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A spatially explicit approach to assessing commodity-driven fertilizer use and its impact on biodiversity

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A R T I C L E I N F O

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A B S T R A C T

Global demand for food, including rising consumption of meat and dairy products, is increasing pressure on the environment and natural resources, often in locations distant from points of consumption. To identify and quantify consumer driven impacts and the components of the supply chain where sustainability interventions will be most effective, spatially explicit consumption-linked indicators that encompass environmental risks are required. Large amounts of phosphorus fertilizers are used in Brazilian soybean cultivation, which potentially cause eutrophication and impact freshwater species. We use a sub-national trade model to develop a spatially explicit approach for assessing commodity-driven phosphorus fertilizer use and its potential impact on biodiversity linked to four key consumers. The use of phosphorus for embedded consumption per capita of Brazilian soybean in China, the EU, the UK, and Sweden are estimated at municipal level and combined with metrics that influence losses of phosphorus to create a normalised relative risk index. The relative risk index is presented in geospatial visualisations to explore geographical patterns of risk to freshwater biodiversity and make the link between consumer and producer countries less obscure. The results indicate high phosphorus-linked species risk in municipalities within Mato Grosso, Rio Grande do Sul, Paraná, and Goiás. Sweden and the UK generate the highest relative risk and the geographical patterns of risk differ between the investigated consuming countries, showing that smaller countries can have relatively large impacts at a spatially explicit scale. In the Amazon biome, risk of nutrient losses and biodiversity are relatively high, creating concerns as soybean production is expanding into the area. The results and methodological approach can contribute to understanding of accountability, agency, and increased transparency for the governance of global supply chains, necessary for enabling transformations towards sustainable food systems.

1. Introduction

Per capita natural resource use has seen a remarkable increase which has been accompanied by severe effects on earth system functions (Mauser et al., 2013; Steffen et al., 2015). Europe and North America have met increased consumption demand with imports, contributing to a fourfold increase in the direct trade in materials since 1970 (UNEP, 2016). Food and water are basic needs that used to be provided locally but are now increasingly met by global trade, with a tenfold increase in food commodity trade in recent decades (Liu et al., 2013). Global food trade contributes to obscuring the effects of consumption, making environmental pollution, land degradation, biodiversity loss and resource use, and associated impacts on human health and quality of life, largely invisible to the consumers that are separated from the place of production (Ali, 2017; Steen-Olsen et al., 2012). This development is exemplified by the shift in the use of mineral phosphorus fertilizers away from Europe and North America towards Asia and South America, which is connected to the increase in imports of soybean and palm oil from the latter regions (Li et al., 2019; Nesme et al., 2016; Schoumans et al., 2015). The globalization of food supply chains thus allows wealthier countries to displace their natural resource use and associated environmental impacts.

The use of protein-rich feed, such as soybean, within livestock-production systems has increased as traditional (lower-intensity) animal husbandry - where animals are reared in grazing-based systems - is replaced with industrial agriculture (Alexandratos and Bruinsma, 2012). In 2014, 85% of the protein-rich feed imported to Europe was derived from soybean, with much of this produced in Brazil (Boerema et al.,

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2016) and Karlsson et al. (2021) estimate that between 2014 and 2016, of the total global cropland used for producing European Union livestock feed, 20% was soybean production in South America. In the past fifty years, the agricultural sector in Brazil has undergone extensive development which can be exemplified by the large increase in soybean production from 1 million tonnes in 1969, to 113 million tonnes in 2019 (Horvat et al., 2015; IBGE, 2020). This extensification of agriculture has driven deforestation that is endangering ecologically valuable habitats in the Cerrado and Amazon (Boerema et al., 2016; WWF, 2016). These deforestation and land-use changes have been a main focus for research, public policy, and multi-stakeholder partnerships during the 2000s, although the use of pesticides and fertilizers have also been pointed out as important sustainability challenges in soybean production (e.g. Ingram et al., 2018; Jia et al., 2020; Partzsch, 2020; Zortea et al., 2018).

Soybean cultivation is the main user of fertilizer in Brazil, responsible for around 35% of national fertilizer application (Horvat et al., 2015; Withers et al., 2018). Phosphorus and potassium are the main nutrients used, while nitrogen is applied in very small amounts or not at all since biological fixation provides most of the nitrogen requirement (FAO, 2004; Raucci et al., 2015). High inputs of phosphorus fertilizers are required in Brazilian agriculture due to the prevalence of iron- and aluminium-oxide rich soils, that make up approximately 50% of Brazilian croplands. These soils 'fix' phosphorus, which is a process where phosphorus is bound to the soil particles, made immobile and thereby inaccessible for plants (Roy et al., 2016). To limit further increases of pressure on natural ecosystems and deforestation, it has been proposed that degraded pastures can be converted to cropland for soybean (Sparovek et al., 2015; Strassburg et al., 2014), which would however require large use of phosphorus fertilizers to overcome nutrient deficiencies (Roy et al., 2016; Sattari et al., 2016; Withers et al., 2018). In addition, the intensification of farming procedures to increase yields on already cultivated land has further increased fertilizer use (Horvat et al., 2015; Lathuillière et al., 2014).

The case of phosphorus fertilizers in Brazilian soybean cultivation provides an opportunity to study complex global food systems where local and global actors and processes are intertwined. The high phosphorus application rates in Brazil are of global concern in relation to sustainable use and management of a finite and geopolitically vulnerable resource that is closely linked to food security (Chowdhury et al., 2017; Brownlie et al., 2022; FAO, 2022a; 2022b). The loss[1] of phosphorus from the soil to water, and the subsequent risk of freshwater eutrophication, hypoxia and toxic cyanobacterial algal blooms in water bodies (Lehmann and Schroth, 2003; Rabalais et al., 2009; Shigaki et al., 2006; Steffen et al., 2015) can have severe effects on freshwater biodiversity (Scherer and Pfister, 2015) and drinking water quality (Compton et al., 2017; Rosset et al., 2014). A large number of Brazilian freshwater ecosystems are characterised by high biodiversity and endemism (Azevedo-Santos et al., 2019; Reis et al., 2016; Schiesari et al., 2013), with several species in the region relatively sensitive and vulnerable to changes in environmental conditions (Schiesari et al., 2013).

Empirical case studies at farm and river catchment level in Brazil have resulted in diverse findings regarding the contribution of agricultural phosphorus to freshwater eutrophication. Fischer et al. (2016), who studied farms in the state of Minas Gerais, and Riskin et al. (2013a), focusing on the state of Mato Grosso, conclude that there are minor losses of phosphorus from the studied soils and no clear risk of eutrophication in nearby freshwater systems. Boitt et al. (2018), Bortolon et al. (2016) and Pellegrini et al. (2010), on the other hand, identified significant losses of phosphorus and subsequent eutrophication risks in the southern parts of Brazil. Concerns have also been raised that stocks of legacy phosphorus can be released from Brazilian soils and fluvial sediment to a larger extent than is seen at present (Sharpley, 2016) and eutrophication caused by fertilizers has been identified as a key component when assessing the sustainability of soybean production in southern Brazil (Zortea et al., 2018).

