the USA (Q4) were consumed within safe environmental limits as vegetable and fat products in India (Q3), China (Q3) and Asia (Q3). Other examples included the virtual cropland flows embedded in the production and domestic

consumption of cereals (excluding wheat and rice) in China (Q3) as poultry products; virtual cropland flows embedded in the production of wheat in the USA (Q4), Australia (Q4), Asia (Q3) and Russia (Q4) consumed as cattle, pigs, rice and other food products in Asia (Q3).

Virtual cropland flows embedded in agri-food commodities produced in unsafe production regions (Q3 and Q4) and consumed in unsafe consumption regions (Q2 and Q4) are shown in Figure 4 with grey flows. Flows of multiple commodities fell into that category. For example, virtual cropland flows embedded in the production of oilseeds in Europe (Q4), Africa (Q4) and the USA (Q4) were produced outside of safe environmental limits and consumed outside of safe environmental limits as vegetable, fat and fish products in Mexico (Q4), Africa (Q4) and Europe (Q4). Similarly, virtual cropland flows embedded in the production of cereals (excluding wheat and rice) in China (Q3), Africa (Q4), Russia (Q4), Europe (Q4) and the USA (Q4) were consumed as dairy, animal, meat and other food products in Africa (Q4), Russia (Q4), Europe (Q4) and the USA (Q4).

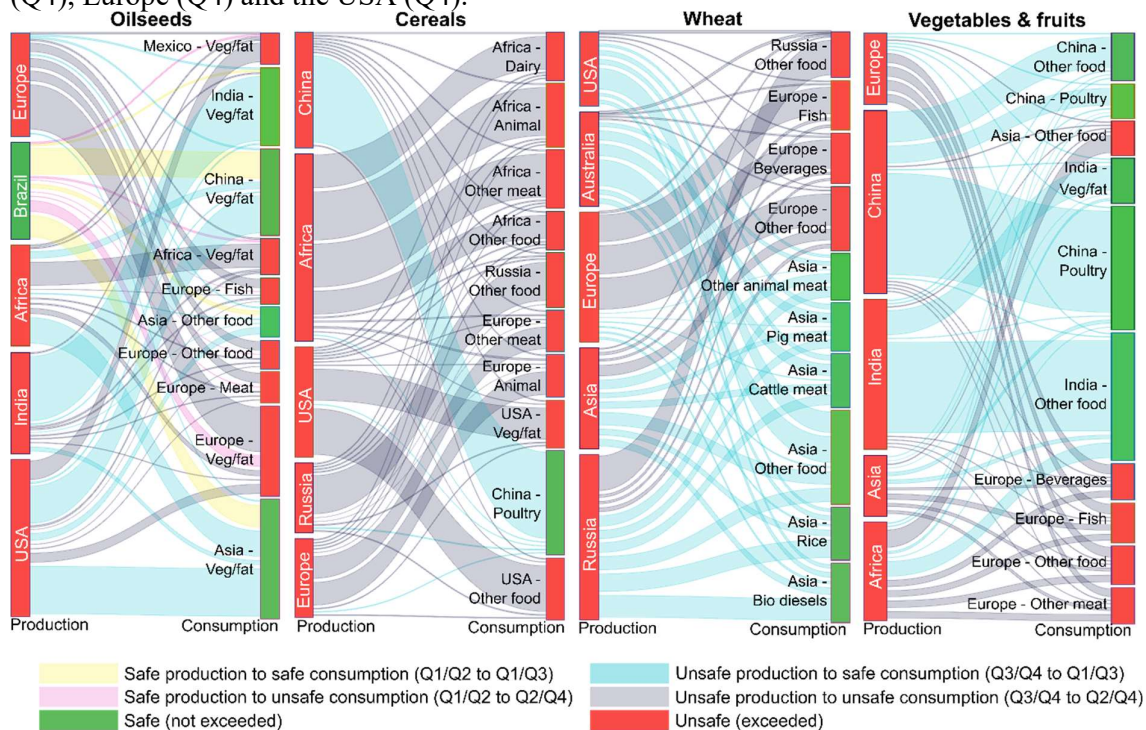


Figure 4. Global flows for four types of crops among countries within or exceeding their production-based or consumption-based environmental limits for cropland. Safe production countries refer to countries in Q1 and Q2 of Figure 1, unsafe production countries refer to countries in Q3 or Q4, safe consumption countries refer to countries in Q1 or Q3, and unsafe consumption countries refer to countries in Q2 and Q4.

4 Discussion

We have linked telecoupled cropland impacts of agri-food consumption and production across the global supply chain by classifying countries into quadrants based on their national environmental limit exceedance. We have shown that, except for Q1 and Q2 regions (Brazil and the Americas (others)), all other countries exceeded their production-based environmental limits. In addition, regions in Q3 (China, India, Indonesia and other Asian countries) were within safe consumption-based environmental limits. However, their consumption significantly contributed to the exceedance of domestic and international production-based environmental limits. These findings can inform responsible agri-food consumption and

production by nations, which should be seen as the joint responsibility of both consumers and producers (Lenzen et al., 2007).

