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Baoxiao Liu

b.liu@cml.leidenuniv.nl

Institute of Environmental Sciences (CML), Leiden University

Paul Behrens

Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, 2300 RA Leiden, the Netherlands; Oxford Martin School, University of Oxford, Oxford, United Kingdom

https://orcid.org/0000-0002-2935-4799

Zhongxiao Sun

College of Land Science and Technology, China Agricultural University

Laura Scherer

Leiden University https://orcid.org/0000-0002-0194-9942

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Two-thirds of agricultural carbon and biodiversity loss occurs on one-third of the agricultural area

Baoxiao Liu [1,*], Paul Behrens [1,2], Zhongxiao Sun [3], Laura Scherer [1]

1. Institute of Environmental Sciences (CML), Leiden University, 2333 CC, Leiden, the Netherlands.
2. Oxford Martin School, University of Oxford, Oxford OX1 3BD, United Kingdom
3. College of Land Science and Technology, China Agricultural University, 100193, Beijing, China.

* Baoxiao Liu. Email: b.liu@cml.leidenuniv.nl

Abstract

Carbon storage and biodiversity loss are both heavily impacted by the food system. Here, we map and trace carbon and biodiversity loss in global agriculture along international supply chains at a high spatial and product resolution. While the northern hemisphere in general sees greater carbon loss and the southern higher biodiversity loss, the areas of highest carbon and biodiversity loss are often co-located, comprising a third of the total area and almost two-thirds of both total losses. Brazil is the largest net exporter for both losses, and China the largest net importer. Food consumption drives 83% of losses, of which animal-sourced foods drive 59% of carbon and 71% of biodiversity loss. Bovine meat and milk alone comprise 29% carbon and 41% biodiversity losses. The overlap between regions and products of high loss strengthen calls for joint efforts in carbon and biodiversity policy that involve both supply and demand interventions.

The food system sits at the intersection of both climate change and biodiversity loss. Agriculture covers around 43% of the world's habitable land[1] and has driven a general reduction in biodiversity and ecosystem functioning as both land and energy are diverted away from nature. Overall, land use is the main driver for biodiversity loss[2–4]. Simultaneously, changes in vegetation carbon storage and soil disturbance have a substantial impact on the global carbon cycle[5,6]. Land-based carbon storage is now approximately half of its natural potential[7]. It is increasingly clear that climate change and biodiversity loss are interconnected and need to be addressed jointly[8,9].

There have been efforts to understand agricultural land use impacts on carbon and biodiversity separately. Previous work has analyzed agricultural impacts on carbon stocks by mapping carbon–crop tradeoffs (as the ratio of carbon loss to crop yield)[10]. Others have assessed total food-system emissions and carbon loss from the food supply chain[11]. In parallel, researchers have explored the impact of food consumption and trade on biodiversity loss for a variety of indicators, including species threats[12,13], mean species abundance[14], potential species loss[15–18], and others [19]. Some have focussed on food trade across specific regions and products (e.g., Brazilian soy in Green et al[13]). A recent study explored land- and climate-driven biodiversity loss in the global food system[19].

There has been some limited work on investigating carbon and biodiversity at the same time, often at the regional level, for example: local patterns of agricultural expansion and their impacts on biodiversity and carbon storage[20], and carbon and biodiversity loss in conversions of Africa's wet savannahs to cropland[21]. Global work has focused on investigating the optimisation of carbon and biodiversity outcomes globally while maintaining production levels via crop relocation[22]. Consumption-based approaches have been used to connect ongoing environmental harm to specific products, with the largest impact on bird diversity being driven by cattle production[18].

A consumption-based approach is important if we are to explore the impacts of different products through the supply chain. For example, it is important to allocate the impacts of animal feed to the ultimate consumption of animal products. While many approaches trace the origin of products back to the country level[23], a much higher spatial resolution is important for environmental impacts with high spatial heterogeneity, such as biodiversity and carbon storage[24,25]. There have been efforts to combine global economic models with spatial mapping, making footprints spatially explicit to a sub-national level[13] or even grid-cell level[17,26–28] but focussing only on a single impact category.

Despite previous efforts, it remains unclear how carbon and biodiversity loss co-occur spatially in agricultural land, which becomes increasingly needed in pursuing climate and biodiversity co-benefits via land-based strategies. Further, effective demand-side policies to jointly address climate and biodiversity issues require spatially explicit food product footprints regarding both losses. So far, we still lack this knowledge of detailed food products. Therefore, integrating grid-cell-level carbon and biodiversity losses as well as their combined loss from a consumption-based perspective at a high product resolution is also needed.

Here, we estimate cumulative carbon and biodiversity loss in present-day cropland and pasture, identifying where they are co-located at a high spatial resolution. We attribute these impacts to food production and follow these impacts through the supply chain to consumption using spatially explicit input-output modelling[29]. We explore areas of strong biodiversity and carbon loss and identify the food groups driving both losses and their combined loss. To do this, we employ the Food and Agriculture Biomass Input-Output (FABIO) database[30], crop area maps from CROPGRIDS[31] and the HILDA+ pasture/rangeland map[32]. Carbon loss is estimated as the carbon stock reduction driven by land use, based on biomass[7,33] and soil carbon data[6]. Biodiversity loss is quantified using the global species loss characterization factors (CFs) for land occupation from Scherer et al.[34].

