

Beyond deforestation: spatial heterogeneity and supply-chain drivers of terrestrial and aquatic biodiversity footprints of Brazil's soy

Nelson K. Sinisterra-Solís

nelsiso@upv.edu.es

Universitat Politècnica de València

Neus Sanjuán

Universitat Politècnica de València

Neus Escobar

Basque Centre for Climate Change

Article

Keywords:

Posted Date: October 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10949373/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Decoupling global agricultural trade from biodiversity loss remains critical for international environmental governance. We conducted a spatially explicit life-cycle assessment of 103,310 Brazilian soy supply chains in 2004–2022, covering domestic consumption and exports to estimate terrestrial (TBL) and aquatic (ABL) biodiversity footprints. The soy market caused a TBL of 0.123 PDF·yr and an ABL of 0.601 PDF·yr. China, the EU, and Brazil's domestic consumption accounted for most of the impacts (80% ABL; 84% TBL). While TBL decreased, due to reduced deforestation in EU-bound trade and China's shift toward less sensitive biomes, ABL has steadily worsened due to synthetic fertiliser use. The framework improves transparency by attributing biodiversity loss to trade routes, supply chain stages, and traders. Our findings suggest that biodiversity governance should account for drivers beyond deforestation and consider spatial heterogeneity in agricultural production and trade, as well as the sensitivity of associated ecosystems, to achieve clean supply chains.

Introduction

Biodiversity loss stands as an urgent global environmental concern^{1,2}. Habitat loss due to land and sea use change is the main direct driver of recent biodiversity loss worldwide, followed by direct exploitation of natural habitats³, while the influence of other drivers, such as climate change and pollution, is expected to increase progressively^{4,5}. Biodiversity loss influences climate change by weakening ecosystems^{6,7}, while climate change alters species distributions and ecosystem functionality globally⁸. This feedback effect emphasises the need for an integrated approach to address these interconnected phenomena⁹. As a land- and resource-intensive activity, agricultural production contributes significantly to both biodiversity loss and climate change, whether through the direct land occupation (LU) and transformation (LUC)¹⁰ or through pollution¹¹.

International trade in agricultural commodities also drives LUC and deforestation, leading to biodiversity loss^{12,13}, particularly with products such as cocoa, oil palm, and soy, produced in tropical regions and exported worldwide^{14,15}. In response, many zero-deforestation commitments now adopt market-based, supply-chain approaches to enforce environmental governance and combat deforestation. The Amazon Soy Moratorium (ASM) is an example of a successful voluntary initiative in Brazil, though it has recently faced political and industry pressure¹⁶. Effective policies require clear targets, broad market coverage, robust monitoring, enforcement mechanisms, transparency, and alignment with public regulation^{17,18}. In the European Union (EU), the EU Deforestation Regulation (EUDR) mandates companies to trace supply chains and assess embodied deforestation impacts, establishing legally binding due diligence obligations and penalties for non-compliance¹⁹.

Monitoring supply chains becomes key to preventing the impacts of deforestation-risk commodities and assessing the effectiveness of such policies. Environmental footprint analysis provides a systematic framework for measuring the impacts embodied in consumption and trade, which can then be attributed

to both producers and consumers, depending on the perspective²⁰. However, assessing the biodiversity footprint of commodities such as Brazilian soy faces several challenges. The first is selecting quantitative indicators that capture biodiversity impacts at the production site^{20,21}. The most common indicators reflect the loss of terrestrial species richness at the ecoregion level, linked to both LU and LUC through habitat loss and degradation,^{22,23}. This is usually done using the Countryside Species-Area Relationship (SAR) models²⁴, where species decline depends on their affinity for converted versus original habitats, and biodiversity gains occur only if land use is reversed to another LU with higher affinity. Other indicators include the Biodiversity Intactness Index (BII), which integrates richness and abundance aspects based on PREDICTS²⁵; or the Mean Species Abundance (MSA) metric for biodiversity intactness based on the GLOBIO model²⁶, considering multiple environmental pressures. The endpoint indicator Potentially Disappeared Fraction of species over time (PDF-yr) measures biodiversity loss in aquatic and terrestrial systems as the share of species lost over time due to land and water use and pollution (e.g., eutrophication, acidification, climate change, etc). It is based on regionalised characterisation factors (CFs) from LC IMPACT²⁷, a life cycle impact assessment (LCIA) method used in LCA to capture supply-chain impacts beyond LU-LUC.

The aforementioned methods aim to provide spatially-explicit metrics, either at the grid-cell or site-specific (PREDICTS, GLOBIO) or at the ecoregion level (LC IMPACT). However, they have limited ability to capture the temporal ecological dynamics that determine biodiversity. GLOBIO measures biodiversity impacts in discrete time steps, while PREDICTS measures biodiversity BII as a steady-state response to a pressure. The characterisation factors (CFs) used in life cycle assessment (LCA) are normally based on long-term average conditions and represent steady-state impacts, often as potential damage. Although many LCA studies use these CFs for product-based assessments, they typically offer low spatial and temporal resolution, leading to simplified supply chain representations^{28,29}. While scientific advancements in CFs aim to integrate high-resolution land-use and intensity data or to expand the taxa covered, the complexity and variability of LUC and trade dynamics are often overlooked. As shown by Escobar et al.³⁰, differences in municipal-level LUC, crop management, and domestic transport routes lead to significant variability in the carbon intensity of Brazilian soy exports depending on the specific supply chain. This can translate into substantial differences in biodiversity impacts across Brazilian biomes as well as in biodiversity footprints across importing countries.

The present work develops a spatially-explicit LCA to assess the aquatic and terrestrial biodiversity footprints of the entire Brazilian soy market from 2004 to 2022, capturing nationwide variation in LUC and crop management practices, domestic transport logistics, industrial processing, and international shipping by combining detailed trade data, land use maps, and agricultural statistics. The life cycle includes impacts from LUC prior to the crop establishment through the stage at which soybeans and derivatives (cake, oil) enter the corresponding industry as intermediate inputs, whether in importing countries or in Brazil, excluding downstream processes up to final consumption, as well as potential re-exports. The LCA traces 103,310 supply chains, defined as combinations of 2,577 producing municipalities, 47 export ports, and 149 destination countries (see Methods). Biodiversity footprints are

estimated as PDF·yr for the period 2004–2022 and per year, at the municipal, state, regional, and national levels, and for the traders involved. By integrating consumption and trade data with PDF indicators, this framework improves transparency by attributing biodiversity loss to trade routes, supply chain stages, and ultimately the actors involved.

Results

The biodiversity footprints of the Brazilian soy market are determined by both total traded volumes and the impact intensity (i.e., impact per amount of commodity) of the underlying supply chains. The results are expressed in soybean equivalents (soy-eq), or the flow of raw soybeans embodied in the derivatives ultimately consumed (beans, oil, and cake), allowing comparison of biodiversity-loss intensities across commodities while avoiding double-counting. The results are reported as median values and the 2.5th and 97.5th percentiles (in brackets), based on the uncertainty analysis described in Methods (Dataset S1 in Zenodo³¹).

Evolution in market structure and biodiversity footprints

The Brazilian soy market reached 1,524.5 Mt, expanding by 144% from 2004 to 2022, or 5.5% per year (Fig. 1a). The number of soybean-producing municipalities increased from 1586 to 2283, and that of importing countries from 72 to 83. Most soy is traded as beans, up to 72.29% in 2018 (Fig. 1a), with differences between destinations (Fig. 2). China imported mostly beans throughout the period (96.46%); Brazil consumed mostly oil (60.11%) and cake (34.99%), while beans and cake dominated the EU, and the remaining markets. The entire Brazilian soy market generated a potential terrestrial biodiversity loss (TBL) of $1.23 \cdot 10^{-1}$ PDF·yr [$9.82 \cdot 10^{-2}$; $1.45 \cdot 10^{-1}$] and an aquatic biodiversity loss (ABL) of $6.01 \cdot 10^{-1}$ PDF·yr [$5.12 \cdot 10^{-1}$; 1.17]. Aligned with market growth, ABL increased by 146%, from $1.83 \cdot 10^{-2}$ PDF·yr [$1.55 \cdot 10^{-2}$; $3.99 \cdot 10^{-2}$] in 2004 to $4.50 \cdot 10^{-2}$ PDF·yr [$3.9 \cdot 10^{-2}$; $7.5 \cdot 10^{-2}$] in 2022 (Fig. 1b). TBL is more variable due to underlying LUC, showing a 23% decline between 2004 and 2022, with peaks in 2005, 2015, and 2018, at around $9.43 \cdot 10^{-3}$ PDF·yr [$6.99 \cdot 10^{-3}$; $1.14 \cdot 10^{-2}$] (Fig. 1c).

Brazilian soy trade was concentrated among a few nodes throughout the supply chain (Fig. 2). 79% of total trade volume corresponded to five of the 23 producing states: Mato Grosso (28%), Paraná (17%), Rio Grande do Sul (14%), Goiás (11%), and Mato Grosso do Sul (8%) (Video S1). Mato Grosso and Goiás exported mainly through the Santos port; whereas Paraná and Mato Grosso do Sul exported via the Paranaguá port; and Rio Grande do Sul via the port of Rio Grande. These five states accounted for 79.7% of total ABL (Figs. 3b and 5d) and 46% of total TBL (Figs. 3a and 5a); ABL is, therefore, more correlated with traded volumes than TBL. Roraima shows the largest TBL footprint among states (21% of the total), despite its negligible market share (0.1%). At the municipal level, nearly half of the total TBL (45%; $5.38 \cdot 10^{-2}$ PDF·yr) was concentrated in just 1% of producing municipalities, notably Alto Alegre (13%), Bonfim (4.36%) and Cantá (2.74%) in Roraima, and Sorriso (2.12%) in Mato Grosso (Fig. 4a).

China (36.1%) and the EU (18.1%) were the main international destinations of soy commodities (Fig. 2). Together with Brazil's domestic market (26.4%), they represented 81% of total trade and were associated with 80% of ABL and 84% of TBL (Figs. 3 and 6). Over time, both traded volumes and ABL increased consistently by more than 100% in China, Brazil, and the rest of the world; whereas TBL is less correlated with market volume. In contrast, the EU showed declining trends in imported soy volumes and in embodied ABL, and especially TBL, between 2005 and 2008.

