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National-level consumption-based and production-based utilisation of the land-system change planetary boundary: patterns and trends

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ABSTRACT

To achieve responsible consumption and production under UN Sustainable Development Goal (SDG) 12, national agri-food consumption and production need to be assessed against environmental limits. We downscaled the land-system change planetary boundary and allocated national-scale cropland environmental limits for agri-food consumption via fair-share allocation based on population, and for agri-food production via biophysical allocation based on available arable land. We assessed country-level utilisation of the land-system change planetary boundary via quantifying national cropland footprints (including imports/exports) using an environmentally extended multi-regional input–output model. Consumption-based footprints were assessed against fair-share cropland limits and production-based footprints were assessed against biophysical cropland limits. Most countries' agri-food consumption footprints exceeded their fair-share cropland limit while production utilisation of biophysical limits was less pronounced. Conversely, China and India's cropland consumption footprints were safely within their fair-share environmental limits (utilisation percentages of 80% and 74%, respectively), while their cropland production footprints exceeded biophysical limits (utilisation percentages of 132% and 165%, respectively). Assessing country-level utilisation of the environmental limit for cropland can provide a basis for countries to act as individual entities, or collectively, to develop policies that mitigate their global cropland demand and minimise the risks associated with the exceedance of the land-system change planetary boundary.

1. Introduction

Large-scale conversion of land for agri-food production is adversely affecting land systems and consequently stressing the Earth's sustainable environmental limits (Godfray et al., 2010; Gopalakrishnan et al., 2011; Newbold et al., 2016; Ramankutty et al., 2018; Schneider et al., 2011; Zhao et al., 2014). The *planetary boundaries* framework identifies critical environmental limits for nine Earth-system processes which delineate the safe operating space for humanity at a global level (Rockström et al., 2009; Steffen et al., 2015). These nine Earth-system processes include land-system change, climate change, freshwater use, ocean acidification, biochemical flows, stratospheric ozone depletion, biosphere integrity, atmospheric aerosol loading, and novel entities. Exceeding planetary boundaries could destabilize the Earth system and increase the likelihood of irreversible and catastrophic consequences (Steffen et al., 2018). Of these nine globally defined boundaries, the land-system change planetary boundary focuses on bio-geophysical processes that regulate the land surface and atmosphere (Steffen et al., 2015). As a widely used indicator (or *control variable*) of the land-system change planetary boundary, total cropland area (hereafter, *cropland*) must remain within safe environmental limits to achieve responsible consumption and production targets mandated under the United Nations Sustainable Development Goal (SDG) 12 (UN, 2015). To support UN member countries in achieving this goal, national-level information is required on the impact of consumption-based and production-based cropland footprints on environmental limits for the land-system change planetary boundary.

Consumption-based and production-based footprint perspectives are widely used to analyse the environmental pressures of the global food system (Peters, 2008). Global displacement of land embodied in trade connects the cropland footprints of countries of agri-food production to countries of consumption. These trade-facilitated flows (i.e., imports/exports) are often referred to as *direct/indirect, virtual flows,* and *telecommections* (Liu et al., 2015). Consumption-based cropland footprint analysis allocates agri-food impacts across the entire product life-cycle to the country where final consumption occurs, irrespective of the country of origin (i.e., production) (Kastner et al., 2014b; Rodrigues et al., 2018; Tramberend et al., 2019). Conversely, the actual on-ground biophysical pressures on domestic cropland resources in the form of cropland intensification, deforestation, biodiversity impacts, and losses

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in ecosystem services are reported by analysing the production-based cropland footprint (Yu et al., 2013). Thereby, production-based cropland footprint analysis assigns agri-food impacts to the country of production, rather than where final consumption occurred (Wiedmann et al., 2011a). Analysing national utilisation of the land-system change planetary boundary from both the consumption-based and production-based perspectives is crucial to comprehensively assess the human-induced environmental pressures of nations.

To assess the environmental pressure of national agri-food consumption and production, the global-scale land-system change planetary boundary for cropland must be downscaled to the national level (Conijn et al., 2018; Heck et al., 2018; Li et al., 2019; O'Neill et al., 2018; Springmann et al., 2018; Willett et al., 2019). Häyhä et al. (2016) and O'Neill et al. (2018) proposed a conceptual framework to downscale the planetary boundaries by using multi-stage approaches that consider biophysical, socio-economic, and ethical dimensions. Fang et al. (2015b), Dao et al. (2018), and Nykvist et al. (2013) downscaled the planetary boundaries based on a per capita approach, and Meyer and Newman (2018) introduced a quota-based approach to study planetary boundaries and human footprints. Chaudhary and Krishna (2019) quantitatively compared the changes required in consumption-based footprints to achieve sustainable diets. These planetary boundary downscaling approaches have potential for the assessment of consumption-based cropland footprints.

For production-based cropland footprints, the endowment of the arable land that can be cropped without threatening environmental sustainability i.e., the *biophysical* limit, varies widely between countries and depends on multiple factors such as total land area, topography, soils, climate, population, level of technological development, and overall production efficiency (Hoff et al., 2014). Hence, production-based cropland footprint assessments should focus on whether the total land area used for agri-food production in each country exceeds biophysical limits. Therefore, to assess production-based cropland footprints, there is a need to downscale the land-system change boundary for cropland based on the available cropland of the country. This is essential to measure country-level pressure on domestic cropland resources due to agri-food production.

In this study, we undertook a global assessment of the utilisation of national environmental limits for cropland due to consumption and production of agri-food products from 1995 to 2011. We calculated national consumption-based and production-based cropland footprints by incorporating direct (i.e., domestic) and indirect (i.e., international) effects of virtual flows via global trade. We downscaled the global land-system change planetary boundary for cropland and assigned environmental limits using two methods: fair-share allocation and biophysical allocation. We assessed national consumption-based cropland footprints against fair-share cropland limits and assessed production-based footprints against biophysical limits to present a comprehensive national-level assessment of cropland utilisation of environmental limits via consumption and production of agri-food products. We discuss the complex global virtual flows of cropland via agri-food trade and assess the implications of national-level pressure on the land-system change cropland boundary due to agri-food consumption and production.

2. Methodology

2.1. Overview

We calculated annual cropland footprints using Environmentally Extended Multi-Regional Input-Output (EE-MRIO) analysis for 44 countries and five Rest of the World (RoW) regions, and assessed these against nationally-downscaled cropland environmental limits (Fig. 1). This involved quantifying the utilisation percentage of fair-share cropland limits by national agri-food consumption footprints (i.e., domestic production plus imports minus exports) and quantifying the utilisation percentage of biophysical cropland environmental limits by national agri-food production footprints. We tracked inter-country virtual cropland flows in terms of imports and exports of agri-food products to identify annual country-to-country (cropland) trade and cropland limit exceedance from 1995 to 2011.

2.2. Environmental footprint analysis

EE-MRIO modelling is the state-of-the-art method for calculating country-level, consumption and production-based footprints (Wiedmann and Lenzen, 2018). Multi-Regional Input-Output (MRIO) models use economic input–output tables for capturing global trade flows and the interdependencies between economic sectors of countries. The environmental satellite accounts in EE-MRIO databases translate trade flows into environmental units which enables the quantification of the direct/indirect environmental impacts for consumption and production (Kissinger and Rees, 2010; Weinzettel et al., 2013). We used an EE-MRIO model to calculate the direct and indirect displacement of cropland impacts embodied in global trade (Acquaye et al., 2011; Hoekstra and Wiedmann, 2014; Liu et al., 2015; Suh and Huppes, 2005; Wiedmann et al., 2011b). Global economic trade interdependencies were captured using the Exiobase 3.0 database from 1995 to 2011 (see Supporting Information for further details on MRIO and country aggregations) (Behrens et al., 2017; Wood et al., 2018). The RoW regions aggregate data from individual countries whose national input–output tables are not included in the database. A detailed explanation of the construction of the Exiobase database is provided by Stadler et al. (2018). We carried out EE-MRIO analysis to determine national dependencies on domestic (direct) and international (indirect) cropland resources to satisfy their domestic agri-food requirements. We used this methodology to calculate the virtual cropland embodied in the consumption and production of agri-food products (Kastner et al., 2014a; Tramberend et al., 2019).