Results

Losses in agricultural land We estimate a total carbon loss of 296 Pg C (Fig. 1a), comprising 111 Pg C in pasture and 185 Pg C in cropland (including both crops for human and livestock consumption). This is equivalent to 178 years of emissions from agricultural activities (cradle-to-farm gate, 6.1 Pg CO_2 eq yr^{-1}in 2017[35]). Carbon losses in cropland are comprised of 153 Pg C in biomass and 31.7 Pg C in soil carbon. For pasture, biomass carbon loss is 74.4 Pg C and soil carbon loss 36.7 Pg C. Biomass carbon storage changes (227 Pg C) drive 76.8% of total agricultural carbon loss. Carbon loss per land area is, on average, 13.3 Pg C/M km^2 in cropland and 3.79 Pg C/M km^2 in pasture (with total cropland of 13.9 M km^2 and pasture of 29.3 M km^2). We find a global potentially disappeared fraction (PDF) of species in agricultural land of 0.137, with $5.62 \cdot 10^{-2}$ PDF in cropland and $8.04 \cdot 10^{-2}$ PDF in pasture (Fig.

1b). Here, pasture accounts for a higher total biodiversity impact than cropland. However, in terms of biodiversity loss per area, cropland ($4.03 \cdot 10^{-3}$ PDF/M km^2) is nearly 1.5 times that in pasture ($2.73 \cdot 10^{-3}$ PDF/M km^2). A comparison against other estimates at different levels of spatial and product resolutions is offered in the Supplementary Information.

Half of carbon loss is concentrated in just 12% of the agricultural area and 80% in 32% of the area. For biodiversity, half of the loss is concentrated in 10% of the area and 80% in 34% of the area (Fig. S6). Some areas see a high loss in both carbon and biodiversity, including Mexico and Central America, northern South America (Colombia), southern and western Brazil, the south of Western Africa (e.g., Nigeria, Côte d'Ivoire), India, central and southeast China, along with a large area of southeastern Asia (Fig. 1c). Carbon loss is much higher than biodiversity loss across areas of Eastern Europe, the northeastern United States, southern Canada, the UK, Finland and Sweden. Conversely, areas with much higher biodiversity include coastal Australia, areas of Kenya, Somalia and Morocco, northern Algeria and Borneo in Indonesia. In general, we find that the northern hemisphere is relatively higher in carbon loss and the southern hemisphere sees higher biodiversity loss, although both see high levels of loss in both.