Current phosphorus emission data have large gaps (Scherer and Pfister, 2015) and are complex to collect or model because of spatial and temporal variations (Withers and Jarvie, 2008). Model deficiencies, and a lack of information about agricultural practices, make it especially difficult to estimate nutrient losses at a regional level (Fu et al., 2021); current models are lacking specific data on nutrient retention and erosion, or are based on universal data for these factors (Morelli et al., 2018; Scherer and Pfister, 2016). The LC-IMPACT project (https://lc-impact.eu/) has modelled global phosphorus emissions at a resolution of 5 arc-minutes (~50 km grid). However, the model uses a phosphorus retention rate based on US soil characteristics, not taking into account the specific properties of tropical soils, such as in Brazil, where retention rates are higher (Helmes et al., 2012). This model has been applied by Huang et al. (2017) to investigate nutrient losses and eutrophication in Chinese croplands and by Verones et al. (2017) in a study on biodiversity loss in wetlands. Scherer and Pfister (2015) have estimated phosphorus emissions globally linked to 169 crops with the help of the LC-IMPACT model and further coupled the results to Swiss food consumption, showing that Brazil is one of the countries with the highest emissions of phosphorus caused by this demand (Scherer and Pfister, 2016). Mekonnen and Hoekstra (2018) have used a different method to study global phosphorus emissions to freshwater linked to agriculture and other human activities. In efforts to link phosphorus use in countries of production to global trade and countries of consumption, Li et al. (2019) and Nesme et al. (2018, 2016) have estimated countries' phosphorus consumption embedded in international trade flows. Although these models and studies report the pressure on resources and emissions, they do not couple countries of consumption with biodiversity impacts caused by phosphorus fertilizer use in countries of production.

In this paper, we contribute to this field by exploring the possibilities of coupling embedded soybean consumption in key consumer countries with spatially explicit impacts on freshwater and biodiversity in the producing country of Brazil. China, the European Union (the EU), the UK and Sweden are investigated as consumer countries in this study as they provide important examples for consumption-based assessments due to their role in global food trade and current policy developments for transformations towards sustainable food systems. China and the EU are the two largest importers of soybean globally; China accounts for more than 60% of global soybean imports, and the EU imports comprise around 9% (Gale et al., 2019). Moreover, the EU has taken on a role of leading global transformations towards sustainable food systems and have proposed measures to tackle the region's global environmental impacts caused by consumption of imported products (European Commission, 2020, 2021; European Parliament, 2021). Sweden and the UK are selected to represent two wealthy European countries, with different population sizes, high import rates for agricultural products (Department for Environment Food and Rural Affairs, 2018; Strandberg and Persson, 2017), and both currently performing poorly on Sustainable Development Goal 12: Responsible Consumption and Production (Sachs et al., 2019). In each country, the need for consumption-based accounting of environmental impacts related to high imports have been recognised in policy and research (Cederberg et al., 2019; Croft et al., 2021b; Steinbach et al., 2018).

This paper aims to develop the methodological approaches for assessing environmental impacts of consumption at a spatially explicit scale, linking places of production with embedded consumption in a global food system, and to support the sustainable governance of global supply chains and sourcing choices. The research was guided by two questions: (1) How can a relative risk index be developed for spatially explicit impacts on freshwater biodiversity of commodity-driven use of phosphorus? (2) What spatially explicit patterns of impact can be found

[1] In this paper, phosphorus/nutrient loss is defined as; losses from soil linked to soil erosion by water, by surface runoff or water movement through soils (phosphorus bound to sediment), and leaching (as dissolved soluble phosphate) (Alewell et al., 2020; Riskin et al., 2013a; Smil, 2000).

through this relative risk index? We first present the materials and methods used to explore these questions and then the results are reported with the help of geospatial visualisations. The opportunities and challenges of the methodological approach as well as implications for policy and sustainability in supply chain governance and management are then discussed and lastly, conclusions are drawn.

2. Material and methods

2.1. Data used and summary of procedures

To investigate the spatial dimensions of biodiversity impacts associated with Brazilian soybean production, this paper utilise sub-nationally linked supply chain data provided by the IOTA model. IOTA to date has only been implemented at the subnational level for Brazilian soy but provide data for other commodities at national levels. A detailed description of the model can be found in (Croft et al., 2018, 2021a). In this study, data from the IOTA model has been coupled with phosphorus use in Brazilian soybean production, Brazilian ecological characteristics that influence nutrient losses and freshwater species distribution to create a relative risk index. The reference year 2011 is used as a baseline as this is the latest year which the sub-nationally linked supply chain data provided by the IOTA model for soybean is available (Croft et al., 2018). The methods can be readily applied to later years and other commodities as appropriate data become available. Where multiple date-stamps exist in the underlying datasets, source data has been selected as close as possible to this baseline.

Several consecutive steps have been taken to estimate a relative nutrient loss risk (L_{risk}) for Brazil based on nutrient retention, surface runoff, natural potential for erosion, and distance to surface water. L_{risk} has further been linked to phosphorus use[2] in soybean production and consumption activity for respective key consumer country or region (P_{MS}) and freshwater species richness to create a normalised relative risk index (P_{bio}). A quantification of phosphorus losses is not presented as it is not within the scope of this study (see further section 2.3). Fig. 1 summarises the different methodological stages and data utilised to render the final results. Data has been normalised on several occasions using equation (1).

$$x_{norm} = \frac{(x - x_{min})}{(x_{max} - x_{min})} \quad (1)$$

To visualise the results, data are resampled to 200 m grids, projected using SIRGAS 2000 Brazil Mercator, and presented in geospatial visualisations produced in the software ArcGIS, version 10.4.1 (Esri Inc., 2015).

2.2. Municipal phosphorus use in soybean production (P_{MS})

The FAO, 2004 report *Fertilizer use by crop in Brazil* is the only source, to our knowledge, that provides country-wide information for fertilizer use in soybean farming in Brazil, and has been used previously in several studies within the field (e.g. Hoekstra et al., 2011; Lathuillière et al., 2014; Liu et al., 2012; Lorz et al., 2013; Schipanski and Bennett, 2012). The report conveys data at regional scale, providing values for kg/ha phosphate (P_2O_5) used in crop production within the Brazilian administrative division of five regions: North, Northeast, Southeast, South, and Centre-West (IBGE, 2017; see Fig. S1 in Supporting information). Other identified sources of data on fertilizer use in soybean farming in Brazil have not been possible to implement within the scope of this study since the scale of the reported data is either at farm level or just for a single state (e.g. Pashaei Kamali et al., 2017; Riskin et al., 2013b, 2013a; Roy et al., 2016).