Drivers of biodiversity loss intensities

TBL exhibited marked spatial and temporal heterogeneity, due to variations in its impact intensity (iTBL) (Figs. 4b, 5a, 5b). The highest iTBLs were found in the North and North-East, particularly in Maranhão, Tocantins, Piauí, and Bahia (MATOPIBA), highlighting biodiversity loss in natural ecosystems and rainforests beyond the Legal Amazon. Yet, the highest intensity was found in Roraima, indicating natural habitat loss in the Amazon biome, despite the ASM. Lower iTBLs reflect a smaller contribution of land transformation relative to other supply chain stages (Fig. 5a). This is observed in Southern states (Rio Grande do Sul and Santa Catarina), where most LUC occurred in earlier decades, and CFs are lower than in the Amazon. Across states, the relative importance of LUC declined, while the contributions of land occupation, farming, and domestic transport increased; except for Roraima, where habitat transformation consistently accounted for $\sim 99\%$ of iTBL (Video S4). As a result, total iTBL decreased from $1.17 \cdot 10^{-10}$ PDF·yr/t soy-Eq. [$9.29 \cdot 10^{-11}$; $1.36 \cdot 10^{-10}$] in 2004 to $3.69 \cdot 10^{-11}$ PDF·yr/t [$3.18 \cdot 10^{-11}$; $4.55 \cdot 10^{-11}$] in 2022 (Fig. 1e). Negative intensities should be interpreted as a reduction in potential species loss (avoided impact) rather than as biodiversity restoration or species recovery, primarily driven by net positive changes in soil organic carbon and above-ground biomass. This is observed in 192 municipalities, mainly in the states of São Paulo (57.3%) and Minas Gerais (13.0%), linked to the Cerrado and Atlantic Forest biomes; as well as in municipalities of Paraná (16.7%), linked to the Pampa biome (Video S3).

The ABL intensity (ABLi) across the period was $3.71 \cdot 10^{-10}$ PDF·yr/t [$3.15 \cdot 10^{-10}$; $7.22 \cdot 10^{-10}$], remaining nearly constant (Fig. 1d), with $\sim 94\%$ of the impact attributable to pollution and climate change, primarily through fertiliser production (Figs. 1d and 5f). The highest municipal iABL was found in Nova Mamoré (Rondônia), at $5.62 \cdot 10^{-10}$ PDF·yr/t [$5.43 \cdot 10^{-10}$; $5.83 \cdot 10^{-10}$]. The lowest was in Videira (Santa Catarina), at $7.11 \cdot 10^{-11}$ PDF·yr/t [$3.64 \cdot 10^{-11}$; $4.38 \cdot 10^{-10}$]. iABLs were evenly distributed across municipalities (Figs. 4d and 4e), partly due to the assumption of standardised agricultural and processing practices at the state level, particularly regarding fertilisation rates (Methods).

iABL and iTBL are not necessarily correlated, given the different underlying drivers. iABL is largely driven by the use of agricultural inputs and energy and the resulting emissions, while iTBL is mainly driven by land-use dynamics prior to soy establishment. For instance, Mato Grosso, which has the largest market volume, records the highest ABL despite its moderate iABL. However, it ranks second in TBL due to its relatively low iTBL (Fig. 3). This relates to the timing of land transformation and to soil properties, which

influence agricultural practices and determine iABL. The contribution of the processing stage to both iTBL and iABL is negligible.

Biodiversity footprints of destination countries, traders, and supply chains

From the destination perspective, the highest iTBLs were estimated for Brazil, El Salvador, Guatemala, Honduras, Martinique, Mexico and Venezuela (Latin America and the Caribbean); Portugal, Spain, the United Kingdom and Russia (Europe); Israel, Syria and Yemen (Asia); and Australia (Oceania), ranging from $1.01 \cdot 10^{-10}$ PDF·yr/t [$6.60 \cdot 10^{-11}$; $1.20 \cdot 10^{-10}$] in Russia, to $2.20 \cdot 10^{-10}$ PDF·yr/t [$1.82 \cdot 10^{-10}$; $2.43 \cdot 10^{-10}$] in El Salvador (Fig. 6b). These countries sourced soy-eq. from municipalities recently linked to soy-driven deforestation across Brazil. For instance, El Salvador's imports were mostly linked to high iTBL supply chains, mainly from Bahia and Piauí. Regarding the major destination markets, China showed the lowest iTBL at $5.49 \cdot 10^{-11}$ PDF·yr/t [$4.79 \cdot 10^{-11}$; $6.60 \cdot 10^{-11}$], whereas Brazil and the EU had iTBLs 99% and 49% higher than China's, respectively. The iTBL of Brazil is associated with producing municipalities in Roraima. Although China and the EU sourced their soy imports from similar states, EU's imports were responsible for a larger deforested area (38%) in the biodiverse regions of Maranhão, Tocantins, and Piauí. In contrast, the largest deforestation from China's soy supply chains was mainly concentrated in less sensitive areas of Rio Grande do Sul and Mato Grosso (57%), with only 26% of it occurring in the MATOPIBA regions. As for ABL (Fig. 6a), iABL values across countries were of the same order of magnitude, with Peru exhibiting the highest value at $4.86 \cdot 10^{-10}$ PDF·yr/t [$4.11 \cdot 10^{-10}$; $9.04 \cdot 10^{-10}$]. China, Brazil and the EU show non-significant differences between their iABLs, which account for $3.61 \cdot 10^{-10}$ PDF·yr/t [$3.01 \cdot 10^{-10}$; $7.14 \cdot 10^{-10}$], $3.69 \cdot 10^{-10}$ PDF·yr/t [$3.09 \cdot 10^{-10}$; $7.86 \cdot 10^{-10}$], and $3.80 \cdot 10^{-10}$ PDF·yr/t [$3.25 \cdot 10^{-10}$; $6.95 \cdot 10^{-10}$], respectively.

The framework allows mapping supply chain biodiversity footprints at the trader level (excluding the uninformed domestic market), covering 2,023 exporters and 1,809 importer groups. International trade was dominated by six groups acting both as exporters and importers: Bunge, Cargill, Amaggi, Louis Dreyfus, Cofco, and Coamo. Together, they controlled nearly 50% of exports with a similar share of the total ABL, equivalent to $2.20 \cdot 10^{-1}$ PDF·yr [$1.88 \cdot 10^{-1}$; $4.29 \cdot 10^{-1}$] and of the total TBL, equivalent to $3.71 \cdot 10^{-2}$ PDF·yr [$2.96 \cdot 10^{-2}$; $1.54 \cdot 10^{-1}$], with moderate impact intensities. Overall, the highest intensities were observed among trading groups with low market share. It must also be noted that unknown exporters accounted for 3% of volume (1% TBL, 3% ABL), while unknown importers accounted for 26% of imports (26% ABL, 17% TBL) (Figs. 3 and 4).

At the supply-chain level, critical high footprints combine high market shares with high impact intensities. According to this, 127 of the 103,310 supply chains (0.12%) were classified as critical (iTBL > $1.0 \cdot 10^{-10}$ PDF·yr/t), representing 5.2% of the market but 26.7% of the total TBL. Of these, 46 originated in the South (45 in Rio Grande do Sul and 1 in Santa Catarina), 14 in the Central-West (12 in Mato Grosso

and 2 in Goiás), 53 in the North-East (22 in Maranhão, 20 in Bahia, and 11 in Piauí) and 14 in the North (6 in Tocantins, 5 in Pará, 2 in Roraima, and 1 in Rondônia). 56 of these critical supply chains ended in China, 31 in the EU, and 30 in the Brazilian market, with the remainder distributed among other global markets. The supply chain with the highest TBL – $1.53 \cdot 10^{-2}$ PDF·yr [$9.03 \cdot 10^{-3}$; $1.86 \cdot 10^{-2}$] – originated in Alto Alegre (Roraima) and supplied the domestic market. Its iTBL was comparatively lower, ranking 22nd overall at $2.96 \cdot 10^{-8}$ PDF·yr/t [$1.75 \cdot 10^{-8}$; $3.59 \cdot 10^{-8}$].

Influence of market volume and impact intensity

We evaluated the trends in TBL and ABL by municipality of origin and country of destination, decomposing changes into market volume and impact intensity (iTBL and iABL) (Fig. 7). Seven spatially-explicit patterns emerged: growth in biodiversity footprints dominated by market volume; growth dominated by impact intensity; growth driven by both components, which represents a scenario with market expansion combined with an increasing impact intensity; decline through market volume contraction; decline through reductions in impact intensity; decline through simultaneous decreases in volume and intensity; and no clear trend due to the offsetting effects of the two components.

90 (3.5%) of the 2,577 municipalities of origin provided data for only one year and were therefore excluded from this analysis. 62% and 35% of the remaining 2,487 municipalities showed a steady upward trend in biodiversity footprint for ABL and TBL, respectively, driven primarily by increases in market volume (Figs. 6a and 6c). 31.3% of municipalities with increasing TBL trends experienced reductions in iTBL, thereby moderating the net impact increase. More than 70% of these cases were found in municipalities in the South and South-East (Rio Grande do Sul, São Paulo, Paraná, Santa Catarina, and Minas Gerais), where soy is mostly grown on long-established agricultural land. However, most municipalities (52% or 1,330) showed no net trend in the TBL. In 322 of them – mainly in Rio Grande do Sul, Goiás, Mato Grosso, and Tocantins – this was due to an increase in market volume combined with a decrease in the iTBL, indicating an offsetting effect. 34% of municipalities did not show a clear trend in the ABL, either in market volume or iABL.

At the destination-country level (Figs. 7b and 7d), 28 (19%) countries had data for only one year and were excluded. Most countries showed no trend (58 in ABL and 81 in TBL). Among those that showed significant changes over the period, 29% exhibited increases in ABL and 14% in TBL, largely driven by market volume growth. 12.8% of countries showed declining trends, driven mainly by volume reductions for ABL and by decreases in both volume and impact intensity for TBL. Brazil's domestic consumption showed growth in ABL, driven by market volume, while TBL showed no trend due to trade-offs between volume and intensity. China exhibited increases in both, driven by market volume; although iTBL declined, moderating TBL growth. In the EU, the Netherlands, France, and Germany experienced declines in ABL, associated with reduced market volumes, as well as in TBL, reflecting the combination of lower volume and intensity. Spain reduced its TBL footprint by decreasing iTBL, while ABL increased due to market expansion; whereas Portugal showed no net trend, due to trade-offs between volume and iTBL.