Our MRIO model follows the standard framework (Leontief, 1970). The technical coefficient matrix $\boldsymbol{A^{pq}}$ calculated as $a_{ij}^{pq} = z_{ij}^{pq}/x_j^q$, represents the inter-sectoral monetary flow from sector i in country p to sector j in country q required to fulfil the intermediate sector demand (z), and x_j^q represents the total output of sector j in country q:

$$\boldsymbol{A} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix} \tag{1}$$

$\boldsymbol{Y^{pq}}$ is the matrix representing the final demand of country q produced in country p:

$$\boldsymbol{Y} = \begin{bmatrix} Y^{11} & Y^{12} & \cdots & Y^{1n} \\ Y^{21} & Y^{22} & \cdots & Y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y^{n1} & Y^{n2} & \cdots & Y^{nn} \end{bmatrix} \tag{2}$$

The Leontief inverse matrix $\boldsymbol{L}$ is calculated by:

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \tag{3}$$

Where $\boldsymbol{I}$ is the identity matrix, and the total output of each sector $\boldsymbol{(x)}$ is calculated by:

$$\boldsymbol{x} = \boldsymbol{LY} \tag{4}$$

To calculate the cropland impacts $\boldsymbol{G}$ associated with the final demand of each country, we used the following equation:

$$\boldsymbol{G} = \hat{\boldsymbol{e}}\ \boldsymbol{x} = \hat{\boldsymbol{e}}\ (\boldsymbol{I} - \boldsymbol{A})^{-1}\ \boldsymbol{Y} \tag{5}$$

where $\hat{\boldsymbol{e}}$ is the diagonalised direct intensity matrix representing the cropland pressures associated with the unit dollar value of economic transaction of the corresponding economic sector in each country.

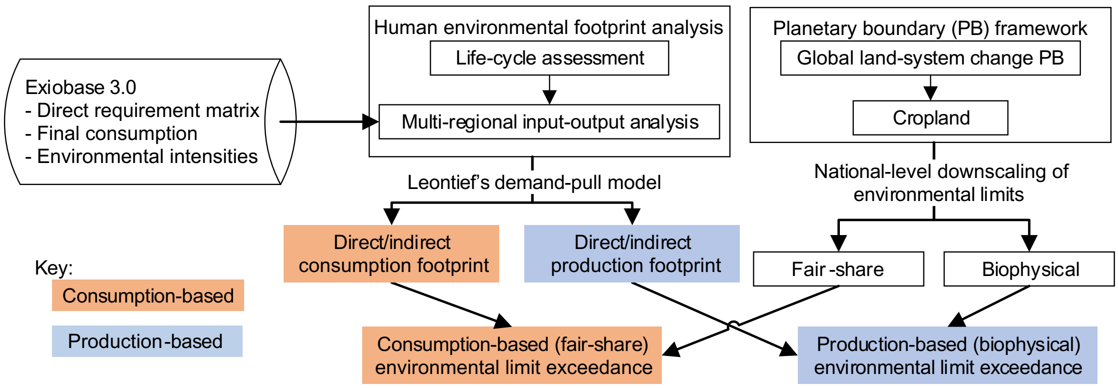

Fig. 1. Schematic diagram of the methods used to link environmental footprint analysis with planetary boundaries.

Table 1
Planetary boundary utilisation zones of cropland limits. Utilisation percentage define national planetary boundary zones and is calculated as the ratio of cropland footprint and the best estimate of the planetary boundary (12.6 Mkm^2).

Zone	Colour	Global cropland limits (Mkm^2)	Utilisation (%)	Description
Safe		< 10.6	0 to 83	Below lower environmental limit
Potentially unsafe (lower)		10.6 to 12.6	84 to 100	Between lower and best estimate environmental limit
Potentially unsafe (higher)		12.6 to 16.4	101 to 129	Between best estimate and higher environmental limit
Unsafe		> 16.4	130 +	Above higher environmental limit

2.3. *Defining the land-system change planetary boundary for cropland*

The environmental limits of the land-system change planetary boundary are widely debated (Usubiaga-Liaño et al., 2019). Rockström et al. (2009) originally proposed a land-system change planetary boundary as the total cropland area of no more than 15% of the global ice-free land surface. While Steffen et al. (2015) proposed area of forest remaining as a control variable on the premise that forests are the major driver of land-surface/climate dynamics compared to other biomes (Heck et al., 2018; West et al., 2010), cropland remains the most commonly reported and well-established land-system change planetary boundary in food system studies (Chaudhary and Krishna, 2019). A wide range of estimates for the cropland planetary boundary have been reported, with several refinements since originally introduced by Rockström et al. (2009). We reviewed published estimates of the land-system change planetary boundary for cropland as a basis for downscaling national-level environmental limits.

With the world's ice-free land area estimated at 132 Mkm^2 (UNCCD, 2017), the original 15% cropland area planetary boundary suggested by Rockström et al. (2009) equates to 19.8 Mkm^2. This estimate is close to the 19.5 Mkm^2 estimate of Nykvist et al. (2013) and the 20.1 Mkm^2 estimate of Henry et al. (2018). Even before the revision of the land-system change boundary (Steffen et al., 2015), UNEP (2014) proposed a tighter estimate of 16.4 Mkm^2 for the cropland boundary based on the precautionary principle (Van Vuuren and Faber, 2009). Recent modelling takes into account conservation levels for each forest biome to preserve ecosystem integrity, producing an estimate of 12.6 Mkm^2 (with a range 10.6–14.6 Mkm^2) (Springmann et al., 2018). In accordance with the precautionary principle, we therefore adopted the conservative estimates of 10.6 Mkm^2 and 12.6 Mkm^2 as the low and best estimate of the boundary based on the revised definition of the land-system change planetary boundary. To encompass the range of uncertainty in cropland limits due to conversion of pasture into cropland (Springmann et al., 2018), we used the 16.4 Mkm^2 value from UNEP (2014) as our high estimate. We used these low, best, and high estimates of the cropland limits and used them to define land-system change planetary boundary utilisation zones (Table 1).

2.4. *Downscaling the land-system change planetary boundary*

We downscaled the global land-system change planetary boundary for cropland to the national level based on a per capita fair-share for assessment of the consumption-based cropland footprints and based on biophysical limits for assessment of production-based cropland footprints.