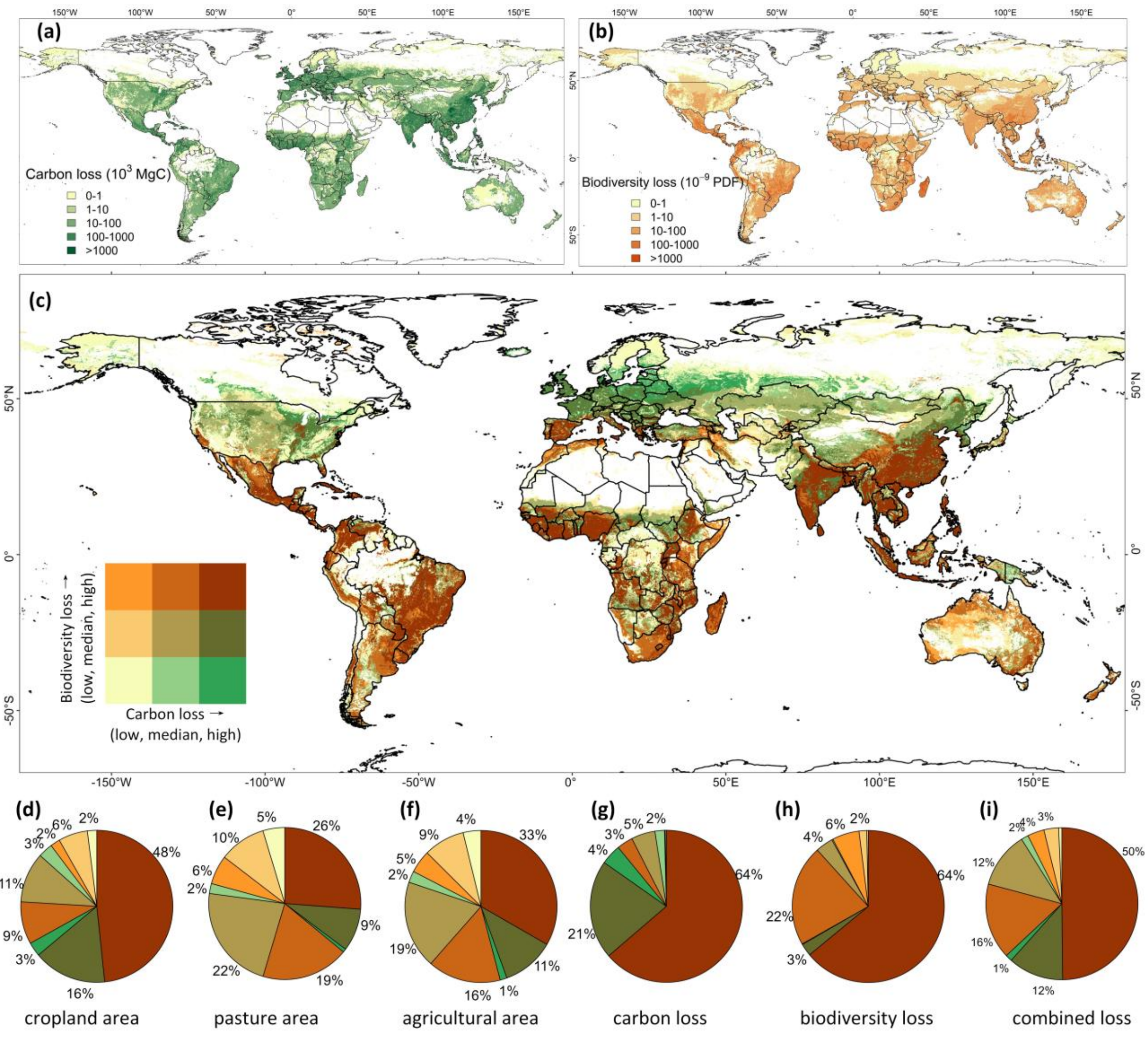

Fig. 1. Carbon loss (a), biodiversity loss (b) and bivariate loss (c) in global agricultural land, and shares of areas with different bivariate loss (d-i). (a) and (b) are generated by multiplying the land use area with carbon and biodiversity loss densities in each grid cell at 3 arcmin. Cells represent values of the total loss (sum of loss in cropland and pasture) that has occurred within each grid cell. The bivariate map (c) is derived from overlaying the two loss maps when binned into terciles (including zero cells). Pie charts show the shares in terms of cropland area (d), pasture area (e), agricultural area (f), carbon loss (g), biodiversity loss (h) and combined loss (i). The colours in (d)-(i) align with the colours in (c). The agricultural area in (f) is the sum of the cropland area in (d) and the pasture area in (e). Shares of at least 1% are labelled in each pie chart.

We find that areas of higher carbon and biodiversity loss are often co-located (Spearman's rank correlation rho=0.60, p-value < 0.001, see Fig. S7 for more details). Areas with both high biodiversity and carbon loss (classified as dark brown areas in Fig. 1c) are in 6.71 M km^2 cropland and 7.68 M km^2 pasture, representing a third of the total agricultural area (Fig. 1d-f). Within this area, losses are 188 Pg C and $8.75 \cdot 10^{-2}$ PDF, respectively, comprising ~64% of both total carbon and biodiversity loss across global agricultural land (Fig. 1g-h, see Table S5 for detailed results).

Carbon and biodiversity loss driven by food consumption Food production covers 35.6 M km^2, accounting for 82% of global agricultural land (the remaining is dedicated to biofuels, textiles, and other uses). Food production drives 83% of the total carbon and biodiversity loss in agricultural land (247 Pg C of carbon loss and 0.114 PDF of biodiversity loss). In terms of product type, we find that animal-sourced food (ASF) consumption occupies 28.1 M km^2 of land, accounting for 79% of food-related land (or 65% of total agricultural land) (Fig. 2a). This results in 145 Pg C carbon loss (52.6 Pg C in cropland, 92.8 Pg C in pasture) and $8.06 \cdot 10^{-2}$ PDF biodiversity loss ($1.23 \cdot 10^{-2}$ PDF in cropland, $6.83 \cdot 10^{-2}$ PDF in pasture). The remaining 21% of food-related land (7.49 M km^2 or 17% of total agricultural land) is driven by plant-sourced food (PSF) consumption, resulting in 101 Pg C carbon loss and $3.36 \cdot 10^{-2}$ PDF biodiversity loss.

ASF consumption is associated with 59% of food-related carbon loss and 71% of food-related biodiversity loss while representing 37% of total protein (excluding fish) and less than 15% of humanity's total calorie intake (excluding fish). The average carbon and biodiversity loss per kcal of ASF is around 8 times and 14 times higher than that of PSF, respectively (Table S6). Focusing on the areas of high carbon and biodiversity loss (as shown in Fig. 1), we see lower but still considerable impacts from ASF, accounting for 53% of food-related carbon loss and 66% of food-related biodiversity loss in these high-loss areas (Fig. S8).