Discussion

Drivers of biodiversity loss beyond deforestation

While most biodiversity footprint studies have focused on deforestation as the primary driver of biodiversity loss^{32,33}, the proposed LCA framework enables the inclusion of downstream biodiversity impacts in great detail. Although LUC accounted for the largest share of the 2004–2022 biodiversity impacts, its relative contribution to the impact intensity declined over time. This shift reflects a decreasing role of direct land conversion and a growing contribution from other supply chain stages, such as farming and domestic transport, in iTBL. Agricultural and other polluting emissions are the main drivers of iABL, especially in rainfed systems.

The concentration of trade in specific regions and the spatial variability of TBL suggest that policies based solely on preventing deforestation, such as zero-deforestation commitments and the EUDR, are unlikely to achieve substantial global biodiversity gains and can increase leakage risks^{34,35}. Our findings question sustainability narratives and policy framings that equate environmental risk with deforestation rates or total trade volumes. While deforestation remains a key contributor to biodiversity decline, climate change and pollution also contribute to biodiversity loss in global supply chains^{36,37}. Addressing LUC without simultaneously tackling pollution and climate change, therefore, risks shifting biodiversity pressures across ecosystems. Our findings reinforce the view that biodiversity loss is inherently a multi-driver phenomenon, requiring integrated governance responses that recognise spatial heterogeneity as a defining feature of sustainability challenges.

Displacement of biodiversity loss along supply chains

Our results support the common claim that global trade externalises biodiversity loss from wealthier consumer regions to ecologically rich regions of the Global South^{30,32,36,38,39}. By making biodiversity loss spatially explicit, the analysis reveals patterns often overlooked in country-level assessments²⁸. While EU imports in 2004–2018 were associated with a decline in deforestation, China's imports showed the opposite trend⁴⁰. However, our results show that China's deforestation did not lead to greater biodiversity loss, as its impact on biodiversity is lower than that of the EU, due to the heterogeneity of biodiversity in the affected regions.

China's biodiversity footprint per tonne of soy-eq. is relatively low compared to other countries, such as those in the EU. This pattern was previously identified in the carbon footprints of Brazilian soy exports in 2010–2015, which could be associated with long-standing EU trade links to deforestation-risk municipalities³⁰. Thus, our results challenge governance approaches that rely on national averages or proxy-based risk classifications, as these can mask localised biodiversity vulnerabilities and lead to misdirected regulatory focus. A sustainable transition of global agri-food systems therefore demands not only reductions in total environmental pressures, but also a reconfiguration of the spatial

relationships through which those pressures, caused by different drivers along the supply chain, are generated and displaced. This also highlights the need to consider land use leakage when targeting deforestation, as specific trade policies and import restrictions can generate rebound effects through global markets⁴¹.

Corporate accountability and trader-level footprints

This is the first analysis to quantify soy traders' footprints, adding a new transparency dimension to the consumer-versus-producer footprint debate⁴². The framework also enables for a qualitative assessment of the effects of policy and supply chain interventions in the Brazilian soy market, which directly impact soy cultivation patterns and their links to deforestation^{42,43}. By linking impacts to producer and consumer regions and traders, the approach provides insights into how governance measures, such as the ASM, translate into reduced pressure in specific biomes and production systems. Traders' footprints are directly determined by their sourcing municipalities, highlighting their potential to influence production practices, including LUC, beyond the export routes.

This may also be related to the stickiness between specific traders and suppliers with high soy-driven deforestation risk⁴⁴. In view of the increasing need for approaches to track trade-driven deforestation⁴⁵, this spatially explicit LCA framework measures the biodiversity impacts of producers, traders, and importing countries. It aligns with calls for enhanced supply chain traceability and transparency as prerequisites for effective intervention.

Methodological limitations

The spatially-explicit LCA framework is presented as an accountability tool for the retrospective analysis of the impacts of biodiversity loss embodied in soy trade. The trade data used in the life cycle inventory (Methods) tracks soy-eq. flows until the first country of import, not until the final consumption country. Thus, the resulting footprints are not consumption-based footprints as estimated with other methods^{21,46}. Notably, re-exports are not taken into account, which may be relevant in cases such as the Netherlands, resulting in larger biodiversity footprints for re-exporting countries than expected when adopting a consumption-oriented perspective¹³.

Other limitations are related to the selection of CFs for biodiversity loss, which must be global but also regionalised to reflect ecosystem interactions with sufficient spatial detail⁴⁷. We used two of the most up-to-date and widely accepted LCIA methods^{23,27}. However, these methods focus on the effects on species richness and its vulnerability, neglecting dimensions such as species abundance, species composition, or phylogenetic diversity; and drivers such as invasive species and overexploitation^{48,49}. It must be noted that the damage to biodiversity by pesticides, reported in the literature as high^{50,51}, has not been accounted for due to insufficient detailed data. Methodologically, this approach underscores the need to develop regionalised life cycle inventories, thereby enhancing the accuracy of product-level

assessments within conventional LCA frameworks. Extending this level of spatial and temporal resolution to other commodities may be constrained by data availability and reporting limitations.

Materials and Methods

Our study applies an attributional Life Cycle Assessment (LCA) approach^{52–54} Following an accounting decision context⁵⁵, the impact on biodiversity of the most critical activities along a key global supply chain is assessed, specifically soy from Brazil, which is transported to various destinations.

The impacts on biodiversity are estimated based on the volume of soybean, cake, and oil exported annually from 2004 to 2022, considering the municipality of origin, the export route, and the country of destination. The functional unit (FU) is the mass of soy commodities traded. In this respect, two reference flows are used: the total quantity traded per supply chain from the origin (Brazil) to a destination country, and one ton of the soy commodity (soybean, cake, and oil) marketed, as well as the soybean equivalent (soy-eq.). Soy-eq. is an integrated unit defined as the quantity of raw soybeans embedded in the oil, cake, and bean flows that are ultimately generated at the end of each supply chain. The flow of soy-eq. results from the allocation of soybeans among derivatives (oil and cake) based on data on individual shipments leaving Brazilian ports, soy production in the corresponding municipalities, and the subsequent crushing and storage facilities⁵⁶. It is assumed that soybean crushing delivers soy cake and oil in proportions of 80% and 19%, respectively, accounting for losses³⁰. It allows comparing different life cycles regardless of the product imported, and is the unit commonly used by Trase⁵⁷ database to quantify the global flows of soy and its derivatives.

Under an attributional LCA approach, the environmental assessment consists of transforming activity data into environmental impacts using CFs, a scientific basis that serves as coefficient factors in a linear relationship with the activity data to estimate the respective impact (Eq. 1).

$$Impact = CF \cdot activity_data$$

1

System description

Biodiversity impacts are quantified from cradle to destination country, starting with land transformation for soybean farming to the stage at which soybeans and derived products are delivered domestically or to importing countries. Hence, the system boundaries encompass the sub-stages depicted in Fig. 8: land transformation (related to LUC), land occupation (LU), soybean farming, soybean crushing into oil and cake (when soy is processed in Brazil), domestic transportation, and international transportation.

Each supply chain embedded in the soy export volume is characterised by the municipality where the crop is produced, the Brazilian ports from which soybeans and derivatives are exported, and the destination country's ports of arrival. This study examined 103,310 supply chains, comprising the unique

links between 2,577 municipalities in Brazil that produce soybeans or their derivatives (cake and oil), 43 ports from which soy commodities are exported from Brazil, and 149 importing countries, between 2004 and 2022. These supply chains are identified from the Trase platform⁵⁷. In addition, as detailed in the sections below, other data sources are used to quantify emissions and resource consumption from the cradle to the factory gate for domestic-market shipments, or from the cradle to the destination port for export shipments.

Life cycle inventories

At the beginning of the supply chain, habitat degradation and emissions from direct land transformation and occupation are included, following Scherer et al.²³ and the IPCC guidelines^{58,59}, respectively. Land transformation refers to land conversion from previous natural habitat uses into crop production and land occupation to cropland remaining productive, in this case, soybean. These land cover changes translate into changes in natural habitat and carbon stocks (above and below-ground biomass, litter, dead wood, and soil), ultimately affecting existing biodiversity.

MapBiomas⁶⁰ are used to identify land use prior to soybean production, with a resolution of 30 m. For each pixel with soybean areas in a given year “t,” it was considered that in the year “t-3” the land was cleared for soybean production, assuming that this is the time required for the crop to be established³⁰. Based on the use in “t-3”, pixels were classified into land occupation or land transformation, depending on whether soy is observed in a pixel where there was previously a natural habitat or an anthropogenic use (i.e., soy or another temporal crop), respectively. The share of pixel areas undergoing habitat transformation and occupation was later used to allocate the environmental pressures at the municipal level.

Based on Tier 1 of the IPCC guidelines^{58,59}, activity data on changes in carbon stocks in above-ground biomass and soil organic carbon (SOC) were estimated. In addition, carbon changes in litter and dead organic matter were only considered when the land cover in “t-3” was natural forest, assuming that the carbon in these pools is zero or negligible in other land cover types. In contrast, dead organic matter and litter were not considered for crop-to-crop transitions. The associated difference in carbon stocks is converted into CO₂-eq. Additionally, non-CO₂ greenhouse gas emissions (CH₄, N₂O, and NO_x) from biomass burning were considered when, in the period “t-3”, the pixels with natural vegetation cover were linked to fire disturbances. This approach required Brazilian raster layers at a 30 m resolution as raw data for land cover (collection 9), soil carbon stocks in the first 30 cm of soil (collection 2 beta), and (collection 3) from Mapbiomas^{60–62}.

Besides LUC and LU implications, agricultural emissions from soil preparation, fertiliser application, and fuel combustion during on-field operations, as well as those from the production of agricultural inputs (i.e., seeds, soil correctors, fertilisers, phytosanitary products, and fuel), were used as inventory data to assess the impacts of the farming stage, from cradle to farm gate. Information on average farming practices at the state level was obtained from LCA studies (see SI References). All of them represent

rained soybean production with no-tillage practices. When inventory data for a specific state was unavailable, the regional average (North, North-East, Centre-West, South-East, and South) was used. Fertilisation and limestone application release CO₂ and N₂O emissions, estimated using the IPCC Tier 1 factor emissions^{58,59}. To estimate NH₃ and NO_x emissions, the Tier 1 emission factors from the European Environmental Agency⁶³ are applied. Nitrate leaching and phosphorus emissions are not estimated because of phosphorus's low mobility and the negative nitrogen and phosphorus balances in Brazilian soils⁶⁴. On-field emissions from pesticide application are not considered because most pesticides are unspecified in the literature reviewed. Machinery use (common to the previous activities) is also considered, translating into additional emissions from fuel combustion.