2.4.1. *Fair-share allocation*

A country's consumption-based cropland footprint is directly related to the total food demand of its people. Allocating a share of the global cropland planetary boundary to individual countries based on a per capita equivalent normalises the inequality in arable land endowment between countries and harmonises the comparative advantage of countries with abundant cropland over countries with limited cropland (Dao et al., 2018; Fang et al., 2015a). This widely employed downscaling technique considers that every human has an equal right to global land resources and allocates environmental limits to countries based on their proportion of the global population. To calculate the annual (y) fair-share environmental limit for cropland (PB^{fs}) of each country (c), we multiplied the global cropland limit (PB_g) with the national population proportion (Pop) obtained from UN (2017):

$$PB_{c,y}^{fs} = PB_g * \frac{Pop_{c,y}}{Pop_{g,y}} \tag{6}$$

2.4.2. *Biophysical allocation*

The biophysical downscaling perspective allocated environmental limits to countries based on their potentially available cropland while maintaining sustainable amounts of forest, biodiversity, and other natural resources. Eitelberg et al. (2015) calculated spatially resolved high, medium, and low cropland estimates using model-based approaches by considering several land-cover classes. We summed the potentially available cropland for nations based on the "low" estimate of Eitelberg et al. (2015) by overlaying a national border shape-file in a Geographic Information System. We chose the low estimate because the medium and high potential cropland estimates included savannahs,

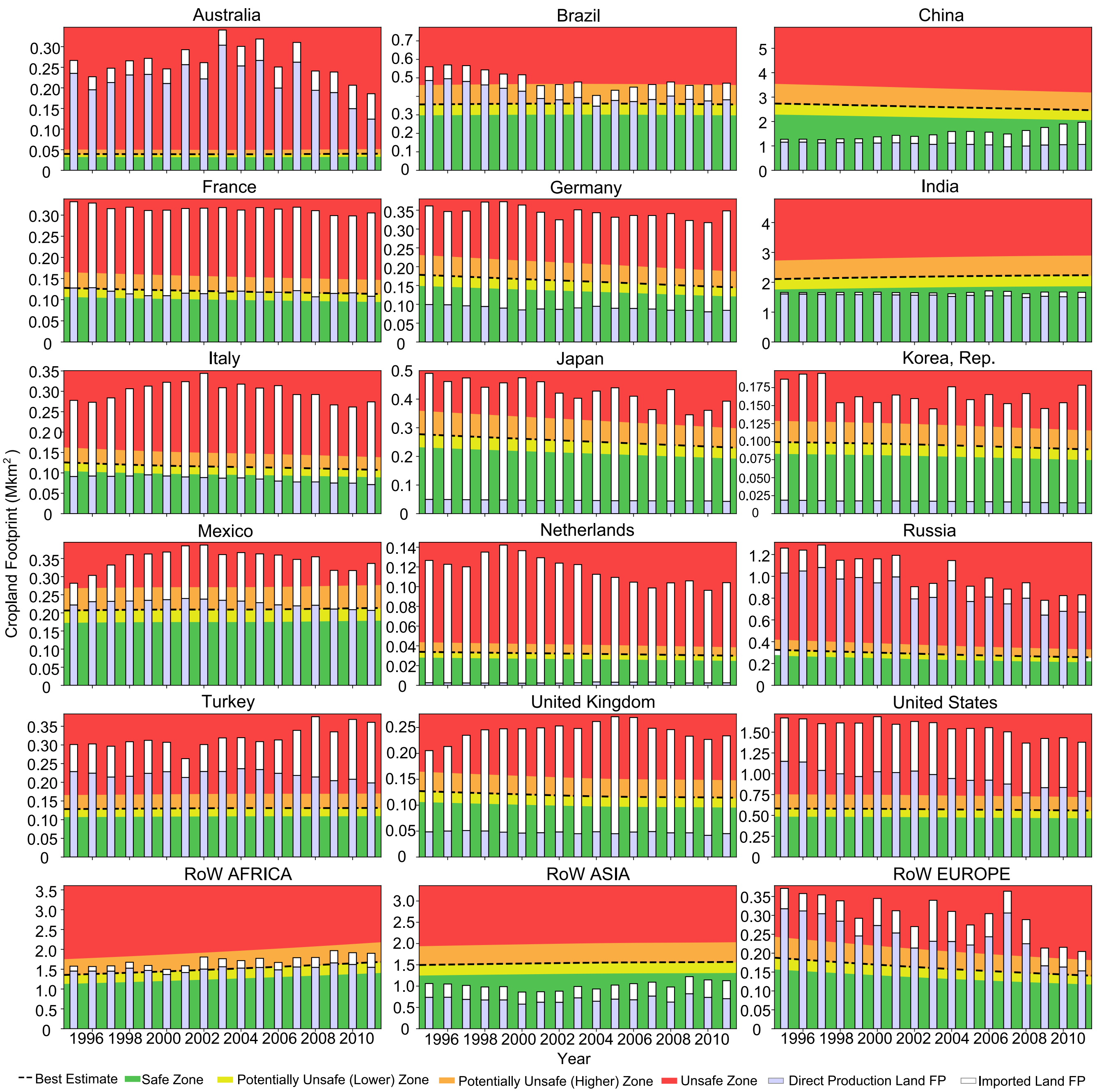

Fig. 2. Comparison of selected countries' consumption-based cropland footprints against their fair-share environmental limit. Background colours show the zones of downscaled environmental limit (Table 1). Vertical bars represent the domestic (direct) and imported (indirect) cropland footprint by countries over time. Note that the scale of y-axis is unique for each country due to the difference in environmental limits and cropland footprints. See Fig. S3.1 for the results of all countries and world regions.

shrublands, grasslands, forests, protected areas, and a range of other natural land-cover classes currently dedicated for biodiversity conservation and other ecosystem services (Eitelberg et al., 2015; Lambin et al., 2013).

Unlike the fair-share limits which vary over time with changes in population, biophysical limits are time-invariant because global arable land-use has remained constant overtime (Ritchie and Roser, 2013). To maintain compatibility between fair-share and biophysical environmental limits, biophysical environmental limit of production (PB^{bio}) for each country (c) was calculated by multiplying the global cropland limit (PB_g) (explained in section 2.3) with the national proportion of the potentially available cropland (PAC) (explained in last paragraph):

$$PB_c^{bio} = PB_g * \frac{PAC_c}{\sum_{c=1}^{49} PAC_c} \quad (7)$$

2.5. Country-level utilisation percentage calculations

To evaluate the utilisation of national fair-share and biophysical environmental limits for consumption and production, we developed a utilisation percentage (U) indicator which was calculated by dividing the cropland footprint (FP) of a country (c) in year (y), by the best estimate ($PB*$) of the country's cropland environmental limit for that same year.

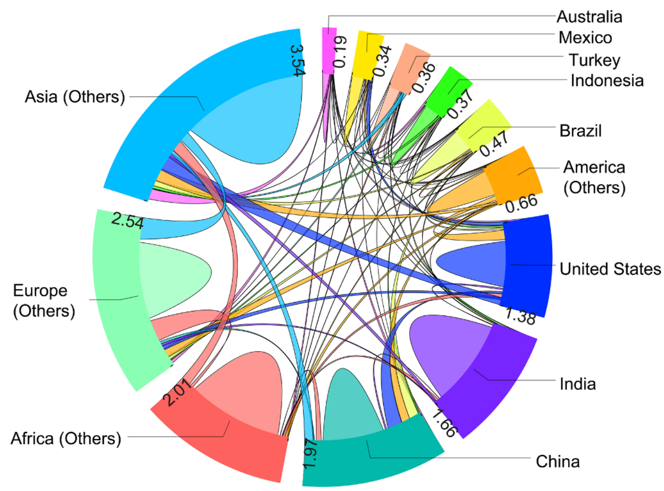

Fig. 3. Consumption-based domestic (direct) and imported (indirect) cropland flows (Mkm^2). For clarity of visualisation, prominent countries are classified separately (see Table S2.1 for country classification and Supporting Data for values).

$$U_{c,y} = \frac{FP_{c,y}}{PB^*_{c,y}} * 100 \quad (8)$$

2.6. Analysis and visualisation

We analysed the results by plotting the consumption-based cropland footprints including direct (i.e., consumption of domestically produced agri-food products) and indirect (i.e., consumption of imported agri-food products) components against fair-share environmental limits; and production-based cropland footprints including direct and indirect (i.e., exported agri-food products) components against biophysical environmental limits. Direct and indirect cropland flows were assessed for national consumption and production footprints and visualised using chord diagrams. The full database of cropland footprints and virtual flows from 1995 to 2011 is presented in the Supporting Data. National-level utilisation of consumption and production-based environmental limits were compared over the time series.