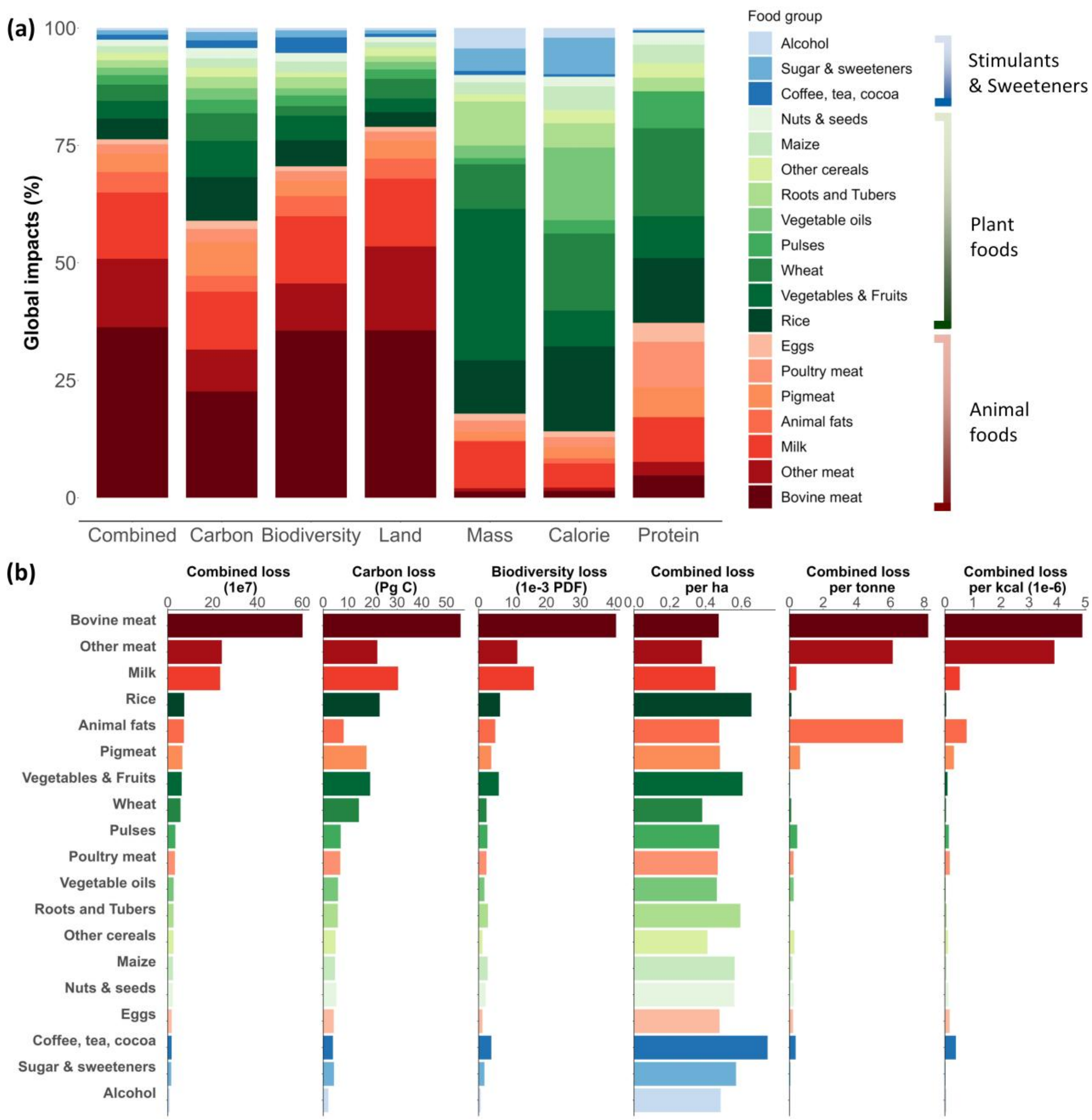

Fig. 2. Global impacts of each food group as a proportion of the total (a), and food group losses as combined loss, carbon loss, biodiversity loss, and combined loss per area, per tonne and per kcal (b). Food groups in (b) are ranked in descending order by total combined loss.

Bovine meat shows the highest combined loss, carbon loss, and biodiversity loss (Fig. 2b), followed by milk then rice in carbon loss and milk then other meat in biodiversity loss. Bovine meat's carbon impact is almost two and a half times that of rice in absolute terms, with a biodiversity impact 6-fold higher. Animal fats see the highest per-tonne carbon loss, while bovine meat is the highest in per-tonne biodiversity loss, and per-kcal carbon and biodiversity loss. In terms of combined loss per area, coffee, tea, and cocoa see the highest impacts, followed by rice and vegetables & fruits. However, per tonne and per kcal, bovine meat is once again very large, and the difference across groups is larger than results per unit of area (see Tables S7 and S8 and Fig. S9 for details).

Hotspots for combined biodiversity and carbon loss driven by ASF consumption (Fig. 3a) show a similar pattern as for global agricultural production (Fig. 1c), except for West Africa, Ethiopia, India and southeast Asia, where PSF groups largely drive losses (Fig. 3b). With our combined loss metric, we find ASF's combined impact is 3.2 times higher than PSF and higher than in each loss separately (Table S7). Driven largely by pasture's higher contribution to food-related combined loss (1.8 times higher than cropland), ASF-related land use tends to occur more often in areas of higher dual loss than PSF.