As to the processing stage, inventory data on inputs (fuel, hexane, water, electricity, natural gas, etc.) per FU were obtained from the same literature as for the farming stage, using consumption at the country level for the impact calculations. Emissions from fuel combustion for crushing were taken from the reference global process in the Sphera database⁶⁵. Data on emissions and resource consumption from energy and chemical inputs used in soy farming and processing were obtained from Ecoinvent v3.10⁶⁶ and considered average for the state or region.

Finally, domestic and international transoceanic transport emissions were estimated by obtaining transport distances in each supply chain and multiplying them by the average impact per t·km from Ecoinvent v3.10. Transport distances were estimated using an optimisation algorithm (cost minimisation). For domestic transport, the ORS tool⁶⁷ was used to estimate the distance between the supply and intermediate nodes based on realistic routes travelled by terrestrial vehicles transporting heavy goods. For international transoceanic transport, the distances along maritime routes between origin ports and demand countries were calculated using the Least Cost Path⁶⁸. From this algorithm, optimised lines were projected from the ports of origin in Brazil to the biggest freight port in each destination country. The algorithm avoids transit through land areas to approximate the actual routes travelled by transoceanic vessels. ORS was also used to calculate international terrestrial routes in some cases where trade happened between Brazil and any South American country. The ORS tool and the Least Cost Path were run in QGIS 3.34.0-Prizren⁶⁹.

Biodiversity impact method

This study assesses biodiversity pressures associated with the Brazilian soy market using the LC-IMPACT method v1.3²⁷. LC-IMPACT is an LCIA method specifically developed to assess impacts on biodiversity. It enables the simultaneous assessment of biodiversity impacts arising from direct land use (land transformation and land occupation), climate change, pollution (including ozone formation, acidification, freshwater eutrophication, marine eutrophication, and terrestrial ecotoxicity), and water stress. LC-IMPACT evaluates impacts on both terrestrial and aquatic biodiversity at a global scale, expressing biodiversity loss as PDF·yr. Although PDF is used as a common impact unit across biodiversity compartments, it is recommended that impacts on different biodiversity types (e.g.,

terrestrial, freshwater, and marine) be reported separately²⁷. Among the modelling alternatives provided by LC-IMPACT based on cultural perspective theory²⁷, an intermediate approach was adopted, encompassing all impacts over a 100-year time horizon, in line with current LCA practice. Consistent with the principles of attributional LCA, average or linear CFs were utilised, except for biodiversity loss related to terrestrial acidification and water stress, for which LC-IMPACT exclusively provides marginal CFs.

For the assessment of impacts associated with land use demand (land transformation and land occupation), the CFs originally provided in LC-IMPACT were replaced with those developed by Scherer et al.²³. These updated factors follow the same conceptual framework as LC-IMPACT but address several limitations of earlier approaches, notably by explicitly accounting for the effects of habitat fragmentation. Impacts from upstream unit processes within the studied supply chains, such as fertiliser production for agricultural activities, electricity generation for processing stages, and transport-related processes, were derived from the Ecoinvent v3.10. Unit impacts were calculated based on the reference flows of each unit process using SimaPro software (v9.3) and subsequently linked to the corresponding activity data.

Filling data gaps and allocation procedures

Data imputation and allocation processes were conducted to align the input data with the goal and scope of the study, taking into account the units of analysis, the indicators to be estimated, and the characteristics of the production systems and reference units. It must be noted that Trase also includes trade flows for which either the municipality or the state of origin is unknown, or the country of destination is unknown. The first procedure involved imputing missing data to conveniently identify missing nodes (i.e., origin municipality, origin port, and destination country) to characterise the full supply chain, as well as the associated land use. Out of the 103,310 supply chains evaluated, 2,818 (93.6%) required no imputation for any variable, 141 (4.7%) required imputation for municipality identification, and 50 (1.7%) required imputation for both the origin municipality and the destination country. The procedure follows a deterministic and iterative data assignment based on retrospective analysis or proportional reasoning derived from soy-eq. data.

Estimating export flows of soybean derivatives as soy-eq units requires clearly identifying the allocation of soy input to each derivative. As mentioned above, soy-eq integrates soybeans, soy cake (including cake from soy cake and from whole beans), and soy oil, with 1 ton of soy-eq equivalent to 1.03 tons of soybeans⁵⁶. While soybeans are the primary output of farming, crushing them is necessary to produce soy cake and oil. Thus, the impact associated with the processing stage was allocated to each supply chain using an economic approach, considering the commercial value of the commodities based on data from the ABIOVE association⁷⁰ share of the soy market between the origin municipality and the destination country for exported soy cake and oil. Besides, ABIOVE data for the domestic market, and export data from the MDIC-Comex platform⁷¹ for the international one, detailing exports per municipality of origin and importer country, were useful for approximating the quantities of each soy commodity (soybeans, cake from beans, soy cake, and oil) traded across supply chains.

Another assumption was needed to represent double-cropping practices at the municipality level. In Brazil, soy is often double-cropped with maize within the same year, depending on the season and the specific region of production. When this occurs, the inventory data on farming practices and their associated impacts must be properly allocated between the two crops. This was done based on the duration of the harvest cycle for soy and maize, respectively, throughout the year^{30,72}. Since both crops occupy the land area for approximately the same number of months (i.e., between September/December and January/April for soy, and between January/March and June/July for maize), the impacts per hectare were allocated 50%-50% to the two crops. This includes the area of transformed habitat, emissions from changes in carbon stocks and input consumption, and emissions related to soil pH correction. The allocation was applied only to the share of soybean area that is double-cropped, based on harvested area statistics⁷³. Double cropping was assessed in municipalities where the harvested area in the first maize season was smaller than that in the second, assuming that soy is produced before maize. Consequently, the double-cropping surface area was estimated as the difference between the harvested areas of the second and first maize seasons. In contrast, the area under a single soy crop was determined as the difference between the total harvested soy crop area and the area used for double cropping.

Uncertainty assessment

The data-intensive nature of LCA, the broad scope of the study, and the type of data used can introduce uncertainty into the results, which, whenever possible, was modelled to improve the robustness of the assessment. In particular, the uncertainty latent in some activity data, the parameters to estimate the activity data and allocate the impact, and the CFs were modelled. The modelling design consisted of a Monte Carlo simulation that used a triangular distribution for the data, with explicit dispersion statistics. Additionally, the bootstrap technique was applied when multiple data replicas were available for the same unit of analysis. A full description of the modelling choices for the uncertainty assessment are shown in the supplemental information, namely uncertainty of parameters to estimate emissions from change in the biomass stocks (Dataset S2, Table S2); uncertainty in CO₂ emissions due to changes in organic carbon stocks in the soil (Dataset S2, Table S3); uncertainty in inputs consumption in farming and processing stages (Dataset S2, Table S4); uncertainty in on-field emissions due to fertiliser and limestone application during farming (Dataset S2, Table S5); and uncertainty in the characterisation factor to assess biodiversity loss direct associated with land used in farming (Dataset S2, Table S6). As a result of the uncertainty assessment, a pool of statistics (i.e., mean, median, standard deviation, coefficient of variation, interquartile range, percentiles 2.5 and 97.5, minimum and maximum values) on the biodiversity impact of the S_BR_EUs, corresponding to the total soy trade and for the trade of 1 kg soy eq. commodity is presented.

Declarations

Data availability

The data supporting this study are available in the supplemental information and in a dedicated public repository. The supplemental information accompanies the main text grouped as: (i) Dataset S1 (available on Zenodo³¹) provides the complete results of the biodiversity loss evaluation across the integrated soy supply chain market (expressed in soy-eq.), as well as for individualised commodities including soybeans, meal from beans, cake, and oil, and can be filtered by municipality, state, destination, etc ; (ii) Dataset S2 details the background processes utilised to integrate the life cycle inventory data, alongside a comprehensive description of the factors and parameters incorporated into the uncertainty analysis; (iii) and Supplemental references presents the literature used to elaborate the inventories of soy farming and processing at the Brazilian state level; (iii); and Dataset S2 details the background processes utilised to integrate the life cycle inventory data, alongside a comprehensive description of the factors and parameters incorporated into the uncertainty analysis.

Videos S1 to S6 display the temporal trends of the results shown in Figures 2 to 6. In addition to these files, all raw input datasets and intermediate computational outputs generated during the modelling and evaluation are openly accessible in Zenodo³¹.

Code availability

The integration of all components involved in the impact estimation process was carried out using a custom R script implemented in RStudio, which constitutes an integral part of this study.

Due to the multi-terabyte size of the high-resolution geospatial LCA and the corresponding datasets (spanning 2004-2022), the complete analytical infrastructure exceeds the standard storage limits of platforms such as GitHub and Zenodo. To ensure open science, transparency, and computational reproducibility, we implemented a decoupled hybrid data-sharing architecture consisting of:

- The R implementation accessed via GitHub at <https://github.com/NKSS9027/Biodiversity-loss-of-the-Brazilian-soy-market> or through its dedicated Zenodo⁷⁴.
- The reproducibility dataset accessed via Zenodo³¹ functions as the core package for workflow validation. It provides an optimised, lightweight subset, including tabular databases, shapefiles, intermediate outputs, and specific raster layers, designed to fully execute and verify the pipeline for a default reference year (2019) and a single selected municipality.
- Some datasets necessary to obtain the full, comprehensive results of the study are omitted from Zenodo³¹ due to storage limitations or restrictive licensing, as detailed in the GitHub README file. In particular, original data are taken from the Ecoinvent v3.10 database⁶⁶, by using Sphera software (<https://gabi.sphera.com/international/software/>). To avoid copyright issues, the original values were replaced with 1 (non-real values). To replicate the environmental impact estimations, those values should be replaced with the real ones by accessing the aforementioned databases.

Acknowledgments

Authors acknowledge the financial support of the European Commission through the Horizon Europe project “Creating leverage to enhance biodiversity outcomes of global biomass trade” (CLEVER; GA No. 101060765).