To align results with previous studies which estimate phosphorus resource use (e.g. Metson et al., 2020; Neset et al., 2016; Papangelou et al., 2021; Roy et al., 2016; Withers et al., 2018), data were recalculated to represent elemental phosphorus, providing *Regional phosphorus use (kg/ha)* (see Fig. 1). The recalculation was done by using a factor of 0.44 since phosphorus constitutes 44% of phosphate (IPNI, 2011).

Spatially explicit consumption data is derived from the Stockholm Environment Institute's Input Output Trade Analysis (IOTA) model (Croft et al., 2018) which allows – via the inclusion of data on soybean supply chains from the Transparency for Sustainable Economies (Trase) database (Trase, 2015) – sub-national supply chain heterogeneity to be captured within an assessment of global consumption-based drivers (Moran et al., 2020). Data from the IOTA model does not solely present direct consumption of soybean but also embedded consumption of soybean through other commodities, linked to Brazilian municipalities, which makes a more comprehensive analysis of environmental impacts and accountability possible. Data from this model have previously been used by Green et al. (2019) to investigate the impact of land-use connected to soybean trade, consumer countries and trading companies on biodiversity in the Brazilian Cerrado. Lathuillière et al. (2021) have used data from Trase to include biodiversity impacts from land-use and water footprints in Brazilian ecoregions and river basins linked to consumption

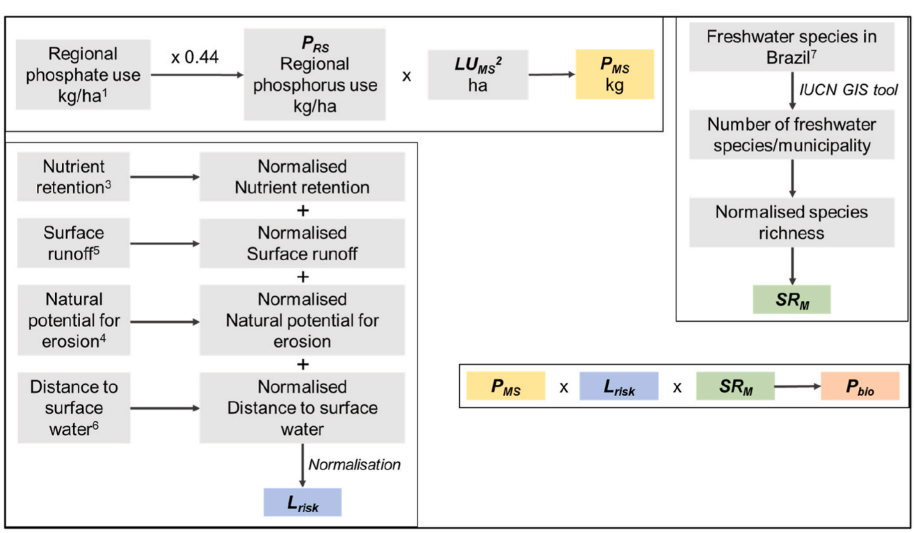

Fig. 1. Method flowchart summarising data used, and steps taken to create intermediate data layers and the final results. Each box represents a layer of data and the lines illustrate how they were combined together using the software ArcGIS, version 10.4.1 (Esri Inc., 2015). Sources: [1]FAO (2004), [2]Croft et al. (2018), [3]Fischer et al. (2008), [4]Marco da Silva et al. (2011), [5]Fekete (2002), [6]Agência Nacional de Águas (2016), [7]IUCN (2016).

of a 'commodity supply mix' based on soybean. However, the model has not been applied to date for impacts to biodiversity resulting from non-land use change-based pressures. In this paper, estimations for hectares of land required in Brazil for embedded consumption of soybean in China, Sweden, the UK, and EU26 (henceforth, EU26 will be used to indicate the results for the EU with Sweden and the UK[3] excluded) are extracted from the IOTA model. The phosphorus use related to these nation's soybean supply chains (P_{MS} in kg) is calculated by multiplying their Brazilian municipality land-use (LU_{MS} in ha) by the appropriate regional phosphorus use (P_{RS} in kg/ha; see equation (2) below).

$$P_{MS} = P_{RS} \times LU_{MS} \quad (2)$$

2.3. Nutrient loss risk (L_{risk})

Nutrient loss rates are determined by several environmental, climatic and biogeochemical factors, but are ultimately dependent on the mobility of the nutrients in the soil and water movement (Lehmann and Schroth, 2003). In recognition of the fact that soil-chemistry processes are complex and site-specific, this paper does not attempt to quantify the volume of agriculturally driven nutrient losses in Brazil. Rather, the risk assessment developed intends to provide an indication of areas in which there could be relatively higher or lower risks for nutrient loss due to natural factors. The parameters included in the compilation of the nutrient loss risk were *nutrient retention, natural potential for erosion, surface runoff*, and *distance to surface water* (see Table 1 for more details on the data used for these parameters). These were selected based on parameters used in previous studies for estimating risks of impacts of nutrient losses (Eghball and Gilley, 2001; Lorz et al., 2013; Orlikowski et al., 2011; Shigaki et al., 2006) in combination with data availability for Brazil. As this paper is performing a spatially explicit assessment, data that are based on local soil conditions are needed. Fertilizer application method, timing, type of fertilizer used (Eghball and Gilley, 2001; Shigaki et al., 2006), subsurface flow, slope, soil texture, and root zone available water capacity (Lorz et al., 2013; Orlikowski et al., 2011) are other parameters that are mentioned as influential. However, in this study they have been categorised either as anthropogenic factors, which are not possible to include at this level, or already linked to the selected parameters.

All data are normalised (0–1) before the nutrient loss risk is generated by an additive combination of the four data layers, as the original units and ranges differ. As the sources of the data layers do not provide information on the relative role of the different loss risk factors - Eghball and Gilley (2001) apply weighting but in relation to specific characteristics of three locations in the United States and Lorz et al. (2013), Orlikowski et al. (2011) and Shigaki et al. (2006) do not use weighting in their studies – each component is weighted equally in the compilation.

Table 1
Summary of data used for Nutrient loss risk.