3. Results

3.1. Consumption-based footprints and fair-share limits

Fair-share cropland environmental limits have changed over time relative to the change in their individual proportion of the global population (Fig. 2). China and India had the highest fair-share environmental limit for consumption due to their high population. These limits varied over time because of variation in population proportions. For example, China's fair-share environmental limit decreased from 2.73 to 2.46 million km^2 and India's fair-share environmental limit increased from 2.10 to 2.24 million km^2. Similarly, from 1995 to 2011, the fair-share environmental limit for RoW Asia and RoW Africa increased, while it decreased for Japan, Korea, and other European countries.

In 2011, China had the highest consumption-based cropland footprint, followed by RoW Africa, India, USA, and RoW Asia. From 1995 to 2011, footprints increased in China (from 1.27 to 1.97 Mkm^2), Turkey (from 0.30 to 0.36 Mkm^2), the UK (from 0.21 to 0.23 Mkm^2), Mexico (from 0.28 to 0.34 Mkm^2), and RoW Africa (from 1.58 to 1.90 Mkm^2), but decreased in the USA (from 1.67 to 1.38 Mkm^2), Australia (from 0.27 to 0.19 Mkm^2), Russia (from 1.26 to 0.83 Mkm^2), Japan (from 0.49 to 0.39 Mkm^2), Korea (from 0.19 to 0.18 Mkm^2), Brazil (from 0.56 to 0.47 Mkm^2), and most European countries. India, however, maintained a fairly constant cropland footprint.

Disaggregating the total consumption-based cropland footprints into direct (i.e., consumption of domestic agri-food production) and indirect (i.e., consumption of imported agri-food production) revealed cropland teleconnections associated with consumption. Major agri-food producers like India, Australia, Brazil, Mexico, United States, RoW Asia, and RoW Africa had lower indirect cropland footprints than smaller producers like Japan, South Korea, the UK, and other European countries. Many countries have become increasingly dependent on imports in order to satisfy agri-food demand. For example, indirect cropland footprints increased in Australia (from 0.03 to 0.06 Mkm^2), Brazil (from 0.07 to 0.09 Mkm^2), China (from 0.12 Mkm^2 in 1995 to 0.91 Mkm^2 in 2011), India (from 0.05 to 0.18 Mkm^2), Mexico (from 0.06 to 0.13 Mkm^2), and the USA (0.52 to 0.59 Mkm^2). Global agri-food imports caused complex virtual cropland flows between countries (Supporting Data). For example, in 2011, consumption of imported agri-food products resulted in major virtual cropland flows in Asia (Others), Europe (Others), China, and the USA (Fig. 3).

Agri-food consumption in Asia (Others) was largely dependent on cropland flows from the USA (0.27 Mkm^2), America (Others) (0.22 Mkm^2), and Africa (Others) (0.19 Mkm^2). Imports in Europe (Others) relied on cropland flows from Asia (Others) (0.37 Mkm^2), and Africa (Others) (0.36 Mkm^2). China's imports embodied significant cropland resources from the USA (0.25 Mkm^2) and Brazil (0.17 Mkm^2), while agri-food imports in the USA were associated with cropland flows from America (Others) (0.16 Mkm^2) and Asia (Others) (0.12 Mkm^2).

3.2. Production-based footprints and biophysical limits

The biophysical environmental limits for RoW Africa (2.02 million km^2), RoW Asia (1.41 million km^2), India (1.03 million km^2), Russia (0.96 million km^2), China (0.95 million km^2), and USA (0.86 million km^2) were highest due to their large endowments of arable land (Fig. 4).

In 2011, the highest production-based cropland footprints were RoW Africa (2.39 Mkm^2), followed by India (1.70 Mkm^2), the USA (1.63 Mkm^2), RoW Asia (1.50 Mkm^2), and China (1.25 Mkm^2). From 1995 to 2011, production-based footprints increased in Australia (from 0.40 to 0.48 Mkm^2), Brazil (from 0.66 to 0.79 Mkm^2), Mexico (from 0.27 to 0.28 Mkm^2), and RoW Africa (from 1.99 to 2.39 Mkm^2), but decreased in China (from 1.32 to 1.25 Mkm^2), Turkey (from 0.27 to 0.24 Mkm^2), and the USA (from 1.84 to 1.62 Mkm^2). India's production-based cropland footprint remained constant.

Exported production-based cropland footprint (i.e., indirect cropland footprint) increased for almost all countries. From 1995 to 2011, increased exports from prominent agri-food producers resulted in increased virtual cropland flows. Of the total cropland use of Australia, 0.17 Mkm^2 was exported to other countries in 1995, which increased to 0.36 Mkm^2 in 2011. Likewise, considerable increases in the indirect production-based cropland footprints were found in Brazil (from 0.17 Mkm^2 to 0.41 Mkm^2), China (from 0.16 Mkm^2 to 0.20 Mkm^2), India (from 0.09 Mkm^2 to 0.21 Mkm^2), Mexico (from 0.05 Mkm^2 to 0.07 Mkm^2), Russia (from 0.26 Mkm^2 to 0.56 Mkm^2), the USA (from 0.69 Mkm^2 to 0.79 Mkm^2), RoW America (from 0.33 Mkm^2 to 0.54 Mkm^2), and ROW Africa (from 0.53 Mkm^2 to 0.84 Mkm^2). In 2011, major virtual cropland flows due to agri-food exports were from Asia (Others), Africa (Others), America (Others), USA, Brazil, and Australia (Fig. 5).

The largest virtual cropland flows (i.e., exports) from Asia (Others) were to Europe (Others) (0.37 Mkm^2), Africa (Others) (0.16 Mkm^2), and China (0.15 Mkm^2). From Africa (Others), cropland flows were typically to Europe (Others) (0.36 Mkm^2) and Asia (0.19 Mkm^2), while from America (Others) they were mostly to Asia (Others) (0.22 Mkm^2) and the USA (0.16 Mkm^2). From the USA, cropland flows were primarily to Asia (Others) (0.27 Mkm^2) and China (0.25 Mkm^2), and from Brazil, they were mostly to China (0.17 Mkm^2) and the USA (0.03 Mkm^2).