Author contributions

Conceptualisation, N.K.S-S., N.S. and N.E.; Data curation, N.K.S-S.; Formal analysis, N.K.S-S., N.S. and N.E.; Funding acquisition, N.S. and N.E.; Methodology, N.K.S-S., N.S. and N.E.; Software, N.K.S-S.; Supervision, N.S. and N.E.; Visualisation, N.K.S-S.; Writing – original draft, N.K.S-S.; Writing – review & editing, N.K.S-S., N.S. and N.E.

Declaration of interests

The authors declare that they have no competing interests.

Disclosure of Delegation to Generative AI

The authors declare the use of generative AI in the research and writing process. According to the GAIDeT taxonomy (2025), the following tasks were delegated to GAI tools under full human supervision:

- Code optimization
- Validation
- Proofreading and editing
- Recommendations

The GAI tool used was: Gemini 3.5 Pro, GPT-5.6 Luna.

Responsibility for the final manuscript lies entirely with the authors.

GAI tools are not listed as authors and do not bear responsibility for the final outcomes.

Declaration submitted by: Nelson K. Sinisterra-Solís

References

1. Ceballos, G. *et al.* Accelerated modern human–induced species losses: Entering the sixth mass extinction. *Sci. Adv.* 1, (2015).
2. Brondizio, E. S., Selette, J., Díaz, S. & Ngo, H. T. (editors). *IPBES (2019): Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. <https://www.ipbes.net/global-assessment> (2019)
doi:<https://doi.org/10.5281/zenodo.3831673>.

3. Jaureguiberry, P. *et al.* The direct drivers of recent global anthropogenic biodiversity loss. *Sci. Adv.* 8, 9982 (2022).
4. Greaver, T. L. *et al.* Key ecological responses to nitrogen are altered by climate change. *Nature Climate Change* 2016 6:9 6, 836–843 (2016).
5. Newbold, T. *et al.* Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* (1979). 353, 291–288 (2016).
6. Shin, Y. J. *et al.* Actions to halt biodiversity loss generally benefit the climate. *Glob. Chang. Biol.* 28, 2846–2874 (2022).
7. Weiskopf, S. R. *et al.* Biodiversity loss reduces global terrestrial carbon storage. *Nature Communications* 2024 15:1 15, 4354- (2024).
8. Warren, R. *et al.* Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change* 2013 3:7 3, 678–682 (2013).
9. Pereira, C. C. *et al.* Scientists’ warning: six key points where biodiversity can improve climate change mitigation. *Bioscience* 74, 315–318 (2024).
10. Cabernard, L., Pfister, S. & Hellweg, S. Biodiversity impacts of recent land-use change driven by increases in agri-food imports. *Nature Sustainability* 2024 7:11 7, 1512–1524 (2024).
11. Zabel, F. *et al.* Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. *Nature Communications* 2019 10:1 10, 2844- (2019).
12. Schwarzmüller, F. & Kastner, T. Agricultural trade and its impacts on cropland use and the global loss of species habitat. *Sustainability Science* 2022 17:6 17, 2363–2377 (2022).
13. Green, J. M. H. *et al.* Linking global drivers of agricultural trade to on-the-ground impacts on biodiversity. *Proc. Natl. Acad. Sci. U. S. A.* 116, 23202–23208 (2019).
14. Pendrill, F. *et al.* Disentangling the numbers behind agriculture-driven tropical deforestation. *Science* (1979). 377, (2022).
15. Singh, C., Persson, U. M., Croft, S., Kastner, T. & West, C. D. Commodity-driven deforestation, associated carbon emissions and trade 2001–2022. <https://doi.org/10.5281/ZENODO.10633818> doi:10.5281/ZENODO.10633818.
16. Heilmayr, R., Rausch, L. L., Munger, J. & Gibbs, H. K. Brazil’s Amazon Soy Moratorium reduced deforestation. *Nature Food* 2020 1:12 1, 801–810 (2020).
17. Garrett, R. D. *et al.* Criteria for effective zero-deforestation commitments. *Global Environmental Change* 54, 135–147 (2019).
18. Gollnow, F., Cammelli, F., Carlson, K. M. & Garrett, R. D. Gaps in adoption and implementation limit the current and potential effectiveness of zero-deforestation supply chain policies for soy. *Environmental Research Letters* 17, 114003 (2022).
19. European Parliament & Council of the European Union. Regulation (EU) 2023/1115 on deforestation-free products (EUDR) - Climate Change Laws of the World. <https://climate-laws.org/document/regulation-eu-20231115-on-deforestation-free-products-1d92> (2023).

20. Marques, A. *et al.* A research perspective towards a more complete biodiversity footprint: a report from the World Biodiversity Forum. *The International Journal of Life Cycle Assessment* 2021 26:2 26, 238–243 (2021).
21. Marquardt, S. G. *et al.* Consumption-based biodiversity footprints – Do different indicators yield different results? *Ecol. Indic.* 103, 461–470 (2019).
22. Chaudhary, A. & Brooks, T. M. Land Use Intensity-Specific Global Characterization Factors to Assess Product Biodiversity Footprints. *Environ. Sci. Technol.* 52, 5094–5104 (2018).
23. Scherer, L. *et al.* Biodiversity Impact Assessment Considering Land Use Intensities and Fragmentation. *Environ. Sci. Technol.* 57, 19612–19623 (2023).
24. Chaudhary, A., Verones, F., De Baan, L. & Hellweg, S. Quantifying Land Use Impacts on Biodiversity: Combining Species-Area Models and Vulnerability Indicators. *Environ. Sci. Technol.* 49, 9987–9995 (2015).
25. Hudson, L. N. *et al.* The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project. *Ecol. Evol.* 7, 145–188 (2017).
26. Schipper, A. M. *et al.* Projecting terrestrial biodiversity intactness with GLOBIO 4. *Glob. Chang. Biol.* 26, 760–771 (2020).
27. Verones, F. *et al.* LC-IMPACT: A regionalized life cycle damage assessment method. *J. Ind. Ecol.* 24, 1201–1219 (2020).
28. Crenna, E., Marques, A., La Notte, A. & Sala, S. Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges. *Environ. Sci. Technol.* 54, 9715–9728 (2020).
29. Sanyé-Mengual, E., Biganzoli, F., Valente, A., Pfister, S. & Sala, S. What are the main environmental impacts and products contributing to the biodiversity footprint of EU consumption? A comparison of life cycle impact assessment methods and models. *The International Journal of Life Cycle Assessment* 2023 28:9 28, 1194–1210 (2023).
30. Escobar, N. *et al.* Spatially-explicit footprints of agricultural commodities: Mapping carbon emissions embodied in Brazil's soy exports. *Global Environmental Change* 62, 102067 (2020).
31. Sinisterra-Solís, N. K., Sanjuán, N. & Escobar, N. Data architecture for: Biodiversity loss of the Brazilian soy market. <https://doi.org/10.5281/ZENODO.21791486> (2026)
doi:10.5281/ZENODO.21791486.
32. Wiebe, R. A. & Wilcove, D. S. Global biodiversity loss from outsourced deforestation. *Nature* 2025 639:8054 639, 389–394 (2025).
33. Kadoya, T., Takeuchi, Y., Shinoda, Y. & Nansai, K. Shifting agriculture is the dominant driver of forest disturbance in threatened forest species' ranges. *Communications Earth & Environment* 2022 3:1 3, 108- (2022).
34. Villoria, N., Garrett, R., Gollnow, F. & Carlson, K. Leakage does not fully offset soy supply-chain efforts to reduce deforestation in Brazil. *Nature Communications* 2022 13:1 13, 5476- (2022).

35. Oliveira, G. M. et al. Blind spots in the EU's Regulation on Deforestation-free products. *Nature Ecology & Evolution* 2024 8:8 8, 1382–1383 (2024).
36. Eliasson, K., West, C. D., Croft, S. A. & Green, J. M. H. A spatially explicit approach to assessing commodity-driven fertilizer use and its impact on biodiversity. *J. Clean. Prod.* 382, 135195 (2023).
37. Boakes, E. H., Dalin, C., Etard, A. & Newbold, T. Impacts of the global food system on terrestrial biodiversity from land use and climate change. *Nature Communications* 2024 15:1 15, 5750- (2024).
38. Chaudhary, A., Pfister, S. & Hellweg, S. Spatially Explicit Analysis of Biodiversity Loss Due to Global Agriculture, Pasture and Forest Land Use from a Producer and Consumer Perspective. *Environ. Sci. Technol.* 50, 3928–3936 (2016).
39. Hoang, N. T. et al. Mapping potential conflicts between global agriculture and terrestrial conservation. *Proc. Natl. Acad. Sci. U. S. A.* 120, e2208376120 (2023).
40. de Oliveira, G. M., Jafari, Y. & Börner, J. Heterogeneous effects of export-market preferences on deforestation in Brazil. *European Review of Agricultural Economics* 52, 1041–1088 (2026).
41. Yarlagadda, B. et al. Emissions leakage and economic losses may undermine deforestation-linked oil crop import restrictions. *Nature Communications* 2025 16:1 16, 1520- (2025).
42. zu Ermgassen, E. K. H. J. et al. Addressing indirect sourcing in zero deforestation commodity supply chains. *Sci. Adv.* 8, 3132 (2022).
43. Rajão, R. et al. The rotten apples of Brazil's agribusiness. *Science* (1979). 369, 246–248 (2020).
44. Reis, T. N. P. dos et al. Explaining the stickiness of supply chain relations in the Brazilian soybean trade. *Global Environmental Change* 78, 102633 (2023).
45. West, C. et al. The global deforestation footprint of agriculture and forestry. *Nature Reviews Earth & Environment* 2025 6:5 6, 325–341 (2025).
46. Sun, Z., Behrens, P., Tukker, A., Bruckner, M. & Scherer, L. Shared and environmentally just responsibility for global biodiversity loss. *Ecological Economics* 194, 107339 (2022).
47. Rabeschini, G., Persson, U. M., West, C. & Kastner, T. Choosing fit-for-purpose biodiversity impact indicators for agriculture in the Brazilian Cerrado ecoregion. *Nature Communications* 2025 16:1 16, 1799- (2025).
48. Tucker, C. M. & Cadotte, M. W. Unifying measures of biodiversity: understanding when richness and phylogenetic diversity should be congruent. *Divers. Distrib.* 19, 845–854 (2013).
49. Miller, D. A. W., Pacifici, K., Sanderlin, J. S. & Reich, B. J. The recent past and promising future for data integration methods to estimate species' distributions. *Methods Ecol. Evol.* 10, 22–37 (2019).
50. de Almeida, V. E. S., Friedrich, K., Tygel, A. F., Melgarejo, L. & Carneiro, F. F. Use of genetically modified crops and pesticides in Brazil: growing hazards. *Cien. Saude Colet.* 22, 3333–3339 (2017).
51. Bøhn, T. & Millstone, E. The Introduction of Thousands of Tonnes of Glyphosate in the food Chain—An Evaluation of Glyphosate Tolerant Soybeans. *Foods* 2019, Vol. 8, Page 669 8, 669 (2019).
52. ISO. *ISO 14040:2006(En), Environmental Management — Life Cycle Assessment — Principles and Framework*. <https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en> (2006).