Data	Description and processing	Scale	Source
Nutrient retention	The capacity of the soil to retain nutrients. Classified into seven categories, from low (1) to high (7) nutrient retention. This scale was inverted to match the low-to-high risk scale in the other components used.	1:5 000 000	Fischer et al. (2008)
Surface runoff	Water flow in millimetres per year. From a global dataset based on values computed from modelled runoff for the years 1950–2000 using the UNH Water Systems Analysis Group Water Balance Model.	Cell size 0.5°	Fekete (2002)
Natural potential for erosion	Based on a modification of the Universal Soil Loss Equation (USLE) excluding anthropogenic factors.	Cell size 0.008989°	Marco da Silva et al. (2011) *Obtained by personal communication*
Distance to surface water	Data were divided into three classes, 0–200 m, 200–800 m, and >800 m, according to classification suggested by (Lorz et al., 2013). The first class indicates the highest risk and was assigned the number 1. The second class was assigned 0.5 and all cells with a value over 800 m were assigned 0.	Country	Agência Nacional de Águas (2016)

2.4. Phosphorus use linked to nutrient loss risk (P_{risk}) and freshwater species (P_{bio})

The nutrient loss risk (L_{risk}) indicates the relative potential for nutrient loss. However, soybean is not cultivated everywhere, and the use of fertilizer varies by extent of soybean production and by region (see Fig. S2 in Supporting information). The estimated phosphorus use for soybean farming (Equation (1)) was therefore multiplied by the nutrient loss risk to provide a risk-adjusted measure of the use of phosphorus (P_{risk}) in different areas of Brazil in 2011 (see equation (3) below).

$$P_{risk} = L_{risk} \times P_{MS} \quad (3)$$

To investigate the risk to biodiversity in Brazil from phosphorus use in soybean production (P_{bio}), data for freshwater species (fish, molluscs, plants, odonata, shrimps, crabs, crayfish and amphibian) were obtained from IUCN (2016). Since these species are dependent on healthy freshwater, their populations can be undermined by eutrophication (Rosset et al., 2014). The number of species per municipality, hereafter titled species richness or SR_M, was calculated using an ArcGIS tool developed by IUCN (IUCN, 2017). The result was then normalised to the range 0–1. P_{risk} for China, EU26, the UK and Sweden was then multiplied by this species richness to create P_{bio} for each country/region (see equation (4) below).

$$P_{bio} = P_{risk} \times SR_M \quad (4)$$

To reflect the difference in each country's population, the results are presented per capita, calculated using population data for 2011 from the World Bank (2019). A global P_{bio} per capita was also calculated for the global embedded consumption of Brazilian soybean, to create a reference point for the investigated countries and region.

3. Results

In the results section the spatially explicit phosphorus used in Brazilian soybean farming linked to consumption activities in EU26 (the EU excluding the UK and Sweden), the UK, Sweden and China are presented. Second, nutrient loss risk (L_{risk}) and potential impact on freshwater species (P_{bio}) are visualized and third, the country-specific spatially explicit results of potential impact on freshwater species are reported.

3.1. Country-specific use of phosphorus for embedded consumption of soybean

Estimates of phosphorus use in soybean production indicate that the municipalities with the highest usage are located in Mato Grosso (MT), Mato Grosso do Sul (MS), Goiás (GO), and Bahia (BA) (see Fig. S3 in Supporting information). In *Fertilizer use by crop in Brazil* (FAO, 2004) it is reported that an average of 29 kg phosphorus were used per hectare of soybean in Brazil. In 2011, close to 24 million hectares of soybean were planted in Brazil (IBGE, 2020) which indicates that approximately 700, 000 tonnes of phosphorus were used in soybean farming.

Of the regions investigated, for the year 2011, Chinese consumption activities account for the largest total amount of phosphorus used in soybean farming in Brazil (see Table 2). Chinese per capita consumption is however only around half that of EU26 (the EU excluding the UK and Sweden), the UK or Sweden. Expressed as a ratio between the phosphorus used in Brazilian soybean farming linked to consumption activities in each of the consuming countries and the phosphorus used domestically for all agricultural production within these countries, the marked difference between the levels of dependence become evident. While China has a 1:35 ratio, the ratio for Sweden and the UK is 1:5 and for EU26 it is 1:8, indicating the high dependency of the European food system on embedded phosphorus in imported food products.

In Fig. 2, per-capita phosphorus use for China, EU26, the UK, and Sweden's consumption are compared for the major soybean producing states in Brazil, illustrating a more diverse account of the phosphorus use than described by the national per capita values in Table 2, where per-capita phosphorus use for the UK, Sweden and EU26 are close to equal. China causes lower use per capita than EU26 in all Brazilian states, and lower than the UK in all states except for Rio Grande do Sul (RS). UK consumption causes more phosphorus use per capita than EU26 in Mato Grosso (MT), Rondônia (RO), and Pará (PA), and is similar to EU26 in Goiás (GO) and Minas Gerais (MG). Phosphorus use caused by Swedish consumption is in most states slightly less than the UK numbers, with the exception of Mato Grosso do Sul (MS) where Sweden causes around three times higher per capita phosphorus use than EU26, the UK and China.

3.2. Nutrient loss risk (L_{risk}) and potential impact on freshwater species (P_{bio})

Areas of higher nutrient loss risk (L_{risk}) can be found in parts of Mato Grosso (MT), Roraima - (RR), Pará (PA), Paraná (PR), Santa Catarina (SC), Amazonas (AM), Goiás (GO), Rondônia (RO), and Rio Grande do Sul (RS) (Fig. 3c). In Goiás (GO), Paraná (PR), Rio Grande do Sul (RS), and in the central parts of Mato Grosso (MT) this elevated risk of nutrient loss coincides with a high use of phosphorus in soybean production whereas areas with high use of phosphorus in Bahia (BA) and Mato Grosso do Sul (MS) concur with lower risks of nutrient loss. Pará (PA), Roraima (RR), Amazonas (AM), Rondônia (RO), and the northern parts of Mato Grosso (MT) experience relatively high L_{risk} values whilst the use of phosphorus is relatively low. Fig. 3d shows P_{bio}, the result of combining phosphorus use for global embedded consumption of soybean, nutrient loss risk, and freshwater species richness. The results indicate "hotspots" in Mato Grosso (MT), Goiás (GO), Rio Grande do Sul (RS), and Paraná (PR) where P_{bio} values are relatively high. Fig. 3a shows that the distribution of species richness to some extent follow the expanse of developed land and high species richness often occur together with less phosphorus use. However, high species richness can

Table 2
Total tonnes and kg/capita of phosphorus (P) used in Brazilian soybean farming linked to consumption activities in respective country/region and tonnes of phosphorus used in domestic agriculture in respective country/region, in 2011. Estimated from Croft et al. (2018)[1], FAO (2019,[21] 2004[32]), and The World Bank (2019)[4].