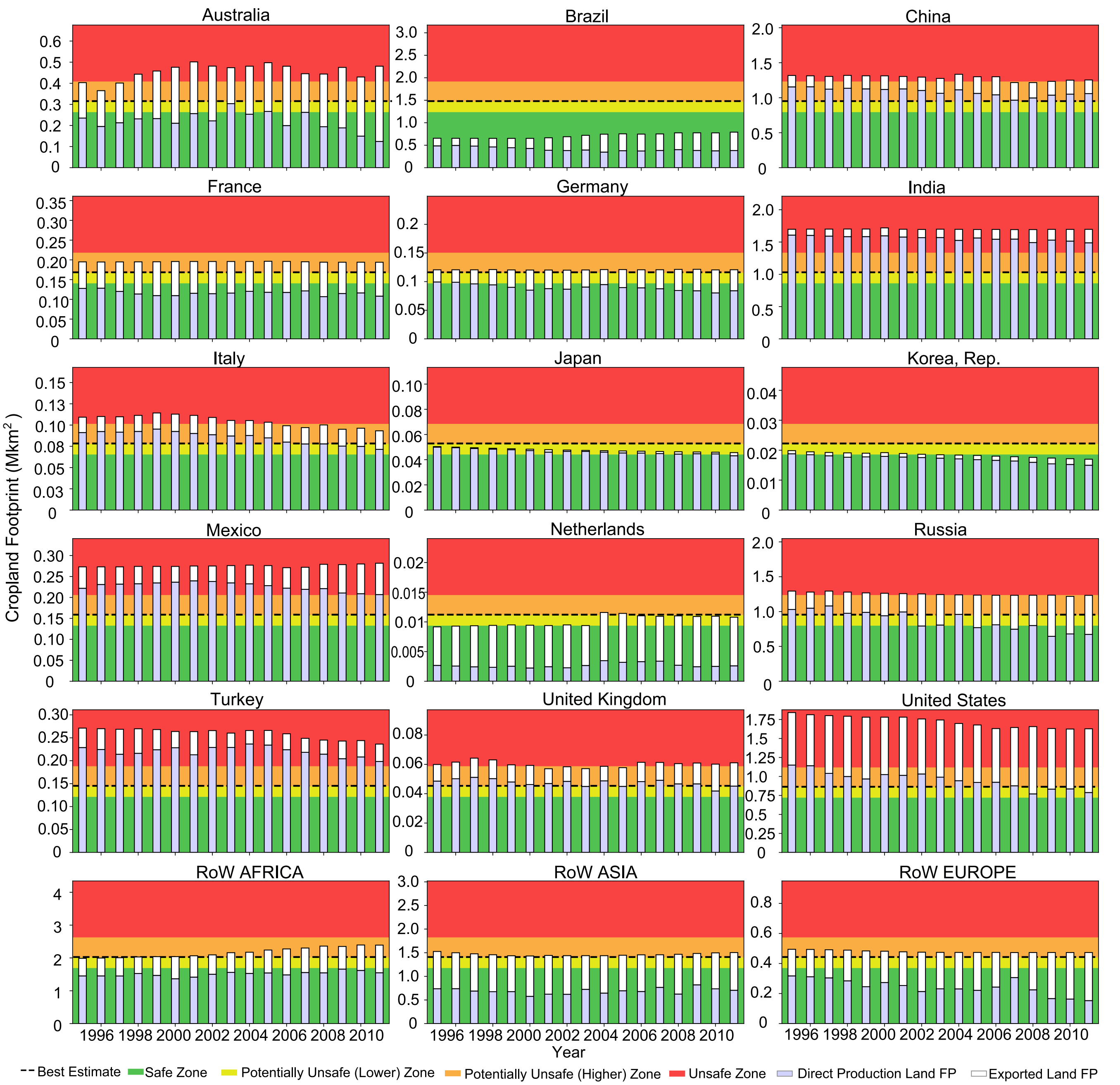

Fig. 4. Comparison of selected countries' production-based cropland footprints against their biophysical environmental limit. Background colours show the zones of downscaled environmental limit (Table 1). Vertical bars represent the domestic (direct) and exported (indirect) use of cropland by countries over time. Note that the scale of y-axis is unique for each country due to the difference in environmental limits and cropland footprints. See Fig. S3.2 for the results of all countries and world regions.

3.3. Consumption and production-based utilisation of environmental limits

Cropland consumption was within fair-share environmental limits for only a few countries (as evidenced by utilisation percentages much greater than 100% in Fig. 6). However, while the cropland production footprints also exceeded biophysical limits for many countries, overall utilisation percentages were lower, and several countries were safely within their biophysical cropland limits. For a few countries (e.g., China, India, RoW Asia, Indonesia), cropland consumption footprints were within their fair-share limits, but their cropland production footprints exceeded their biophysical limits. Many developed countries exceeded their environmental limits for both consumption and production. For example, Australia's cropland consumption greatly exceeded its fair-share limit (utilisation percentage = 461%) and its cropland production also exceeded its biophysical limit (utilisation percentage = 152%). Similarly, the USA exceeded its fair-share environmental limit (utilisation percentage = 247%) and its biophysical environmental limit (utilisation percentage = 188%).

4. Discussion

We have downscaled the land-system change planetary boundary for cropland and allocated national cropland limits for consumption and production using fair-share and biophysical allocation, respectively. We quantified direct and indirect cropland footprints of agri-food consumption and production and assessed these footprints against

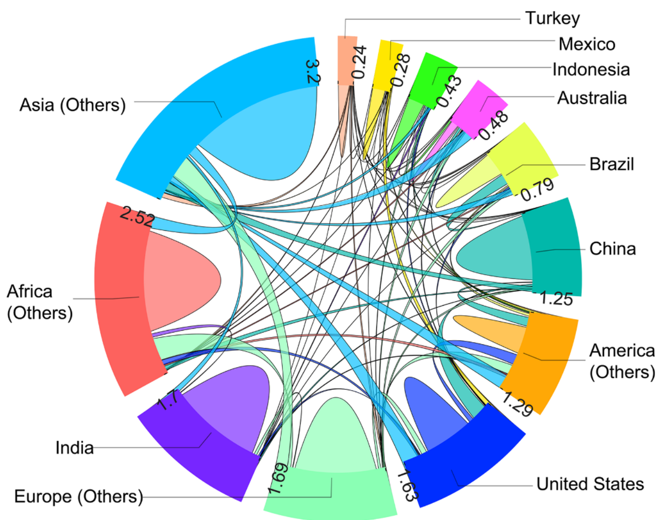

Fig. 5. Production-based domestic (direct) and exported (indirect) cropland flows (Mkm^2). For clarity of visualisation, prominent countries are classified separately (see Table S2.1 for country classification and Supporting Data for values).

the fair-share cropland limit for consumption and biophysical cropland limit for production, while accounting for complex global virtual flows of cropland via agri-food trade. We have shown how countries utilised their downscaled cropland environmental limit for consumption and production of agri-food.

4.1. Global cropland consumption, production, flows, and boundary utilisation

Agri-food consumption in most countries exceeded their fair-share cropland limit. China, India, Indonesia, and RoW Asia were the only countries that remained within their respective fair-share cropland limit within the study period. The large populations of these countries drove a high fair-share environmental limit, and the relatively low agri-food demand per capita resulted in a low consumption-based footprint. However, upward trends of consumption-based cropland footprints suggest that even these countries may have exceeded their fair-share limit by the time of writing (2020). Although many countries had exceeded production-based biophysical limits, utilisation percentages tended to be lower than consumption-based fair-share utilisation percentages. Brazil and RoW America were among the few countries whose agri-food production had not exceeded their biophysical cropland limit within the study period. However, deforestation and cropland intensification to meet growing domestic and export demands are increasingly putting pressure on biophysical limits in these regions (Ramankutty et al., 2018).

Discrepancies between consumption and production-based utilisation percentages were due to the fundamental differences between the calculation of fair-share versus biophysical environmental limits and the weak relationship between the population and available arable land of nations. Consumption and production-based cropland footprints vary with countries' population, wealth, urbanisation, culture and lifestyle, and geography (Willett et al., 2019). Levels of agri-food imports and exports of countries are influenced by production efficiency, environmental impacts, and socio-economic and cultural factors (Osei-Owusu et al., 2019). These factors explain the fluctuations of consumption-based and production-based cropland footprints and associated variation in imports and exports of agri-food products. Trends towards increasing indirect consumption-based footprints provide evidence in support of claims that global outsourcing of agri-food products is increasing (Simas et al., 2017; Yu et al., 2013) and along with it the increasing indirect cropland impacts on biophysical cropland limit of exporting countries.