53. ISO. *ISO 14044:2006(En), Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. <https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en> (2006).
54. ISO. *Environmental Management - Life Cycle Assessment - Requirements and Guidelines - Amendment 1 (ISO 14044:2006/Amd 1:2017)*. <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?c=N0060852> (2017).
55. EC-JRC. *European Commission -Joint Research Centre -Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook -General Guide for Life Cycle Assessment -Detailed Guidance*. (Publications Office of the European Union, Luxembourg, 2010). doi:10.2788/38479.
56. Lathuillière, M. J. et al. Brazil soy supply chain (2004–2020) (Version 2.6) [Data set]. Preprint at <https://doi.org/Trase>. <https://doi.org/10.48650/DCE3-JJ97> (2022).
57. Trase - Insights and analysis on commodity trade sustainability - Trase. <https://trase.earth/>.
58. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use*. vol. 4 (2006).
59. IPCC. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse as Inventories. Volume 4 Agriculture, Forestry and Other Land Use. <https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html> (2019).
60. MapBiomass. Collection [8] of the Annual Land Use Land Cover Maps of Brazil. *Collection 8 land cover and use maps for all Brazil in GeoTiff format from 1985 to 2022* <https://brasil.mapbiomas.org/en/colecoes-mapbiomas/> (2023).
61. MapBiomass. MapBiomass Project - Collection [2 Beta] of Soil Carbon Stocks in Brazil. *Beta Collection of Annual Maps of Soil Organic Carbon (SOD) Stocks in Brazil, Covering the Period 1985 to 2021* <https://brasil.mapbiomas.org/en/dados-mapbiomas-solo/> (2024).
62. MapBiomass. MapBiomass Project - Collection [3] of the Annual Fire Scars in Brazil. <https://brasil.mapbiomas.org/en/metodo-mapbiomas-fogo/> (2025).
63. EMEP/EEA. European Environment Agency. EMEP/EEA air pollutant emission inventory guidebook 2019. *Technical guidance to prepare national emission inventories* <https://op.europa.eu/en/publication-detail/-/publication/ce310211-4bc5-11ea-8aa5-01aa75ed71a1/language-en> (2019).
64. FAO. Food and Agriculture Organization. *Fertilizer Use by Crop in Brazil*. <https://www.fao.org/4/y5376e/y5376e08.htm> (2004).
65. SPHERA. GaBi Databases. *GaBi Databases & Modelling Principles 2022* Preprint at <https://gabi.sphera.com/international/databases/gabi-databases/> (2022).
66. Wernet, G. et al. The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment* 21, 1218–1230 (2016).
67. HeiGIT, H. I. for G. T. Openroute service, ORS Tools QGIS Plugin v1.10.0. Preprint at <https://openrouteservice.org/> (2025).

68. QGIS.org. Plugins by FlowMap Group@SESS-PKU - QGIS Python Plugins Repository. Preprint at <https://plugins.qgis.org/plugins/author/FlowMap%2520Group%2540SESS-PKU/> (2022).

69. QGIS.org. QGIS version 3.34.0-Prizren. <https://www.qgis.org/> (2024).

70. ABIOVE. Brasil - Complexo Soja. <https://abiove.org.br/estatisticas-cadeia-da-soja-mensal/> (2025).

71. MDIC-Comex Stat. Estatísticas de Comércio Exterior em Dados Abertos – Ministério do Desenvolvimento, Indústria, Comércio e Serviços. Exportação por Municípios do exportador/importador (e SH4). <https://www.gov.br/mdic/pt-br/assuntos/comercio-exterior/estatisticas/base-de-dados-bruta> (2024).

72. Castanheira, É. G., Grisoli, R., Coelho, S., Anderi Da Silva, G. & Freire, F. Life-cycle assessment of soybean-based biodiesel in Europe: comparing grain, oil and biodiesel import from Brazil. *J. Clean. Prod.* 102, 188–201 (2015).

73. IBGE-SIDRA. Tabela 1612: Área plantada, área colhida, quantidade produzida, rendimento médio e valor da produção das lavouras temporárias. Sistema IBGE de Recuperação Automática. Instituto Brasileiro de Geografia e Estatística. <https://sidra.ibge.gov.br/tabela/1612> (2024).

74. Sinisterra-Solís, N. K., Sanjuán, N. & Escobar, N. Biodiversity-loss-of-the-Brazilian-soy-market: Core LCA Pipeline and Reproducibility Framework. <https://doi.org/10.5281/ZENODO.20787188> (2026) doi:10.5281/ZENODO.20787188.

Figures



Figure 1

Brazilian soy market and its total footprints of terrestrial and aquatic biodiversity loss in 2004-2022. a) Trends in the global market for Brazilian soybean and derivatives (beans, cake, and oil), including the domestic market share. **b)** total aquatic (ABL) and **c)** terrestrial (TBL) biodiversity loss as Potentially Disappeared Fraction of species over time (PDF·yr), broken down by supply chain stages from cradle to factory gate. **d)** ABL intensity and **e)** TBL intensity, as PDF·yr per t of soy-eq, broken down by supply chain stages from cradle to factory gate.

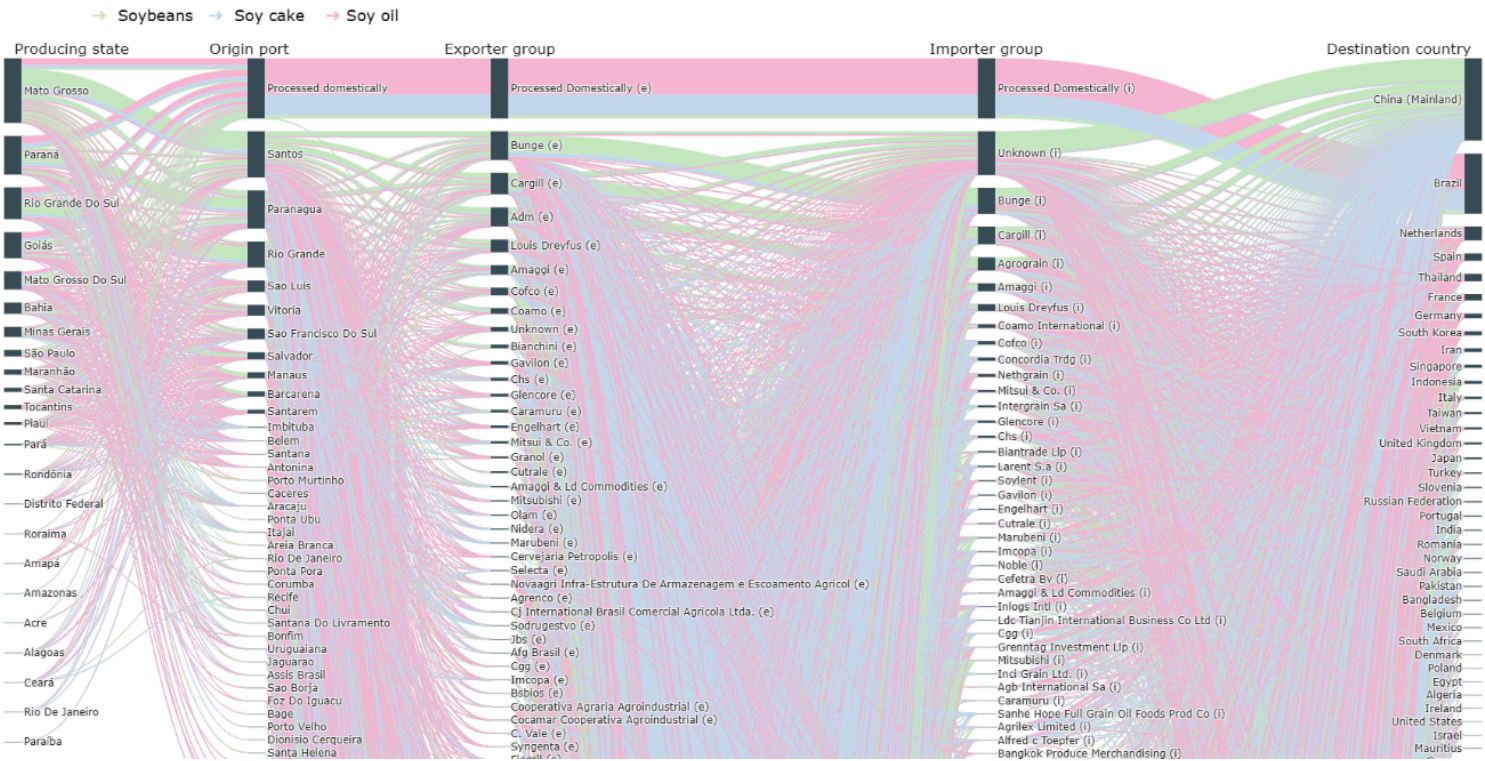


Figure 2

Total flows of Brazilian soy commodities, covering the entire soy-eq. market, 2004–2022. Flow colour indicates the type of derivative commercialised at the factory gate for the domestic market in Brazil and at the import port gate for the international market. Flows distinguish soy processed and consumed domestically in Brazil from exported volumes. To avoid clutter, the figure is truncated at a level that represents ~98% of the total traded volume. In the PDF version of this article, please click anywhere on the figure or caption to play the vide of the temporal evolution of this chart in a separate window, Video S1.