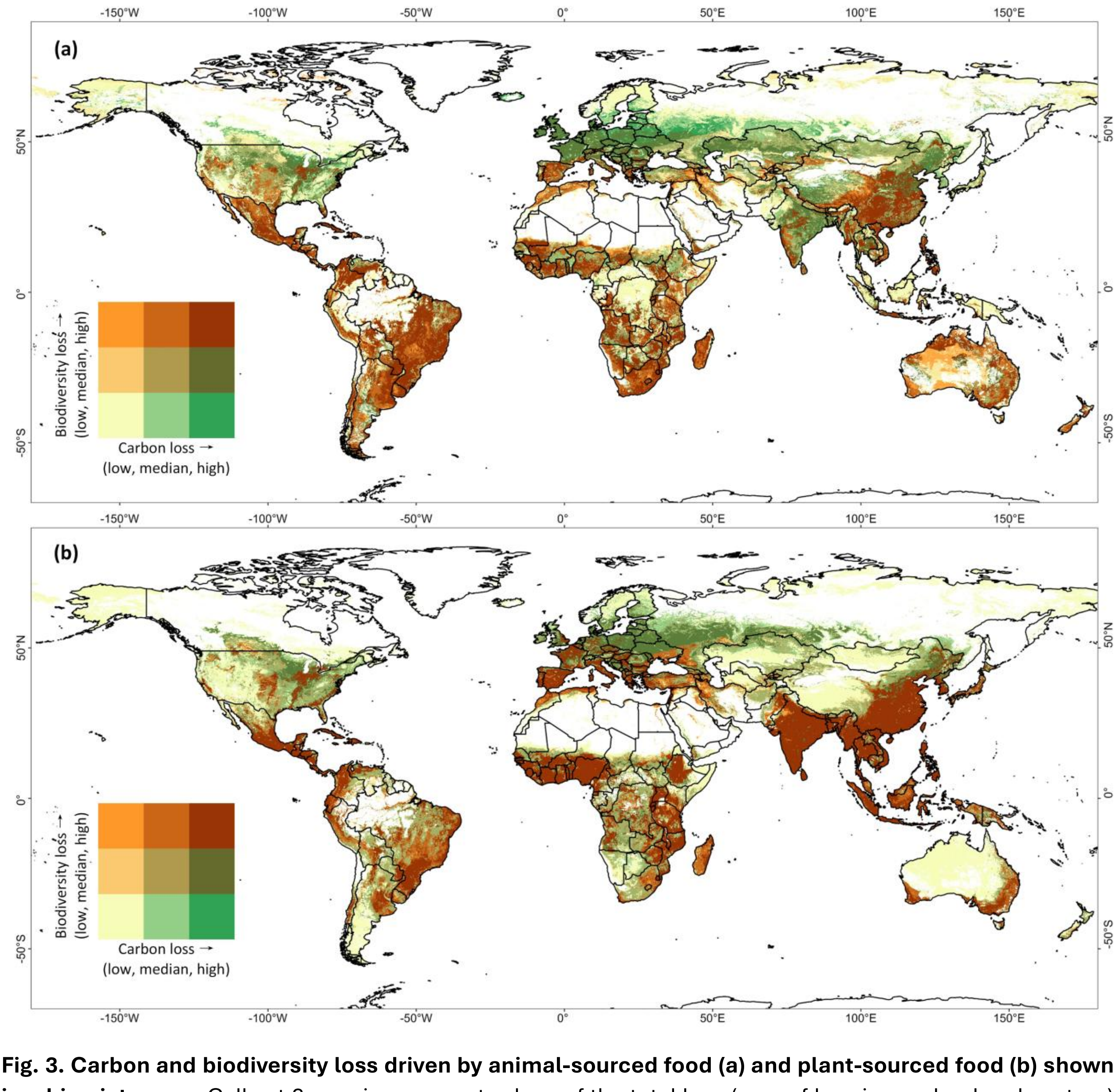

Fig. 3. Carbon and biodiversity loss driven by animal-sourced food (a) and plant-sourced food (b) shown in a bivariate map. Cells at 3 arcmin represent values of the total loss (sum of loss in cropland and pasture) that has occurred within each grid cell. Maps are derived from overlaying the two loss maps when binned into terciles (including zero cells).

Losses embodied in trade Local losses in carbon and biodiversity are tele-coupled through trade from production to consumption (Tables S9-10). The trade-related carbon loss and biodiversity loss are 18%, varying widely for each individual food group. Coffee, tea and cocoa, and vegetable oil show the highest share of trade-related impacts, both for carbon and biodiversity (Fig. 4a-b, Tables S11-12). East Asian countries see the largest net imports both in carbon and biodiversity loss, driven mainly by China (Fig. 4c-d, Tables S13-16). South American and Eastern European countries show the highest net exports of carbon loss, with South America remarkably high for net embodied biodiversity loss exports. ASF still plays a larger role than PSF in global trade, with 61% of carbon loss and 64% of biodiversity loss embodied in trade (Fig. S10).