Country/ region	P used in Brazilian soybean farming (tonnes)[1, 3]	P kg/ capita[1, 3, 4]	P used in domestic agriculture (tonnes)[2]	Ratio – P used in Brazilian soybean farming: P used in domestic agriculture
China	173,711	0.13	6,074,391	1:35
EU26	121,653	0.24	981,811	1:8
UK	15,262	0.24	82,720	1:5
Sweden	2223	0.28	10,690	1:5
Global	670,836	0.10	19,712,971	1:29

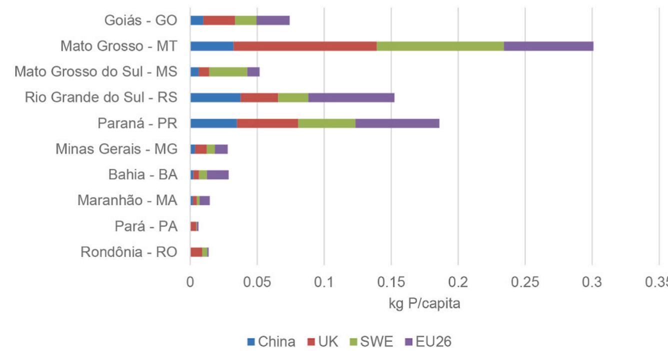

Fig. 2. Phosphorus use (kg) in the major soybean producing states of Brazil embedded in per capita consumption in China, EU26, the UK and Sweden in 2011. Estimated from FAO (2004), Croft et al. (2018) and The World Bank (2019).

also coincide with relatively high risk of nutrient loss. The soybean producing areas of the Amazon biome (states of Amazonas (AM), Acre (AC), Roraima (RR), Rondônia (RO), and Pará (PA)) have high freshwater biodiversity and risk of nutrient loss, nevertheless P_{bio} values are still relatively low due to the lower use of phosphorus per hectare and less soybean production in the region. The eastern parts of Goiás (GO) display a deviant situation where medium levels of species richness occur together with high use of phosphorus and slightly above medium L_{risk} values, creating an area of elevated risk.

3.3. Country-specific potential impact on freshwater species

P_{bio} values per capita were calculated for China, EU26, the UK, and Sweden, and indicates the potential geospatial phosphorus-linked risk imposed on Brazilian freshwater ecosystems linked to these countries' embedded soybean consumption.

In Fig. 4, P_{bio} values are displayed for each country as well as for global consumption. As the scales shown in the legend of each map are aligned, it is possible to compare the relative risk of impact between the countries and regions. The UK has the highest risk of impact (highest value of 10.08) with Sweden in second place (highest value of 9.03), which are both somewhat higher than the values for EU26 (highest value of 6.97) and China (highest value of 4.09).

The southeast area of Rondônia (RO) emerges as a potential high impact area from a UK (Fig. 4d) and Swedish (Fig. 4e) per capita consumption perspective. For Brazilian soybean production as a whole (Fig. 4a), as well as for EU26 (Fig. 4c) and China (Fig. 4b), this area has a relatively low P_{bio} value. Similarly, in the states of Mato Grosso (MT) and Goiás (GO), EU26, the UK and Sweden have a slightly higher potential impact. The most northern municipalities of Pará (PA) stand out as locations where the UK has a higher potential impact than any other country or region investigated, due to a higher embedded consumption of soybean from these particular municipalities. Rio Grande do Sul (RS) and Paraná (PR) in the south are two states with very intensive soybean production and a high risk of impact on freshwater species from total global embedded consumption of soybean (Fig. 3b, not per capita). However, from a per capita perspective, the UK and Sweden appear to impose a relatively low potential risk in these states. In the states of Maranhão (MA), Tocantins (TO), Piauí (PI), and Bahia (BA) (the Matopiba region) the P_{bio} values are low for all countries as well as globally despite relatively high use of phosphorus fertilizers, especially in the northwest of Bahia (BA) (see Fig. S3 in Supporting information). The low P_{bio} value here is caused by a lower risk of nutrient loss and less species richness than in other areas of Brazil.

The results display variations over the soybean producing landscape in Brazil. Since the index is based on high resolution data on conditions of Brazilian soils and ecosystems, phosphorus use, and density of