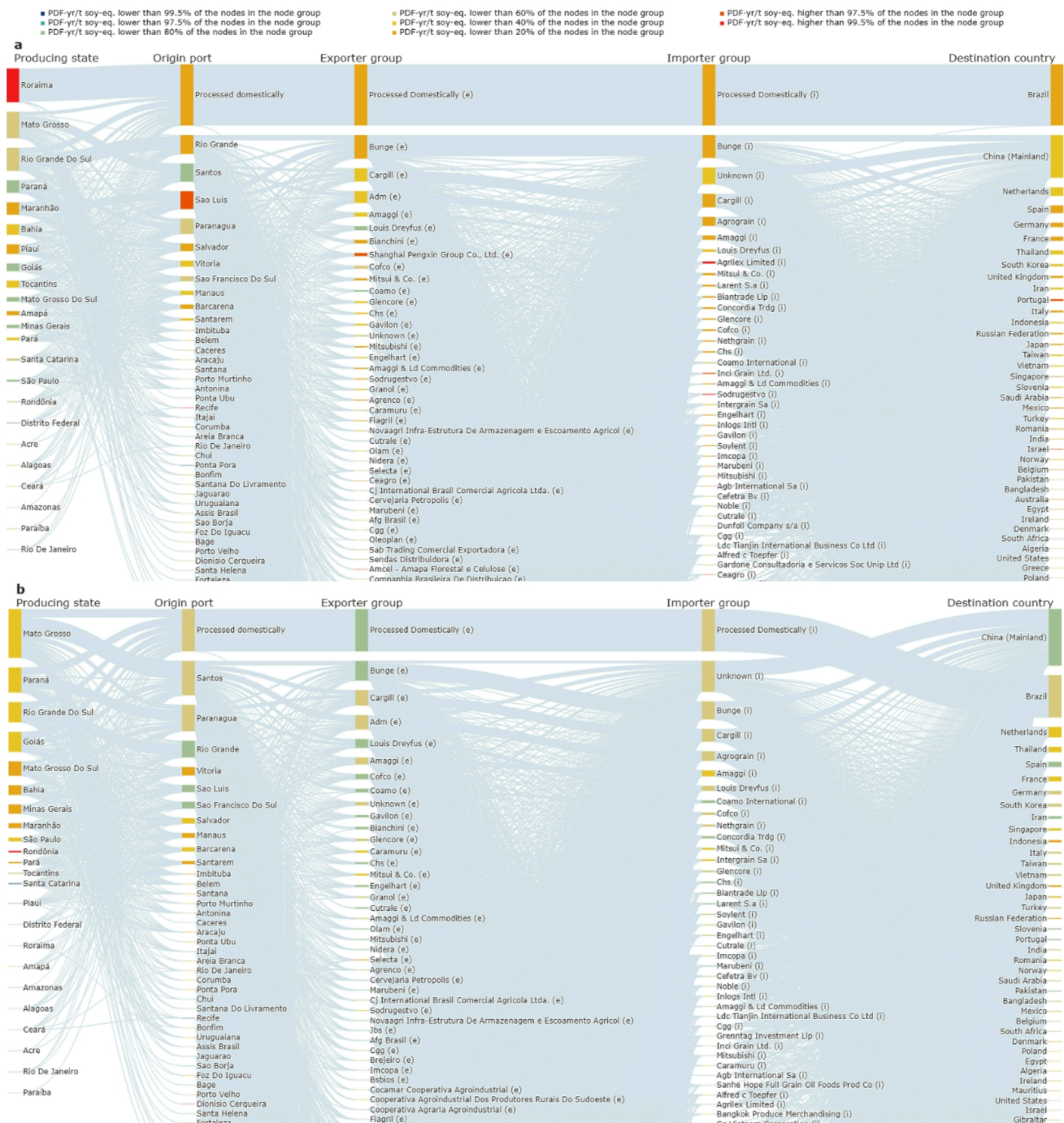


Figure 3

Total flows of terrestrial biodiversity loss (TBL) (a) and aquatic biodiversity loss (ABL) (b) embedded in the Brazilian soy market in 2004–2022, expressed as potential disappeared fraction of species over time (PDF-yr). The flows indicate the origin of soy (aggregated at the state level), port of export, exporter group, importer group and destination country. Node size represents the magnitude of absolute TBL and ABL. Node colour reflects the impact intensity of each actor (PDF-yr/t soy-eq) within each respective

panel, varying from green (low) to red (high). Flows distinguish the impact of soy processed for domestic use in Brazil from that of soy exported. To avoid clutter, the figure is truncated at levels that represent ~99% of the total impact from TBL and ~98% of the total impact from ABL. In the PDF version of this article, please click anywhere on the figure or caption to play the video of the temporal evolution of this chart in a separate window, Videos S2 for TBL and S3 for ABL.

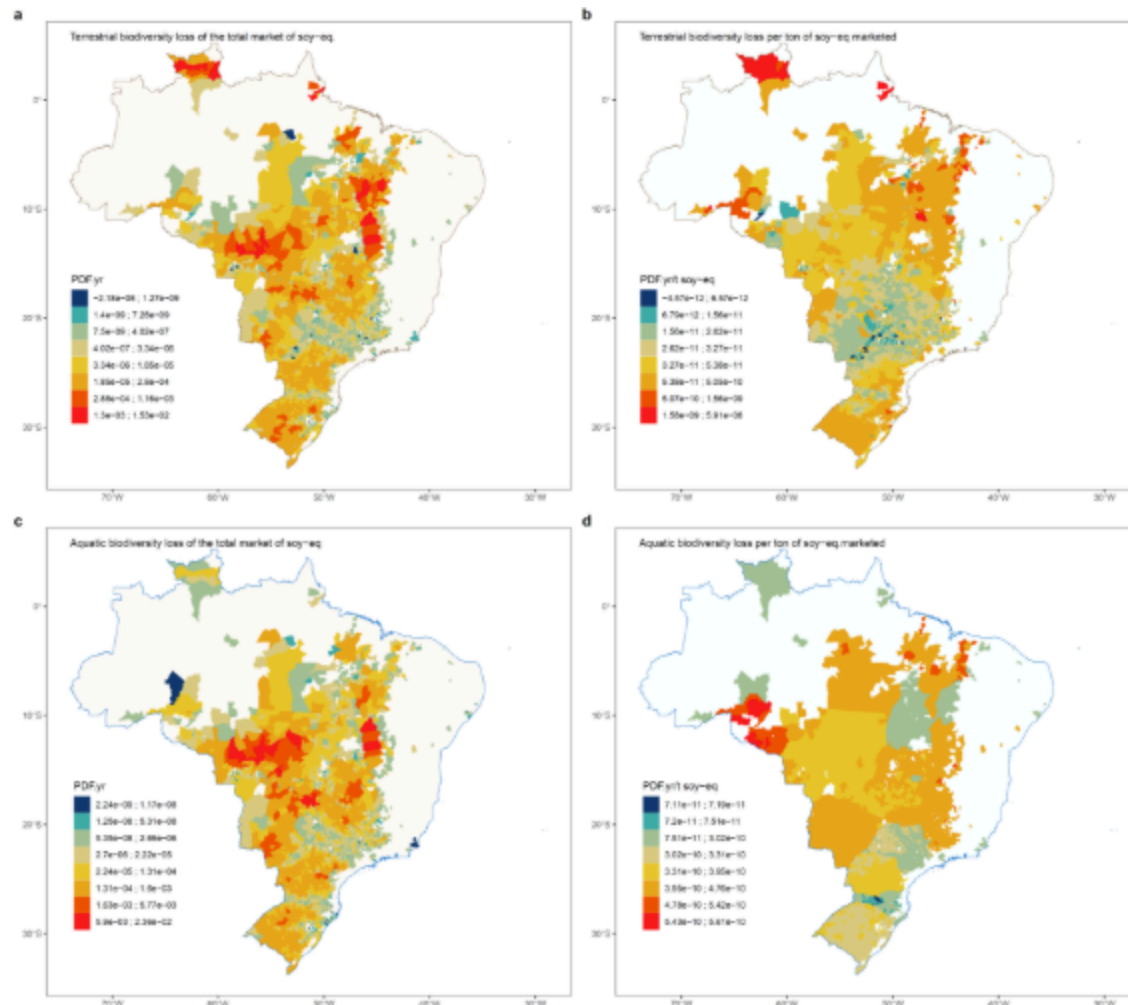


Figure 4

Producer-based biodiversity footprints of the municipalities of origin, expressed as potential disappeared fraction of species over time (PDF-yr), associated with their total output of soybean and derivatives (beans, oil, cake) in 2004–2022. a) total and b) marginal terrestrial biodiversity loss associated with soy-eq sourced from each municipality. c) total and d) marginal aquatic biodiversity loss associated with soy-eq sourced from each municipality. In the PDF version of this article, please click anywhere on the figure or caption to play the video of the temporal evolution of this chart in a separate window, Video S4.