China is the largest net importer of carbon loss, biodiversity loss, and land use, and Brazil the largest net exporter for both carbon and biodiversity (Table S18). Trade flows between these larger trade countries are driven predominately via ASF (Fig. S10). Exports of bovine meat and pigmeat from Brazil to China, along with pigmeat from the USA to China are the largest three international flows of embodied carbon loss. The largest three biodiversity flows are exports of bovine meat and pigmeat from Brazil to China, along with bovine meat from Australia to China (Tables S9-10 and S19).

National losses driven by domestic production Animal products (including domestic use and exports) contribute above 50% of total agricultural carbon and biodiversity loss in more than half of the countries. The median national contribution of animal products to carbon and biodiversity loss is 55.3% and 56.2%, respectively (Fig. S11a). Mauritania, Iceland and Botswana all see over 85% of losses driven by ASFs. Cattle alone (including bovine meat and milk) accounts for 29% and 41% of carbon and biodiversity loss in agricultural loss globally. The median national contribution of cattle to carbon and biodiversity loss is 27.2% and 30.0%, respectively (Fig. S11b). Botswana, Mozambique, Madagascar and Congo represent higher contributions for both losses (see Table S7 and Fig. S12 for more details).

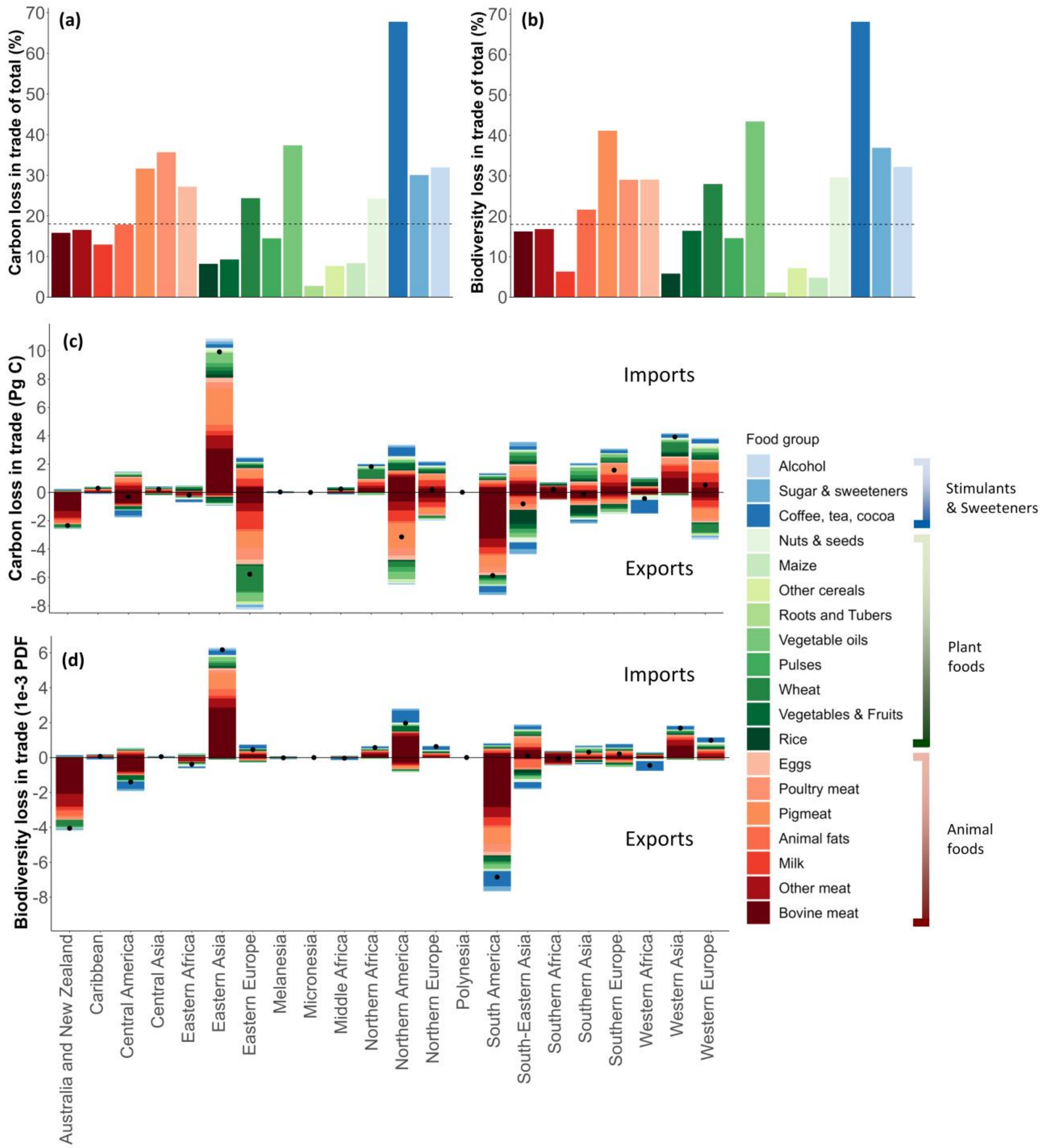

Fig. 4. Percentage of carbon loss (a) and biodiversity loss (b) embodied in the international trade compared to total loss, and the absolute carbon loss (c) and biodiversity loss (d) embodied in exports and imports for 22 geographic subregions. The dashed line in (a) and (b) marks the global percentage (18%) across all food groups. The black circular markers in (c) and (d) show the net losses. Imports and exports of losses are evaluated at the country level, and the results shown at the subregion level are aggregated from the country-level results. Colours represent food groups as in previous figures.