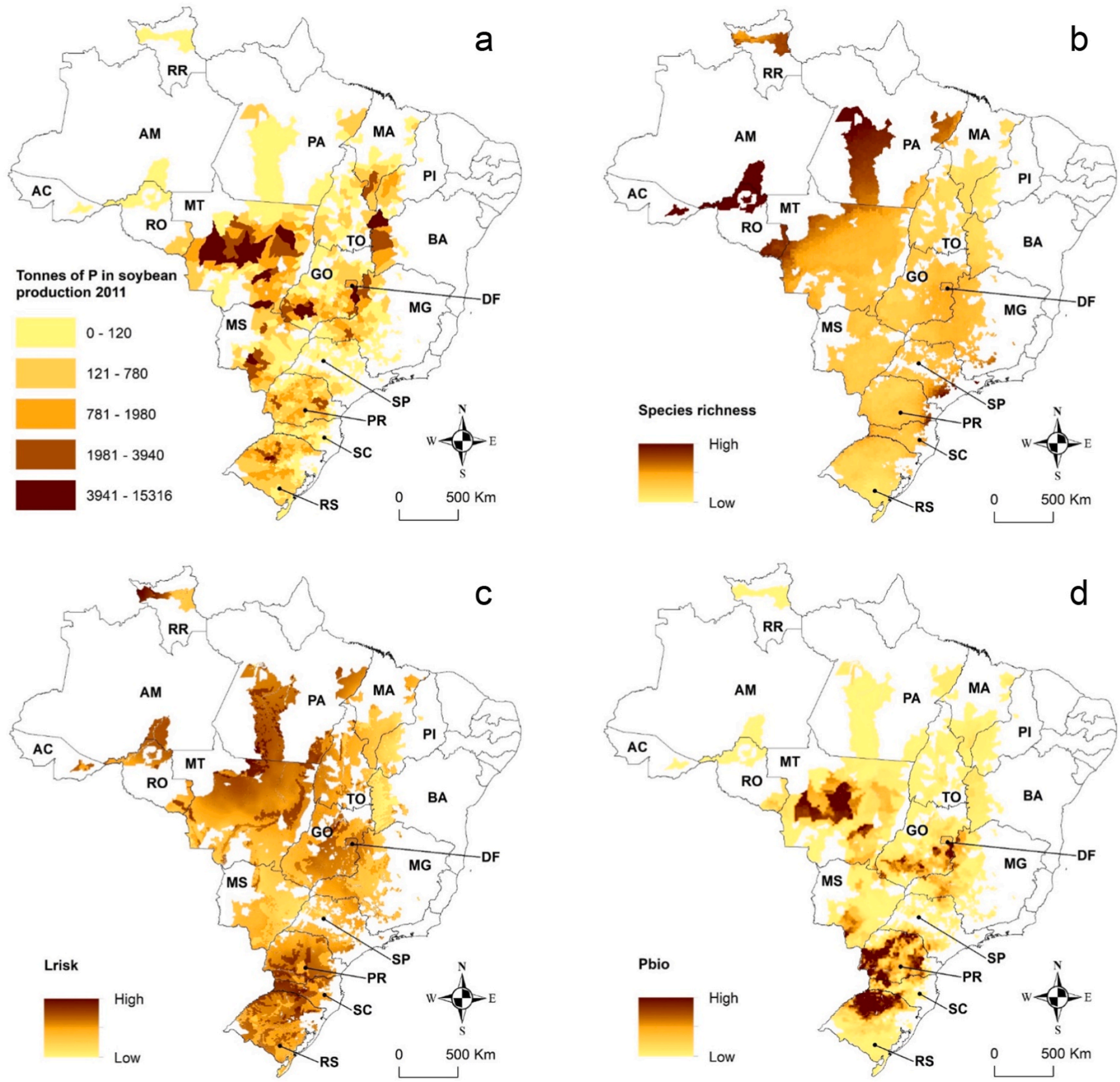

Fig. 3. a) Tonnes of phosphorus fertilizers used in Brazilian soybean production in 2011, per municipality. b) Number of freshwater species in soy producing areas. c) Relative risk of nutrient loss in Brazil, L_{risk}. Darker colours denote higher risk of nutrient loss. d) Relative risk of nutrient loss combined with phosphorus use for global embedded consumption of soybean and freshwater species, P_{bio}. Figure b, c and d are displayed at a resolution of 200 m. Darker colours denote higher risk imposed on freshwater species. Non-soybean producing municipalities are excluded from the maps. Abbreviations of Brazilian states visible in the maps: AC = Acre, AM = Amazonas, BA = Bahia, DF = Distrito Federal, GO = Goiás, MA = Maranhão, MT = Mato Grosso, MS = Mato Grosso do Sul, MG = Minas Gerais, PA = Pará, PR = Paraná, PI = Piauí, RS = Rio Grande do Sul, RO = Rondônia, RR = Roraima, SC = Santa Catarina, SP = São Paulo, and TO = Tocantins.

freshwater species, the spatially explicit approach allows the exploration of differences between adjacent areas (e.g. two neighbouring municipalities), and even within municipalities.

4. Discussion

Soybean production in Brazil is associated with several environmental and resource use challenges as well as complex global supply chains encompassing global trading companies and remote consumer countries (e.g. Green et al., 2019; Jia et al., 2020; Lathuillière et al., 2014; Zu Ermgassen et al., 2020). This paper explores the potential for linking phosphorus fertilizer use in Brazilian soybean production, and associated environmental conditions, to a producer-to-consumer supply chain model, allowing for an integrated analysis of pressure on resources and risk of biodiversity impacts related to national consumption sourcing patterns.

4.1. The importance of scale and system perspective when assessing environmental impacts in global food systems

The UK, Sweden, and EU26 cause considerably higher per capita phosphorus use in Brazil than China and global consumption (see Table 2). These results correspond with other studies (Li et al., 2019; Nesme et al., 2016; Schoumans et al., 2015) that show that the use of phosphorus in European agriculture has decreased in recent decades while the embedded consumption of phosphorus through imported commodities has increased. Sweden has been reported as successfully reducing the use of phosphorus in domestic agriculture and thereby the

[2] The term ‘phosphorus use’ is used throughout the paper, following the terminology of FAO (2004), which refers to the use of phosphorus fertilizers (recalculated to elemental phosphorus) in soybean production.

[3] The UK was still a member of the EU in 2011, the baseline year of this study.

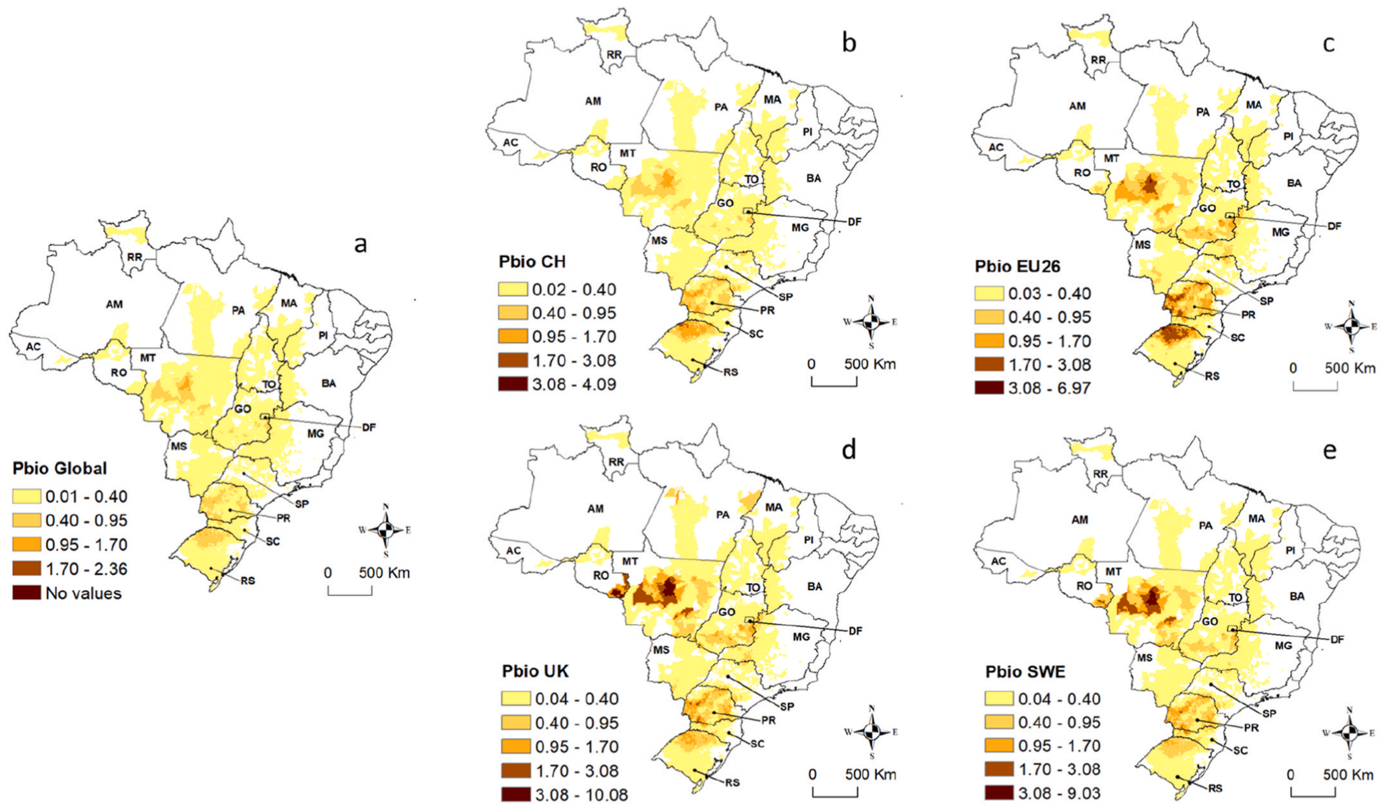

Fig. 4. P_{bio} per capita for a) Global b) China c) EU26 d) UK and e) Sweden. Darker colours denote higher P_{bio} per capita and thereby higher risk imposed on freshwater species. Non-soybean producing municipalities are excluded from the maps. Abbreviations of Brazilian states visible in the maps: AC = Acre, AM = Amazonas, BA = Bahia, DF = Distrito Federal, GO = Goiás, MA = Maranhão, MT = Mato Grosso, MS = Mato Grosso do Sul, MG = Minas Gerais, PA = Pará, PR = Paraná, PI = Piauí, RS = Rio Grande do Sul, RO = Rondônia, RR = Roraima, SC = Santa Catarina, SP = São Paulo, and TO = Tocantins. The scales are unitless since they are the results of a combination of normalised data for nutrient loss risk and species richness, and non-normalised data for embedded soybean consumption and phosphorus fertilizer use.