Global trade in agri-food products illustrates how complex teleconnections result in the exceedance of biophysical cropland limits of exporting countries (Green et al., 2019). For example, China exports cotton, oilseeds, sugarcane, and other products to the USA, Japan, South Korea, and Asia (Yu et al., 2016). The USA exports corn, soybeans, and livestock (Sun et al., 2019) and Australia exports wheat, fruits, vegetables, and other products to Asia and Europe. Hence, agri-food exports of most countries contribute to the utilisation of nationally downscaled production-based biophysical environmental limits for cropland.

4.2. Innovation and contribution

Environmental footprint studies have typically focused on the consumption-based perspective in order to assess environmental sustainability (Cuypers et al., 2013; Davis et al., 2017; Turner et al., 2007), arguing that this perspective best captures the appropriation of natural capital, resource use, and the environmental impacts of human activities (Bruckner et al., 2015; Tramberend et al., 2019; Tukker et al., 2016). While this accounting approach is useful for evaluating the strong coupling between environmental pressures and affluence, we also analysed the production-based perspective because of its relevance in quantifying the environmental impacts of goods and services produced for human use (Croft et al., 2018). However, considering both the consumption and production-based perspectives is essential for sustainability assessment due to fundamental differences in natural resource availability, cropland suitability, and other factors that determine country-to-country trade and drive virtual cropland flows described above (Sun et al., 2019).

A major innovation of this study is in allocating biophysical cropland limits to countries to assess production-based cropland footprints. Studies that have considered the consumption-based footprints against the national environmental limits have mainly used the fair-share (per capita) approach to assign environmental limits for consumption (Fang et al., 2015a, 2015b; Li et al., 2019; O'Neill et al., 2018; Springmann et al., 2018; Willett et al., 2019). The country-level resolution and time-series analysis of our study also goes well beyond the scope of previous global cropland footprint assessments (Dao et al., 2018; Fang et al., 2015b).

Assigning shares of the global safe operating space to countries and assessing their cropland footprints against these environmental limits is used to quantify national environmental pressures on shared global land resources. Currently, downscaling planetary boundaries based on population is the most common downscaling approach (Dao et al., 2018). The framework used in this study provides a novel way to allocate national environmental limit for production based on biophysical limit of countries. This methodology can be replicated for other planetary boundaries by using relevant control variables. Our study considered key nuances in the land-system change planetary boundary by addressing fair-share and biophysical concerns that generally arise in allocating the safe operating space to countries (Häyhä et al., 2016; Newbold et al., 2016).

4.3. Policy implications and SDG 12 implementation

Environmental impacts caused by agri-food production are the shared responsibility of consumers and producers (Lenzen et al., 2007). The principles of responsible consumption and production (SDG 12) require countries to monitor both their direct and indirect footprints, as well as their respective impacts on environmental limits (Tukker et al., 2016). Our results provide a national-level assessment of how cropland resources are utilised for consumption and production. Countries can use these results to analyse resource utilisation resulting from their local production, production efficiencies, and environmental impacts caused

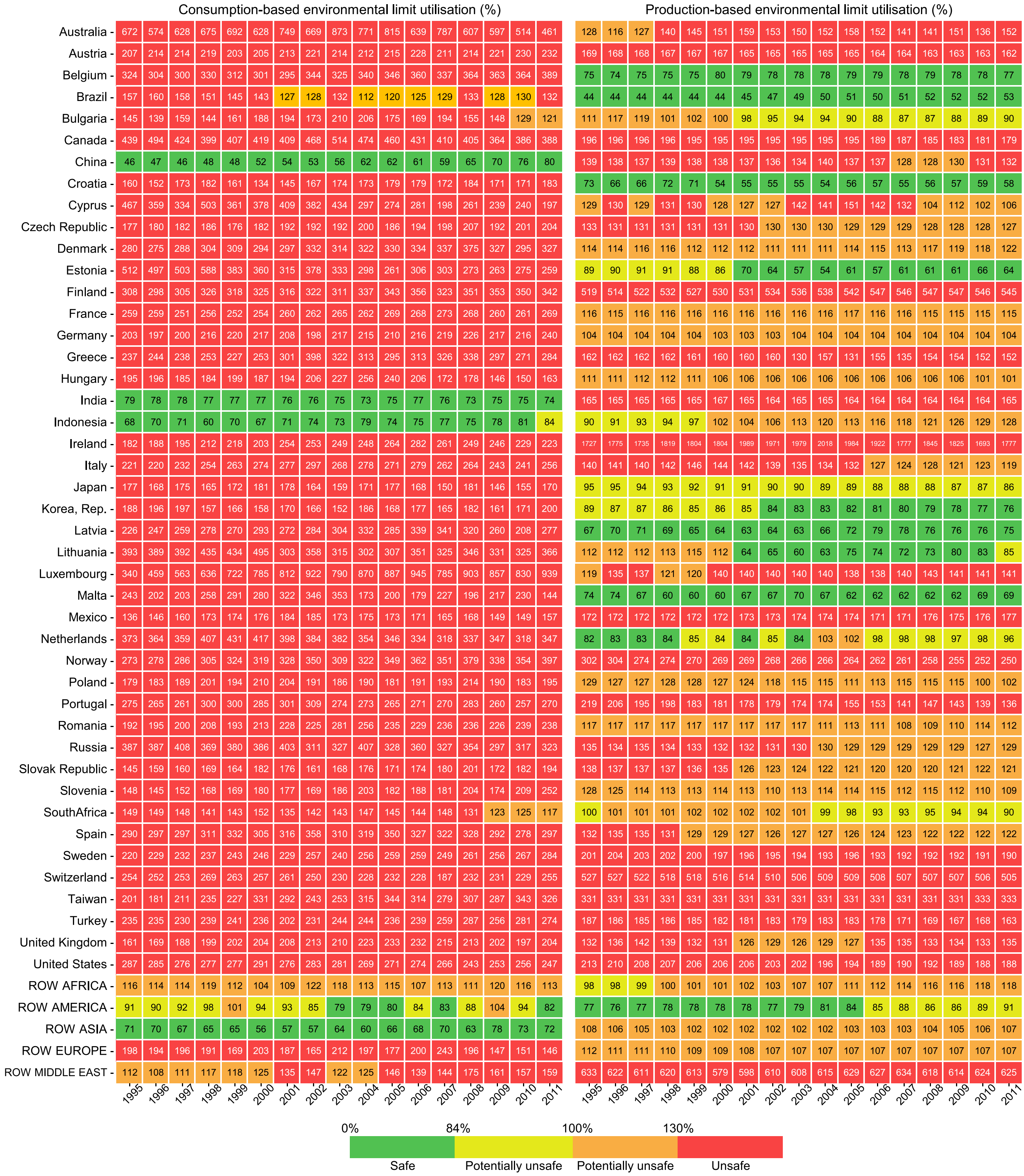

Fig. 6. Utilisation percentages of countries' downscaled cropland boundary including consumption-based utilisation of fair-share limits (left) and production-based utilisation of biophysical limits (right).

by interdependencies among countries in the agri-food sector (Tramberend et al., 2019). The results aim to assist in achieving national commitments towards conserving the global biophysical cropland limits, necessary to achieve sustainable consumption and production under SDG 12. Agri-food trade policies should take into account the direct (domestic) and indirect (overseas) cropland impacts of domestic agri-food consumption. Bilateral and multilateral trade agreements should consider national environmental limits, and the potential consequences of imports and exports on the environmental limits of agri-food producers. Measures towards reducing the consumption- and production-based impacts on cropland resources are essential to reduce stress on the land-system change planetary boundary.