Discussion

According to some estimates, future food demand may increase by more than 50% by 2050, and demand for animal foods by nearly 70%[36,37]. To meet this increasing demand, an estimated 572 Mha of agricultural land could be needed (171 Mha in cropland and 401 Mha in pasture, assuming current productivity increase trends[36]). Using our average carbon and biodiversity losses per area in cropland and pasture, this expansion implies an additional 37.9 Pg C carbon loss and a further 1.78% of species at risk of extinction. This would undermine both global climate and biodiversity targets. Clearly, substantial shifts in both production and consumption are necessary to meet environmental goals while providing sufficient, healthy food for all.

Specific attention is needed to address the role of ASFs. We find that cattle are the largest driver of both carbon and biodiversity losses (at 29% and 41%, respectively), consistent with prior research conducted on different scales and indicators. Shifts towards PSF are essential for large land use reduction and improving biodiversity and carbon outcomes. Studies show that, in general, land sparing for recovery to potential natural vegetation doubles the climate benefits when considering the production emissions alone[38,39].

We also show a high concentration of carbon and biodiversity losses on a relatively limited amount of land. This has implications for the Global Biodiversity Framework 2030 target, calling for a restoration of 30% of degraded land area[40] and other calls for a sparing of half the territorial biosphere[41,42]. Sparing 30% of agricultural land with the highest carbon and biodiversity loss we find here (33% of total agricultural land) would result in 171 Pg C in carbon sequestration, around 15 years of fossil fuel emissions[5]. If half of the most damaging agricultural land is restored, sequestration could reach 234 Pg C, around 24 years of fossil fuel emissions. This would also result in large biodiversity improvements, with a sparing of 30% or 50% of agricultural land resulting in potential extinctions of ~8% or 11% of species prevented in the long term. That is almost 60% or 80% of the total extinction risk in agricultural land, and 50% or 70% of the total risk in global land use[34].

Nevertheless, such land sparing could only be achieved through a large-scale reorganization of the food system[43]. The trade-offs between food demand and nature conservation are specifically challenging in middle- and lower-income nations. They often hold large potential for carbon and biodiversity co-benefits but face severe economic, social, and environmental challenges[44]. Global cooperation is essential in addressing these challenges, including international cooperation across the agricultural supply chain[16]. For example, exports of bovine meat and pigmeat from Brazil to China are the two largest trade flows of embodied carbon and biodiversity loss. Interventions require improvements in both low-productivity Brazilian systems (for example, integrated systems[45]) and curbing Chinese meat demands (as modelled in Zhu et al.[46]), while avoiding economic and social disruption.

Future work could apply our framework to both time-series and scenario analyses. Scenario analyses could incorporate both future demand changes and land use optimization to explore multiple environmental benefits, for example, by applying a multicriteria optimization approach[47]. These could be extended further to explore dynamic changes in carbon and biodiversity due to climate change[48]. For example, they could integrate climate-driven biodiversity loss by adopting CFs for climate change impacts on biodiversity[49,50]. Given that land-driven and climate-driven biodiversity loss can reduce global carbon storage potential[51], it will be important to account for biodiversity-driven carbon loss in future land use projections.

International policy efforts to meet climate and biodiversity goals are often unconnected, with climate change being the primary policy priority. Yet this must change given the complex interactions between climate and biodiversity, along with the threats from biodiversity loss. Several researchers and organizations have called for a joint policy approach, and a clear opportunity lies in joint working groups of the UNFCC and CBD [9,52]. Our results demonstrate how important this joint policy approach is by quantifying combined biodiversity and carbon loss for agriculture as the major driver of both.

Methods

We integrate agricultural land use maps, carbon storage data, and land use-induced biodiversity impact factors with the Food and Agriculture Biomass Input-Output (FABIO) database. FABIO details the agricultural and food products for 123 agricultural commodities and 186 regions in recent years[30]. As such, our approach integrates carbon and biodiversity losses from agricultural production across the food supply chain, including trade, to consumption. We use FABIO for the year 2020. For assessing cropland and pasture, we use 173 crop area maps circa 2020 from CROPGRIDS[31] at 3 arcmin (~5.6 km at the equator) and the HILDA+ 2019 pasture/rangeland map at 0.6 arcmin[32]. We harmonize the maps at 3 arcmin resolution (Fig. S1, see SI for more details).