associated biodiversity impacts in the heavily anthropogenically affected Baltic Sea (Hellsten et al., 2019). The use of the finite natural resource phosphorus in Brazilian soybean production destined for European consumption is an example of how the UK and Sweden have moved their natural resource use across the world and is an example of spill over effects in telecoupled food systems (Dou et al., 2018; Eakin et al., 2017; Liu et al., 2013, 2018; Newig et al., 2020). These countries are part of the development of large-scale agriculture and globalised agricultural trade that have created a non-circular displacement of phosphorus from phosphate rock deposits to the soybean fields of Brazil. This displacement of resource use and environmental impact subsequently raises the need to address the accountability of consuming countries (Kramarz and Park, 2016, 2017; Moser and Leipold, 2021; Schilling-Vacaflor and Lenschow, 2021).

The results point to the importance of acknowledging consuming countries sourcing patterns and upstream supply chains, in this study exemplified by the UK, Sweden and the remaining EU countries, indicating that countries in the same region of consumption and trade bloc can display different consumption patterns (Croft et al., 2018) and associated environmental pressures and impacts. Compared to China and EU26, in total numbers, the UK and Sweden might not be significant players in soybean trade due to their relatively small populations, but the results of this study indicate that these countries have the highest P_{bio} per capita and hence, at a municipal level in Brazil, have disproportionately large impacts. Embedded consumption and trade in conjunction with subnational production and fine scale environmental conditions is critical to capturing these differences in distributions of risk. Rondônia (RO) is a state where this is highly evident, as well as in the state of Pará (PA) for the UK. These states are located in the ecologically important Amazon biome and have relatively low total production of soybean and use of phosphorus. However, the risk of nutrient loss, as well as the number of species, are relatively high compared to the rest of Brazil. Further agricultural development in the area could create higher phosphorus losses and biodiversity impacts, especially in the initial stage of cropland development when the application of phosphorus fertilizers can be very high. Withers et al. (2018) have reported application rates of 26–122 kg phosphorus/ha in land conversions in the Cerrado, which is significantly higher compared to the rate of 16 kg phosphorus/ha (FAO, 2004) used in this paper for the region.

Heterogeneity in consumption patterns, production and resource use intensity, soil properties, surface run off, and species richness, present a diverse landscape of challenges to transformations towards sustainable food systems. While phosphorus use is particularly intense in the states of Bahia (BA), Mato Grosso (MT), Goiás (GO), and Mato Grosso do Sul (MS), the environmental impacts and risk to biodiversity cannot be assessed without spatially explicit information on the ecological conditions. This becomes evident with respect to the use of phosphorus combined with the risk of nutrient loss and species richness in Bahia (BA), Mato Grosso (MT), Paraná (PR), and Rio Grande do Sul (RS). These states exemplify a situation where the use of phosphorus is high while the risk of impact on freshwater species is low due to a low risk of nutrient loss and a low number of species.

The results discussed here exemplify the need for an analysis that can direct actions for more sustainable sourcing of agricultural products. Without spatially explicit knowledge there is a risk that the main focus of supply chain management and governance is directed towards top producing areas or areas with biodiversity hotspots in a general effort to tackle sustainability. Areas with lower production intensity or land use change could hence be overlooked despite a higher use of phosphorus and/or higher risk of nutrient loss. Moreover, the assessment of phosphorus use in soybean cultivation in Brazil, and the associated potential impact on freshwater biodiversity, could be combined with other assessments of natural resource use and environmental impacts to guide public and private sector decision making. An integrated sustainability evaluation is critical to identify trade-offs generated by the complex soybean production and consumption systems, which can be exemplified with the Matopiba region in the north-eastern part of the Cerrado. In this paper, the risk imposed by fertilizer use in this area is assessed as relatively low since L_{risk} (Fig. 3c), species richness (Fig. 3a) and phosphorus use (Table S2) are all relatively low. This indicates that the Matopiba region would be the most favourable area to source soybean from. However, other studies point to high levels of deforestation (Zu Ermgassen et al., 2020), greenhouse gas emissions (Escobar et al., 2020), and severe threats to biodiversity from land use change (Green et al., 2019) in the same region, highlighting the complexity that need to be addressed by environmental impact assessments.

For the European region, that has very limited mining of phosphate rock (Ott and Rechberger, 2012; Schoumans et al., 2015; van Dijk et al., 2016), the import of Brazilian soybean creates an invisible secondary dependence on externally sourced phosphorus. In addition, the concentrated production and trading patterns of soybean has rendered it a geopolitically exposed commodity (He et al., 2019; Oliveira, 2016; Tu et al., 2020; Wu et al., 2019). These resource dependencies and geopolitical implications could create barriers to changing sourcing locations in efforts to reduce environmental impacts, and exemplify why a systems-level perspective is important, incorporating a broad spectrum of stakeholders and environmental, political, and social processes. Using the approach of this study, which mainly addresses governance actors and trade operators, sourcing locations that require less phosphorus for a country's consumption and generate less risks to ecosystems can be identified. Moreover, the approach can support the development of measures in transnational governance to ensure accountability in global supply chains (Moser and Leipold, 2021; Schilling-Vacaflor and Lenschow, 2021).

4.2. Challenges in spatially explicit assessments of environmental impacts in global food systems

This paper contributes to the development of more complex assessments of environmental impacts of consumption, complementing earlier studies in the field (Li et al., 2019; Mekonnen et al., 2016; Mekonnen and Hoekstra, 2018; Metson et al., 2012, 2016; Nesme et al., 2016, 2018; Scherer and Pfister, 2016). Moran et al. (2016) point out several limitations that must be dealt with in assessments of biodiversity threats in MRIO analysis, such as spatial and economic sectoral detail and difficulties in linking industries with the impacts they are causing. This study suggests one approach to this challenge, although quality of - and access to - data create uncertainties and challenges. Environmental impacts and resource use are not determined just by jurisdictional boundaries, such as municipalities, but by geographical and ecological conditions, farming practices, and decisions by individuals and organisations. Fertilizer application method, timing, and type of fertilizer used are important factors for nutrient losses (Lorz et al., 2013; Orlikowski et al., 2011) but were not possible to include in this work. For example, while manure is an important source of phosphorus, it is difficult to study due to lack of data, especially concerning spatial distribution (FAO, 2004; Withers et al., 2018). Limitations in access to data mean that each factor was weighted equally in the assessment, as has been done in previous studies (Lorz et al., 2013; Orlikowski et al., 2011; Shigaki et al., 2006). To understand to what extent the different factors influence phosphorus losses, results from site specific field studies might be needed which points toward the challenges of spatially-relevant scales in environmental impacts assessments. An assessment that applies a national level approach can be useful in certain contexts as data can be more readily available but will require simplifications of ecological processes and trade relationships. Which approach that is the most fruitful depends on what the assessment is to be used for and by whom.