4.1 Policy implications and SDG 12 implementation

Interdependencies of agri-food trade among countries and regions occur due to large differences in production varieties, production efficiencies, technology, socio-economic status, demographics and resource availability (Jambor and Babu, 2016). This results in a mismatch between supply and demand not only for calories but also for vitamins and minerals contained in food commodities (Geyik et al., 2020; Tramberend et al., 2019). Therefore, agri-food trade has an important role to play in achieving global food security. This makes the linkage of agri-food consumption and production across the global supply chain integral to monitoring national progress towards the targets of SDG 12 in a holistic way.

A country may have several trade relationships that differ in terms of their sustainability status (Figure 4). Our analysis highlighted underlying nuances within these trade relationships. Trade relationship of Q1 and Q2 regions with Q1 and Q3 regions (Figure 4, yellow flows) revealed that agri-food consumption in countries within safe consumption-based environmental limits substantially influenced the exceedance of production-based environmental limits in production countries. Similarly, trade relationships of Q1 and Q2 regions with Q2 and Q4 regions (Figure 4, pink flows) revealed that agri-food consumption in countries exceeding their consumption-based environmental limits placed pressure on the exceedance of production-based environmental limits in production countries. Despite being within safe production-based environmental limits, Q1 and Q2 regions are rapidly losing their biodiversity and natural ecosystems (e.g. rainforests) due to conversion of forests into cropland to produce agri-food commodities, mainly for exports (Yao et al., 2018). For example, soybean production in South America has expanded significantly to meet the increased demand for poultry and pig production in China (Sun et al., 2019). These increasing cropland impacts of agri-food production in Q1 and Q2 regions are likely to result in the exceedance of their production-based environmental limits in the future.

From the perspective of Q1 and Q2 regions, trade relationships to produce agri-food for export are mostly economic arrangements to support the economy and agri-food sector. These are not unsustainable per se. However, the consumption patterns of consuming countries tend to shift the environmental burden to production countries (Bruckner et al., 2012; Kastner et al., 2014b). To achieve SDG 12, Q1 and Q2 countries could account for the environmental implications of cropland expansion and prevent the exceedance of their production-based environmental limits via policies and trade agreements (e.g. the Mercosur-EU trade agreement) that require importing countries to comply with exporting countries' environmental policies (Escobar et al., 2020; Rajão et al., 2020). Limited enforcement of regulations that led to legal deforestation in the past could be prevented and reversed by more substantial socio-political commitments towards protecting the environment. Unfortunately, recent policies in Brazil and other South American countries prioritise economic growth over the environment (Abessa et al., 2019). Countries outsourcing their agri-food production to Q1 and Q2 regions should also acknowledge the hidden environmental costs of their outsourcing on production countries and consider reimbursements in the form of investments and incentives to upgrade technology (Hofmann et al., 2020), improve farming methods (Muller et al., 2017), promote good practices (Marchi et al., 2018), educate farmers on modern agricultural techniques (Zeweld et al., 2020), and other methods that could assist in improving production efficiencies and reducing waste (Pretty, 2018; Tilman et al., 2011), and subsequently, reduce the risk of exceedance of production-based environmental limits in production countries. High-consuming countries

could also manage their dietary requirements by reducing meat consumption and adopting low impact diets to reduce pressures on imported agri-food, as well as to allow the necessary safe operating space for food-insecure nations to increase their consumption to healthy levels (Willett et al., 2019).

Trade relationships between unsafe production regions (Q3 and Q4) with safe consumption regions (Q1 and Q3; Figure 4, cyan flows) revealed that production countries take an environmental hit to provide food security to consumption countries, even in cases where the latter are within their safe consumption limits. In addition, domestic consumption also contributed to production-based environmental limit exceedance in many countries. For example, India (Q3) exceeded its production-based environmental limits to produce agri-food commodities for domestic consumption, which accounted for 89% of its production-based cropland impacts. Trade relationships between unsafe production regions (Q3 and Q4) and unsafe consumption regions (Q2 and Q4; Figure 4, grey flows) revealed that production countries incurred social and environmental costs in terms of cropland exploitation while satisfying over-consumption by some regions. This environmental cost is not reflected in the price received for the exported goods, and no compensation accrues to the citizens of production countries. For example, almost 25% of Australia's cropland impacts of agri-food production were for exports to unsafe consumption regions (Q2 and Q4), mainly in the form of wheat exports to Europe and Asia. This underlines the extent of ongoing environmental deterioration due to agri-food production in Australia for over-consuming countries. Similarly, the majority of global cereal production is associated with unsafe production and consumption. Given the importance of cereals for food security, this highlights the importance of closing cereal yield gaps to achieve global food security and meet nutrition requirements (Folberth et al., 2020; Mueller et al., 2012).