4.4. Uncertainty, limitations, and future research

While we selected cropland to represent the global land-system change planetary boundary, we acknowledge the limitations with this indicator and the existing debate about the amount of available cropland globally and its reduction with time (Steffen et al., 2015; Usubiaga-Liaño et al., 2019). To incorporate uncertainty in global environmental limits for cropland we included lower, best, and upper estimates based on previous formulations of the cropland boundary (Henry et al., 2018; Nykvist et al., 2013; Springmann et al., 2018; UNCCD, 2017; UNEP, 2014). Our fair-share environmental limits varied over time with population, while we assumed constant biophysical environmental limits of countries based on “low” potentially available cropland estimated by Eitelberg et al. (2015). The use of time-invariant national biophysical limits is a limitation of this study. Although global arable land use has remained constant overtime (Ritchie and Roser, 2013), national cropland areas are dynamic with expansion occurring in some areas via deforestation, while in other areas, the amount of arable land is contracting due to factors such as land abandonment and climate change (Doelman et al., 2018; Fritz et al., 2015). Likewise, the effects of worldwide economic lockdown due to the COVID-19 pandemic may have long-lasting impacts on agri-food trade. We can expect changes in consumption and production patterns of domestic and imported agri-food products which will alter country-level utilisation of consumption-based and production-based environmental limits for cropland in the future. Capturing the impacts of dynamic cropland changes within countries due to the COVID-19 pandemic is an important future research avenue.

While the Exiobase 3.0 MRIO database provided a detailed cropland environmental extension to capture cropland footprints, its geographical and temporal coverage is limited (Stadler et al., 2018). Other MRIO databases have a higher geographical resolution (EORA and GTAP databases) but they lack cropland extensions (Andrew and Peters, 2013; Lenzen et al., 2013). Nevertheless, our current geographical and temporal resolution provided sufficient information to downscale the global land-system change boundary and calculate country-level utilisation for cropland environmental limits. The framework developed in this study can be used to identify the commodities and products responsible for direct and indirect environmental impacts. While in-depth commodity-level analysis of cropland flows is outside the scope of this study, further research should focus on exploring the direct and indirect impacts of commodities and their contributions to environmental limit exceedances of other countries. Beyond cropland, further application of this framework can quantify the impacts on freshwater and other environmental resources and emissions, including greenhouse gases, to identify key commodities responsible for the exceedance of different planetary boundaries across countries.

5. Conclusion

We developed a framework to allocate environmental limits for agri-food consumption and production, thereby contributing towards the operationalisation of the planetary boundary framework in the context of global cropland footprints. We assessed the national-level environmental impacts of consumption and production activities in the context of environmental limits for cropland use. This can inform national monitoring of progress towards SDG 12 by allowing countries to analyse their cropland use (including embedded use through trade flows) in the context of globally defined targets, and to subsequently use this information to modify their agri-food trade practices. Countries that are exceeding their biophysical environmental limits must address their direct/indirect cropland use and negotiate their trade relationships to minimise their cropland impacts. The results can be used as a basis for countries to act as individual entities or together in groups, in order to develop policies that mitigate their global cropland impacts and minimise the risks associated with the exceedance of the land-system change planetary boundary.

6. Credit author statement

M. Abdullah Shaikh: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft. **Michalis Hadjikakou:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Brett A. Bryan:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106981.

References

Acquaye, A.A., Wiedmann, T., Feng, K., Crawford, R.H., Barrett, J., Kuylenstierna, J., Duffy, A.P., Koh, S.C., McQueen-Mason, S., 2011. Identification of 'carbon hot-spots' and quantification of GHG intensities in the biodiesel supply chain using hybrid LCA and structural path analysis. Environ. Sci. Technol. 45, 2471–2478.

Andrew, R.M., Peters, G.P., 2013. A Multi-Region Input-Output Table Based on the Global Trade Analysis Project Database (Gtap-Mrio). Econ. Syst. Res. 25, 99–121.

Behrens, P., Kiefte-de Jong, J.C., Bosker, T., Rodrigues, J.F.D., de Koning, A., Tukker, A., 2017. Evaluating the environmental impacts of dietary recommendations. Proc. Natl. Acad. Sci. 114, 13412–13417.

Bruckner, M., Fischer, G., Tramberend, S., Giljum, S., 2015. Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods. Ecol. Econ. 114, 11–21.

Chaudhary, A., Krishna, V., 2019. Country-Specific Sustainable Diets Using Optimization Algorithm. Environ. Sci. Technol. 53, 7694–7703.

Conijn, J.G., Bindraban, P.S., Schröder, J.J., Jongschaap, R.E.E., 2018. Can our global food system meet food demand within planetary boundaries? Agric. Ecosyst. Environ. 251, 244–256.

Croft, S.A., West, C.D., Green, J.M.H., 2018. Capturing the heterogeneity of sub-national production in global trade flows. J. Cleaner Prod. 203, 1106–1118.

Cuypers, D., Geerken, T., Gorissen, L., Lust, A., Peters, G., Karstensen, J., Prieler, S., Fischer, G., Hizsnyik, E., 2013. Comprehensive Analysis of the Impact of EU Consumption on Deforestation. Eur. Commission.

Dao, H., Peduzzi, P., Friot, D., 2018. National environmental limits and footprints based on the Planetary Boundaries framework: The case of Switzerland. Global Environ. Change 52, 49–57.

Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P., 2017. Increased food production and reduced water use through optimized crop distribution. Nat. Geosci. 10, 919–924.

Doelman, J.C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D.E.H.J., Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S., van Vuuren, D.P., 2018. Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. Global Environ. Change 48, 119–135.

Eitelberg, D.A., van Vliet, J., Verburg, P.H., 2015. A review of global potentially available cropland estimates and their consequences for model-based assessments. Glob. Change Biol. 21, 1236–1248.

Fang, K., Heijungs, R., De Snoo, G.R., 2015a. Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework. Ecol. Econ. 114, 218–226.

Fang, K., Heijungs, R., Duan, Z., de Snoo, G., 2015b. The Environmental Sustainability of Nations: Benchmarking the Carbon, Water and Land Footprints against Allocated Planetary Boundaries. Sustainability 7, 11285–11305.

Fritz, S., See, L., McCallum, I., You, L., Bun, A., Moltchanova, E., Duerauer, M., Albrecht, F., Schill, C., Perger, C., Havlik, P., Mosnier, A., Thornton, P., Wood-Sichra, U., Herrero, M., Becker-Reshef, I., Justice, C., Hansen, M., Gong, P., Abdel Aziz, S., Cipriani, A., Cumani, R., Cecchi, G., Conchedda, G., Ferreira, S., Gomez, A., Haffani, M., Kayitakire, F., Malanding, J., Mueller, R., Newby, T., Nonguierma, A., Olusegun, A., Ortner, S., Rajak, D.R., Rocha, J., Schepaschenko, D., Schepaschenko, M., Terekhov, A., Tiangwa, A., Vancutsem, C., Vintrou, E., Wenbin, W., van der Velde, M., Dunwoody, A., Kraxner, F., Obersteiner, M., 2015. Mapping global cropland and field size. Glob Chang Biol 21, 1980–1992.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty,