Data for soybean production represents the year 2011 and since then land cultivated with soybean in Brazil has expanded, especially in the Amazon, and it is mostly conversions of pastures that have contributed to the developments between 2000 and 2019 (Song et al., 2021). As Sattari et al. (2016) describe, pastures are often nutrient deficient due to losses through overgrazing, manure removal and soil erosion, and require large inputs of fertilizer, which indicates that the soybean expansion could have influenced fertilization patterns. Moreover, since the Amazon has been a main location for recent expansion, and there is generally a higher degree of biodiversity in the Amazon region, the potential impacts on freshwater species in Brazil today might be even more significant than displayed in this paper. The study does not include all species that could potentially be indirectly affected by phosphorus losses, such as invertebrates and terrestrial species dependent on healthy freshwater ecosystems, and the method does not take into account differences in eutrophication sensitivity among species. Although greater data availability and alignment with established environmental assessment methodologies, such as life cycle impact assessments, are needed to facilitate a deeper understanding of resource use and environmental impacts related to food consumption and agricultural production, this paper can contribute to multi-facetted perspectives on complex interconnections in global food systems and shortcomings of established methodologies. These perspectives are important for management and governance of global food supply chains, at the global as well as local level, and highlight the accountability of both producer and consumer countries.

4.3. Policy implications

Several public and private initiatives have been launched focusing on deforestation in Brazil and the Amazon in relation to soybean and other agricultural products, e.g. *Brazilian Forest Code* and *Amazon Soy Moratorium*, or a broad set of environmental and social issues, e.g. *Round Table on Responsible Soy Association*, *ProTerra*, and *Soja Plus* (Jia et al., 2020) (see The Sustainable Trade Initiative (2020) for more examples). *The Swedish Soy Dialogue* was created in 2014 and *The UK Roundtable on Sustainable Soya* in 2018 to promote a more responsible sourcing of soybean in these two countries (Axfoundation, n.d.; Efeca, n.d.). At the European level, the *Amsterdam Declarations Partnership* is addressing the "import" of deforestation through agricultural trade, with soybean as one commodity in focus (Amsterdam Declarations Partnership, 2018). In China there is work in progress since 2015 with the *China-South America Sustainable Soy Trade Platform* and *Responsible Soy Sourcing Guidelines* (Solidaridad, 2018). In November 2021 the European Commission launched a proposal for a regulation that will establish mandatory due diligence rules for actors placing commodities linked to deforestation, such as soybean, beef, cocoa, coffee, palm oil, and wood, on the EU market (European Commission, 2021). While this development is important, the initiatives are mainly focusing on deforestation and no other threats towards biodiversity, and there is a risk that they despite their intentions might become drivers of land conversions. Converting degraded pastures to cropland has become a practice to increase agricultural productivity without causing deforestation (Song et al., 2021; Sparovek et al., 2015; Strassburg et al., 2014). If this would become a strategy to meet the demands of an EU regulation tackling deforestation, there could potentially be a trade-off effect of higher application rates of phosphorus fertilizers (Sparovek et al., 2015; Strassburg et al., 2014).

Since freshwater species are particularly sensitive to water pollution (Schiesari et al., 2013), its causes and effects are especially important for a profound understanding of threats towards biodiversity. Several agreements and directives within the EU policy framework aim to protect freshwater systems from eutrophication (Ibisch et al., 2016), but do not take the fertilizer use or eutrophication that are caused by European consumption outside the jurisdictional borders of the European union into account. Ahlström and Cornell (2018) conclude that regional governance of phosphorus use and emissions works well in some parts of the world, but that international regimes display gaps in governance at the global level. Not acknowledging the global aspects of European resource use and environmental impacts (Li et al., 2019; Nesme et al., 2016; Schoumans et al., 2015) could lead to a reduction of impacts within Europe via increased imports and relocation of production activities outside of Europe. The *Farm to Fork strategy*, presented in 2020 as a part of the *EU Green Deal*, outlines the goal that the use of fertilizer should be reduced by 20% and nutrient losses by 50% by 2030 (European Commission, 2020). While the strategy does not specify how the externalisation of phosphorus use and associated environmental impacts should be dealt with, it states a general ambition to avoid externalisation of unsustainable practices by creating policies and trade agreements that contribute to a raise in sustainability standards globally (European Commission, 2020). A similar ambition is described by the Swedish government in the *National Food Strategy for Sweden* (Ministry of Enterprise and Innovation, 2017).

The relationship between place of production and consumption is addressed in *Sustainable Development Goal number 12: Responsible consumption and production* of the 2030 Agenda (UN, 2015). It is emphasised that the major consumers must take responsibility for the impacts they are causing globally, often in low-income countries that might have less financial and structural resources to mitigate and adapt. The results of this study point to the value of developing and applying approaches that link global as well as local levels, integrating spatially explicit environmental assessments with global trade patterns and supply chains of specific countries. There is a need for further investigations and discussions on how these assessments can support allocating responsibilities and creating agency within the global food system.

5. Conclusions

Developing methodological approaches to support assessments and policy related to sustainable production and consumption of food and resources is essential. The global food system is complex, and local and global actors are indirectly linked, which obscures the environmental impacts along supply chains and presents a significant challenge to food system governance. This paper presents geospatial visualisations of a spatially explicit risk index, enabling the exploration of potential risk of impact on freshwater species in Brazil, related to the use of phosphorus fertilizers linked to the embedded consumption of soybean of EU26, Sweden, the UK and China. The results point towards the multifaceted aspects of environmental impacts assessments and geographical scales. Even though China is a large consumer of Brazilian soy, per capita it has lower risk of impact than EU26. The UK and Sweden display different patterns and levels of risk impacts than EU26 and, even though it is a relatively small country, Sweden displays significant relative impacts in specific municipalities. These kinds of assessments are therefore important in processes of identifying major actors in global supply chains and to enable transformations towards sustainable food systems, but also to attribute responsibility and accountability for environmental impacts. This study makes a conceptual contribution toward the current policy developments in the EU, the UK, and Sweden, which are increasingly focusing on consumption-based accounting of environmental impacts and measures to regulate impacts of global trade. Further integration of studies on biodiversity, water use, deforestation, pesticides, geopolitics, and impacts on local and indigenous communities will strengthen a system perspective on sustainability of global food supply chains. The results and methodological approach can contribute to dialogues on responsibility, accountability, and transparency in the governance of global supply chains, necessary for enabling transformations towards sustainable food systems.

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CRediT authorship contribution statement

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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

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