To achieve SDG 12, Q3 and Q4 regions could reduce the exceedance of production-based environmental limits by slowing domestic demand growth (Amos and Lydgate, 2019; Hertel, 2015), reducing food loss and waste (Ellison et al., 2019), avoiding excessive allocation of cropland to produce crops for biofuels (e.g. corn, sugarcane) (Renzaho et al., 2017), and improving yield efficiencies of agri-food crops without expanding cropland area (Searchinger et al., 2018). Targeted efforts to reduce losses and improve efficiencies could be made for specific commodities, such as oilseeds and cereals, that have significant production-based cropland impact (Table 1). However, from an equity perspective, the primary responsibility lies with the countries of consumption, particularly Q4 regions that are exceeding their consumption-based environmental limits. Consumption countries could reduce their influence on the exceedance of production by using demand-based solutions such as adopting sustainable diets, reducing household waste, improving inefficient patterns and reusing products where possible, particularly focusing on commodities that have significant consumption-based cropland impact (Searchinger et al., 2018).

4.2 Innovation and contribution

Linking consumption and production perspectives is essential for sustainability assessment considering drastic differences in national-level natural resource availability, cropland suitability and other factors that determine international trade and cropland flows (Sun et al., 2019). Previous studies quantifying the displacement of cropland impacts between countries via trade had either a country-specific scope or only provided standalone analyses without any benchmarking criteria (Cooper and Dearing, 2019; Fang et al., 2021; Hoekstra and Mekonnen, 2012; Hossain et al., 2017; Kastner et al., 2014a; Kucukvar et al., 2019; Sato, 2014; Tukker et al., 2016; Yang et al., 2020; Zheng and Xu, 2020). Our novel perspective, comparing both

consumption and production, has not been used previously in the literature (Dao et al., 2018; Fang et al., 2015a; Fang et al., 2015b; Li et al., 2019; Willett et al., 2019) and could help nations assess progress towards SDG 12. Our approach accounted for variation in national demand for agri-food commodities due to population size and differences in arable land endowments among countries. We contributed to the literature by benchmarking the consumption and production impacts of the agri-food sector on cropland with nationally defined consumption-based and production-based environmental limits.

4.3 Uncertainty, limitations and future research

We acknowledge the heterogeneity of cropland resources and seasonal variations of agri-food production within countries, particularly in large countries such as Australia and the USA (Escobar et al., 2020). Scaling the current analysis from national to sub-national level resolution is an important future research avenue. While we used the MRIO model to quantify the telecoupled environmental impacts embedded in domestic and traded commodities (Cabernard and Pfister, 2020; Wang et al., 2017), we acknowledge the inherent approximation errors that arise in capturing the environmental impacts of production and consumption, global trade flows and interdependencies among economic sectors (Andrew et al., 2009). We also acknowledge the uncertainty within the land-system change planetary boundary and the existing debate about the total available global cropland area (Steffen et al., 2015; Usubiaga-Liaño et al., 2019). We included potentially safe and unsafe environmental limit zones derived using the previous literature to incorporate the uncertainty (Henry et al., 2018; Nykvist et al., 2013; Shaikh et al., 2021; Springmann et al., 2018; UNCCD, 2017; UNEP, 2014). Lastly, we chose cropland as a case-study to assess environmental limits defined for the land-system change planetary boundary. The framework of this study could be extended to assess environmental limit exceedance of other natural resources (for example, freshwater use, GHG emissions).

5 Conclusion

Faced with the threat of exceeding environmental limits, achieving responsible food consumption and production becomes an essential strategy for sustainable agri-food systems. Our reporting of trade linkages between countries based on their quadrant classification can inform national progress towards sustainable agri-food consumption and production patterns mandated under SDG 12. The global coverage of our analysis captured the far-reaching, complex and telecoupled cropland impacts of agri-food consumption and production across the global supply chain. SDG 12 requires all countries to be within Q1 (safe production and consumption), yet most countries and regions assessed were in Q4 (unsafe production and consumption). Trade relationships among countries, in the context of their quadrant classification, highlighted underlying nuances from the perspectives of consumption and production countries. Brazil and other low-income countries support their economy and provide global food security at the expense of intense deforestation due to the expansion of cropland to meet export requirements, causing substantial exceedance of their production-based environmental limits. Australia, the USA and other high-income countries exceeded both their consumption and production-based environmental limits, often putting pressure on the cropland resources of production countries. China and India also exceeded their production-based environmental limits to meet growing domestic agri-food demand. Our analysis allows countries and regions to identify the major commodities driving the exceedance of agri-food environmental limits, adding further specificity to the allocation of responsibility and highlighting the critical aspects of the supply chain that are responsible for most of the exceedance. To achieve SDG 12, both consumption and production countries require stricter

regulations and commitments in national and international policies to reduce the exceedance of environmental limits and thereby safeguard the global land-system planetary boundary.

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