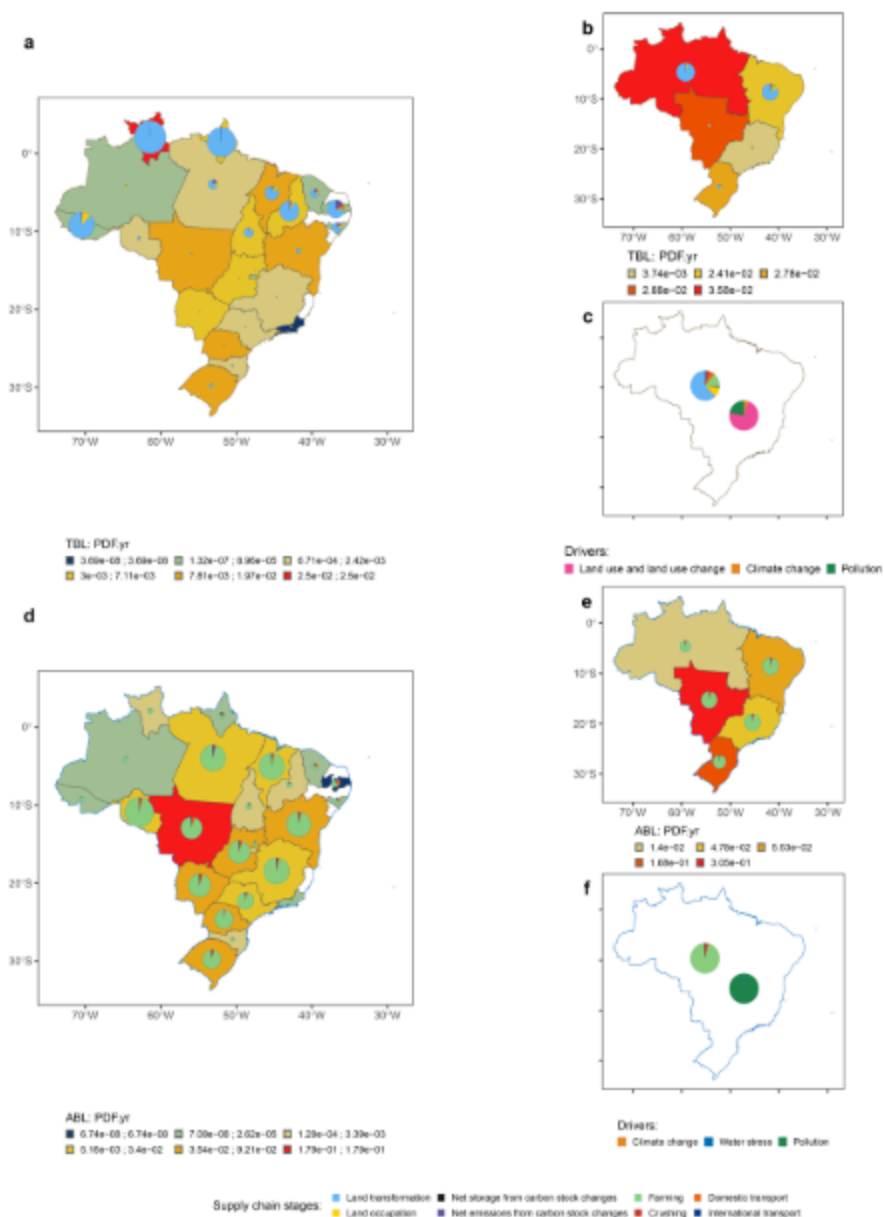


Figure 5

Producer-based biodiversity footprints at the state, region and country levels, expressed as potential disappeared fraction of species over time (PDF-yr), associated with their total output of soybean and derivatives (beans, oil, cake) in 2004–2022. Terrestrial biodiversity loss (TBL) at the state (**a**), region (**b**) and country (**c**) levels, respectively, attributed to the soy volume sourced from each spatial unit. Aquatic biodiversity loss (ABL) at the state (**d**), region (**e**) and country (**f**) levels, respectively, attributed to the soy volume sourced from each spatial unit. Pie charts in **a**, **b**, **d** and **e**, and the upper pie charts in **c** and **f**, represent the biodiversity impact intensity of each spatial unit (i.e., per tonne of soy-eq); pie size indicates the relative magnitude of each spatial unit, and colour indicates the contribution of each supply-chain stage. The lower pie charts in **c** and **f** show the relative contribution of impact drivers to the intensity of biodiversity loss. In the PDF version of this article, please click anywhere on the figure or caption to play the video of the temporal evolution of this chart in a separate window, Video S5.

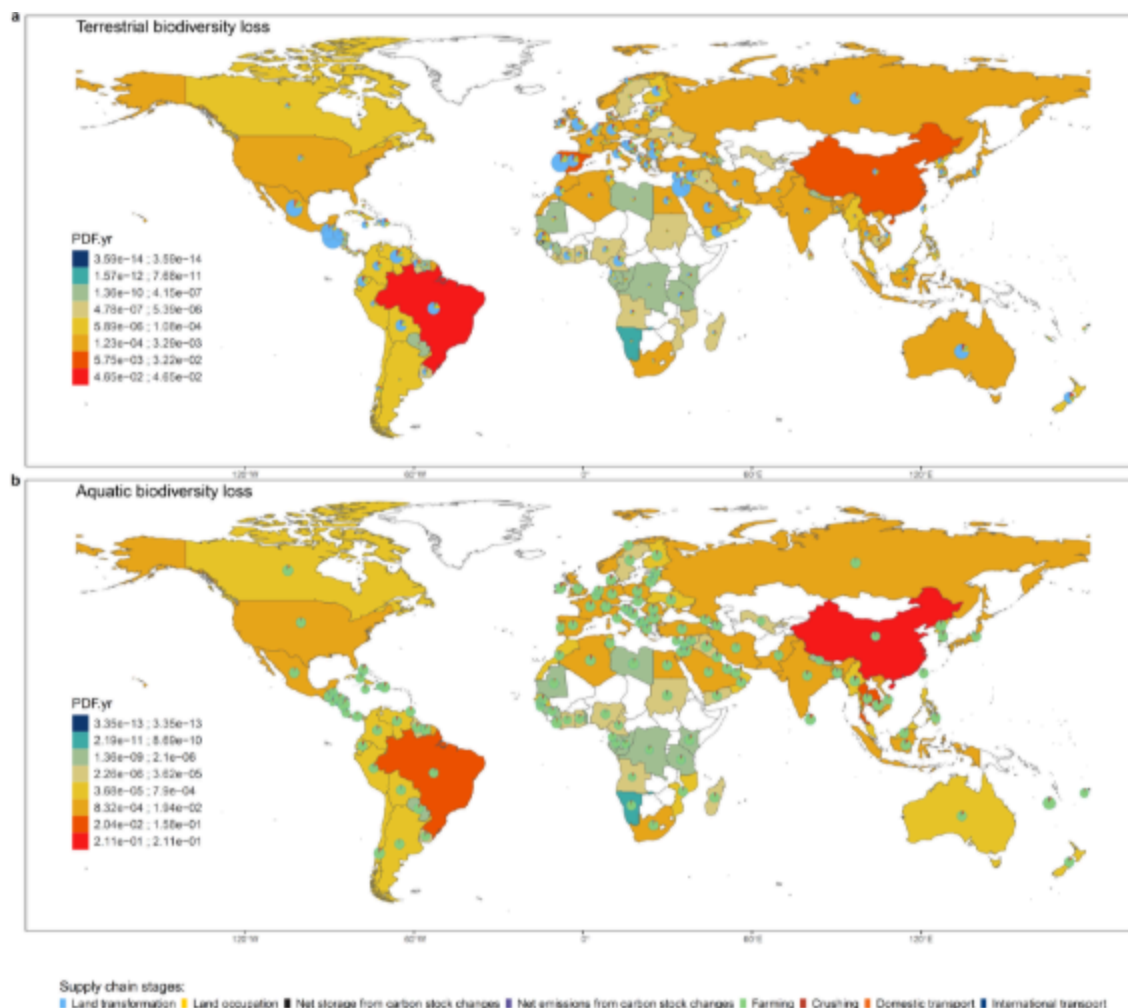


Figure 6

Biodiversity footprints of destination countries associated with their demand for Brazilian soy and derivatives in 2004-2022, including Brazil's domestic market, expressed as potential disappeared fraction of species over time (PDF-yr). a) Terrestrial biodiversity loss attributed to each country's demand. b) Aquatic biodiversity loss attributed to each country's demand. Pie charts represent the country's biodiversity footprint per tonne of soy-eq. at the farm gate; pie size indicates the relative impact intensity, and colour denotes the contribution of each supply-chain stage. In the PDF version of this article, please click anywhere on the figure or caption to play the video of the temporal evolution of this chart in a separate window, Video S6.

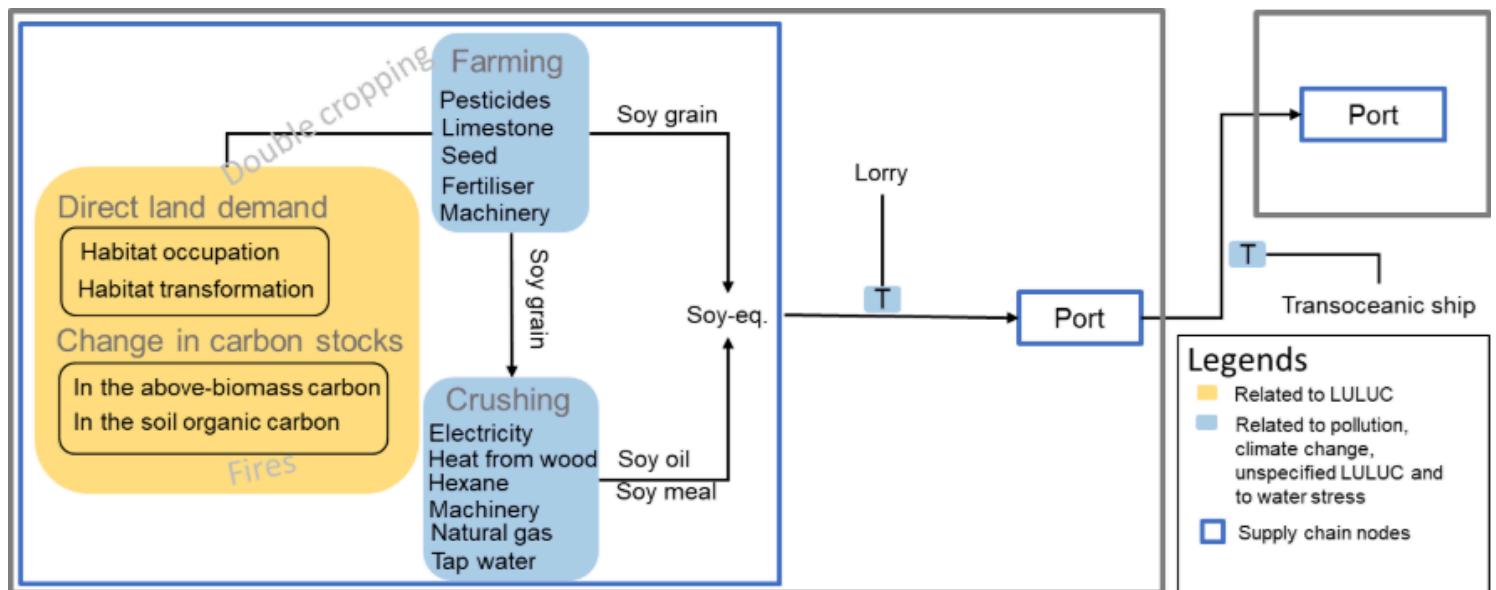


Figure 8

System analysed for the global Brazilian soy commodities marketed. Soy-eq. is an integrated unit defined as the quantity of raw soybeans embedded in the oil, cake, and bean flows that are ultimately generated at the end of each supply chain.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [DatasetS2.TablesS1S6..xlsx](#)
- [VideoS5.mp4](#)
- [VideoS6.mp4](#)
- [VideoS2.mp4](#)
- [VideoS4.mp4](#)
- [VideoS3.mp4](#)
- [VideoS1.mp4](#)
- [Supplementalreferences.docx](#)