J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.
Gopalakrishnan, G., Cristina Negri, M., Snyder, S.W., 2011. A novel framework to classify marginal land for sustainable biomass feedstock production. J. Environ. Qual. 40, 1593–1600.
Green, J.M.H., Croft, S.A., Duran, A.P., Balmford, A.P., Burgess, N.D., Fick, S., Gardner, T.A., Godar, J., Suavet, C., Virah-Sawmy, M., Young, L.E., West, C.D., 2019. Linking global drivers of agricultural trade to on-the-ground impacts on biodiversity. Proceed. Natl. Acad. Sci. USA.
Häyhä, T., Lucas, P.L., van Vuuren, D.P., Cornell, S.E., Hoff, H., 2016. From Planetary Boundaries to national fair shares of the global safe operating space — How can the scales be bridged? Global Environ. Change 40, 60–72.
Heck, V., Hoff, H., Wirsenius, S., Meyer, C., Kreft, H., 2018. Land use options for staying within the Planetary Boundaries – Synergies and trade-offs between global and local sustainability goals. Global Environ. Change 49, 73–84.
Henry, R.C., Engstrom, K., Olin, S., Alexander, P., Arneth, A., Rounsevell, M.D.A., 2018. Food supply and bioenergy production within the global cropland planetary boundary. PLoS ONE 13, e0194695.
Hoekstra, A.Y., Wiedmann, T.O., 2014. Humanity's unsustainable environmental footprint. Science 344, 1114–1117.
Hoff, H., Nykvist, B., Carson, M., 2014. "Living well, within the limits of our planet"? Measuring Europe's growing external footprint. Stockholm Environment Institute, pp. 2014–2015.
Kastner, T., Erb, K.-H., Haberl, H., 2014a. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. Environ. Res. Lett. 9, 034015.
Kastner, T., Schaffartzik, A., Eisenmenger, N., Erb, K.-H., Haberl, H., Krausmann, F., 2014b. Cropland area embodied in international trade: Contradictory results from different approaches. Ecol. Econ. 104, 140–144.
Kissinger, M., Rees, W.E., 2010. An interregional ecological approach for modelling sustainability in a globalizing world—Reviewing existing approaches and emerging directions. Ecol. Model. 221, 2615–2623.
Lambin, E.F., Gibbs, H.K., Ferreira, L., Grau, R., Mayaux, P., Meyfroidt, P., Morton, D.C., Rudel, T.K., Gasparri, I., Munger, J., 2013. Estimating the world's potentially available cropland using a bottom-up approach. Global Environ. Change 23, 892–901.
Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building Eora: A Global Multi-Region Input-Output Database at High Country and Sector Resolution. Economic Systems Research 25, 20–49.
Lenzen, M., Murray, J., Sack, F., Wiedmann, T., 2007. Shared producer and consumer responsibility — Theory and practice. Ecol. Econ. 61, 27–42.
Leontief, W., 1970. Environmental Repercussions and the Economic Structure: An Input-Output Approach. Rev. Econom. Statist. 52, 262–271.
Li, M., Wiedmann, T., Hadjikakou, M., 2019. Towards meaningful consumption-based planetary boundary indicators: The phosphorus exceedance footprint. Global Environ. Change 54, 227–238.
Liu, J., Mooney, H., Hull, V., Davis, S.J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K.C., Gleick, P., Kremen, C., Li, S., 2015. Sustainability. Systems integration for global sustainability. Science 347, 1258832.
Meyer, K., Newman, P., 2018. The Planetary Accounting Framework: a novel, quota-based approach to understanding the impacts of any scale of human activity in the context of the Planetary Boundaries. Sustainable. Earth 1.
Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., De Palma, A., Ferrier, S., Hill, S.L., Hoskins, A.J., Lysenko, I., Phillips, H.R., 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353, 288–291.
Nykvist, B., Persson, A., Moberg, F., Persson, L.M., Cornell, S.E., Rockström, J., 2013. National Environmental Performance on Planetary Boundaries: A study for the Swedish Environmental Protection Agency.
O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustainability 1, 88–95.
Osei-Owusu, A.K., Kastner, T., de Ruiter, H., Thomsen, M., Caro, D., 2019. The global cropland footprint of Denmark's food supply 2000–2013. Global Environ. Change 58.
Peters, G.P., 2008. From production-based to consumption-based national emission inventories. Ecol. Econ. 65, 13–23.
Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., Rieseberg, L.H., 2018. Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. Annu. Rev. Plant Biol. 69, 789–815.
Ritchie, H., Roser, M., 2013. Land Use. Our World in Data.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J.J.n., 2009. A safe operating space for humanity. Nature 461, 472.
Rodrigues, J.F.D., Moran, D., Wood, R., Behrens, P., 2018. Uncertainty of Consumption-Based Carbon Accounts. Environ. Sci. Technol. 52, 7577–7586.
Schneider, F., Buehn, A., Montenegro, C.E. 2011. Shadow economies all over the world: New estimates for 162 countries from 1999 to 2007.
Simas, M., Pauliuk, S., Wood, R., Hertwich, E.G., Stadler, K., 2017. Correlation between production and consumption-based environmental indicators. Ecol. Ind. 76, 317–323.
Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., 2018. Options for keeping the food system within environmental limits. Nature 562, 519.
Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A., Tukker, A., 2018. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. J. Ind. Ecol.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Sustainability. Planetary boundaries: guiding human development on a changing planet. Science 347, 1259855.
Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J., 2018. Trajectories of the Earth System in the Anthropocene. Proc. Natl. Acad. Sci. 115, 8252–8259.
Suh, S., Huppes, G., 2005. Methods for Life Cycle Inventory of a product. J. Cleaner Prod. 13, 687–697.
Sun, Z., Scherer, L., Tukker, A., Behrens, P., 2019. Linking global crop and livestock consumption to local production hotspots. Global. Food Security.
Tramberend, S., Fischer, G., Bruckner, M., van Velthuizen, H., 2019. Our Common Cropland: Quantifying Global Agricultural Land Use from a Consumption Perspective. Ecol. Econ. 157, 332–341.
Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., Wood, R., 2016. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. Global Environ. Change 40, 171–181.
Turner, K., Lenzen, M., Wiedmann, T., Barrett, J., 2007. Examining the global environmental impact of regional consumption activities — Part 1: A technical note on combining input–output and ecological footprint analysis. Ecol. Econ. 62, 37–44.
UN, 2015. Transforming our World: The 2030 Agenda for Sustainable Development.
UN, 2017. World Population Prospects: The 2017 Revision. Department of Economic and Social Affairs, Population Division.
UNCCD, 2017. The Global Land Outlook, first edition. Bonn, Germany.
UNEP, 2014. UNEP 2014 Annual Report. United Nations.
Usubiaga-Liaño, A., Mace, G.M., Ekins, P., 2019. Limits to agricultural land for retaining acceptable levels of local biodiversity. Nat. Sustainability 2, 491–498.
Van Vuuren, D.P., Faber, A., 2009. Growing within limits. A report to the Global Assembly 2009 of the Club of Rome. Netherlands Environmental Assessment Agency PBL.
Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Global Environ. Change 23, 433–438.
West, P.C., Narisma, G.T., Barford, C.C., Kucharik, C.J., Foley, J.A., 2010. An alternative approach for quantifying climate regulation by ecosystems. Front. Ecol. Environ. 9, 126–133.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11, 314–321.
Wiedmann, T., Wilting, H.C., Lenzen, M., Lutter, S., Palm, V., 2011a. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. Ecol. Econ. 70, 1937–1945.
Wiedmann, T.O., Suh, S., Feng, K., Lenzen, M., Acquaye, A., Scott, K., Barrett, J.R., 2011b. Application of hybrid life cycle approaches to emerging energy technologies–the case of wind power in the UK. Environ. Sci. Technol. 45, 5900–5907.
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet 393, 447–492.
Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., Tukker, A., 2018. Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. J. Ind. Ecol. 22, 553–564.
Yu, Y., Feng, K., Hubacek, K., 2013. Tele-connecting local consumption to global land use. Global Environ. Change 23, 1178–1186.
Yu, Y., Feng, K., Hubacek, K., Sun, L., 2016. Global Implications of China's Future Food Consumption. J. Ind. Ecol. 20, 593–602.
Zhao, F.-J., Ma, Y., Zhu, Y.-G., Tang, Z., McGrath, S.P., 2014. Soil contamination in China: current status and mitigation strategies. Environ. Sci. Technol. 49, 750–759.