Carbon loss We calculate carbon loss as the cumulative carbon stock reduction driven by land use for both biomass and soil carbon. We calculate the difference between potential and actual stocks following similar methods in previous assessments[18,38,39,53]). We generate a carbon biomass loss map for 2019 by combining global terrestrial living biomass stock maps from Xu et al.[33] with a biomass carbon reduction percentage map from Erb et al.[7]. Similarly, we produce a soil carbon loss map for 2010 based on Sanderman et al. [6]. We aggregate biomass and soil carbon loss to obtain a total carbon loss map (in Mg C ha^{-1}), assuming no further soil carbon loss nor gains have occurred from 2010 to 2019 (Fig. S2, see SI for more details).

Biodiversity loss Biodiversity loss is estimated using characterization factors (CFs) in potentially disappeared fractions of species per unit of land use (in PDF/m^2). We use the global species loss CFs for land occupation from Scherer et al.[34]. CFs are based on species-habitat relationships and simultaneously consider land use intensities and fragmentation. We use aggregated CFs, which include five species groups: plants, amphibians, birds, mammals, and reptiles, at the ecoregion level. We construct separate biodiversity loss maps for cropland and pasture at 3 arcmin resolution (Fig. S3) by combining CFs with the ecoregion boundaries[54] and land use intensity maps following Scherer et al.[34] (Fig. S4, see SI for more details).

Combined loss To evaluate the combined loss in cropland and pasture, we average the normalized carbon and biodiversity losses into one single, unitless number. We normalize carbon and biodiversity loss (density) values (excluding zero values) from 0-1 by assigning each grid cell with the fraction of other grid cell values less or equal to it and obtain the fractions using a cumulative distribution function (Fig. S5, see SI for more details).

Tracing losses in FABIO We link biodiversity and carbon losses, as well as the combined loss to the production maps described above and further to specific agricultural production in FABIO (see Tables S1 and S2 and SI for detailed specification). We quantify the embodied losses in food consumption by applying the standard Leontief consumption-driven model with:

$$F = diag(f)\,(I - A)^{-1}\,Y \qquad (1)$$

where F is the environmental impact (in our analysis, land use, carbon loss, biodiversity loss or combined loss) driven by final demand (Y). Y is the specific food demand matrix (the final food use by each country across 123 commodities and 186 regions) (see Tables S2 and S3). $diag(\quad)$ indicates a diagonalization. A is the technical matrix given by $A = Z \times (x)^{-1}$ where Z is the inter-commodity input-output matrix in physical units (tonnes or 1000 heads) and x the total output vector of all commodities. I is an identity matrix, and $(I - A)^{-1}$ is the Leontief inverse. f is the specific environmental pressure/impact intensity (per unit of output) under investigation, which is derived by $f = e \times (x)^{-1}$ where e is the total environmental pressure or impact. We calculate e for land use by linking map-based and country-specific land use areas to associated items in FABIO. We do the same for carbon loss, biodiversity loss and combined loss.

Mapping spatially explicit footprints For embodied land use driven by specific food group consumption, we obtain spatially explicit land use footprint maps using Eq. 2, following the methods in[17,24,26].

$$U_g = \sum_{p,r} U_{p,r} \times \frac{l_{p,r,g}}{L_{p,r}} \qquad (2)$$

U_g is the land use footprint map of specific food group consumption g. $U_{p,r}$ represents the current land use map for agricultural production p in region r. $l_{p,r,g}$ is the (non-spatial) land use footprint in region r for production p driven by g . $l_{p,r,g}$ is derived from F given by Eq. 1. $L_{p,r}$ is the current total land use area for agricultural production p in region r. To allocate national production per grid cell to exports and domestic consumption, we assume a proportional split as used in other studies[17,24,26,55].

To compare the impact per area, per mass and per kcal across food items, we link the estimated loss to the map-based land use area, food quantity from final demand in FABIO, and global average food energy and protein content derived from the FAO Food Balance Sheets[56]. We use the global average energy and protein content for each food item (Table S4) to convert FABIO food quantity to food energy and protein. For reporting, we aggregate food items into 19 food groups (Table S2) and aggregate countries' trade-related food impacts into 22 geographic sub-regions across the world according to the United Nations geo-scheme[57] (see Table S3 for countries' classification). All analyses are implemented in R version 4.3.3.

Data Availability

The codes and results underlying this study are available in Zenodo (DOI: 10.5281/zenodo.14191750). The FABIO database is available in Zenodo (https://zenodo.org/records/2577067). The CROPGRIDS crop maps can be accessed at the link: https://figshare.com/articles/dataset/CROPGRIDS/22491997 and Hilda+ maps at: https://doi.pangaea.de/10.1594/PANGAEA.921846?format=html#download. The vegetation biomass carbon data is available at: https://zenodo.org/record/4161694, vegetation carbon stock change data at: https://boku.ac.at/wiso/sec/data-download and soil organic carbon data at: https://github.com/whrc/Soil-Carbon-Debt/tree/master. The biodiversity CFs are available in Zenodo (https://zenodo.org/records/10114493).

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Author contributions

B.L., L.S. and P.B. designed the study. B.L. and L.S. developed the methodologies. B.L. performed the analysis with the help of L.S. and Z.S. The manuscript was drafted by B.L., and P.B. and L.S. made major contributions to the writing.

Competing interests

The authors declare no competing interests.

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