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Climate and biodiversity targets require larger reductions in animal-sourced foods from current higher-income levels

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Abstract

There is increasing recognition that biodiversity loss and climate change must be addressed together through integrated land-use policies. Dietary change is a key strategy for doing so. Here, we model the impacts of three dietary scenarios on land use, greenhouse gas emissions, and biodiversity loss. We assess diets with moderate, low, and zero animal-sourced food (ASF) intake aligned with EAT-Lancet recommendations across high- and middle-income nations. Moderate ASF levels, corresponding to reductions across high-income nations but increases in lower-middle-income nations, result in a carbon storage loss of 74 PgC and additional potential species extinctions of 2%. Low and Zero ASF levels yield carbon opportunities of 11 PgC and 93 PgC and extinction risk reductions of 1% and 5%, respectively. We present a case for increased ambition for plant-rich diets in high-income countries, given that even moderate ASF intake diets would be sufficient to threaten climate and biodiversity targets.

The agriculture and food systems are a major driver of global environmental challenges[1–4]. Agriculture occupies ~43% of Earth's ice-free land[5] and has caused ~15-22% of forest loss over the past 300 years[6,7]. This land use change, primarily for food, has substantially contributed to biodiversity decline, putting ~16% of species at risk of extinction—far exceeding the natural background extinction rate[8–10]. Land use has also resulted in an estimated cumulative carbon storage loss of ~600 PgC [11,12]. In addition, the food system is responsible for around a quarter to one-third of total annual anthropogenic greenhouse gas (GHG) emissions[5,13].

Feeding a growing population while meeting sustainable development goals is one of the greatest challenges this century. This challenge is made harder with climate change (e.g., increased climate variability) and biodiversity loss (e.g., reduced pollination) reducing yields[14,15]. In response, researchers have highlighted the need for a Great Food Transformation comprised of three main pillars: dietary change, reductions in food waste, and improvements in production. Among these pillars, dietary change holds the greatest opportunity when compared to other possible interventions[16,17].

The dietary transition predominantly involves a shift away from animal-sourced foods (ASF) towards plant-sourced foods (PSF). Several healthy and more sustainable dietary patterns have been suggested such as the EAT-Lancet diet[18,19]. Work indicates that shifting from typical ASF-rich diets to sustainable dietary patterns could reduce GHG emissions and land use demand by 50-80%[20,21]. This could also provide broad improvements in carbon sequestration and biodiversity[22,23]. A global shift to plant-based diets by 2050 could increase land-based carbon sequestration by more than 330 $GtCO_2$ [23] by using spared land for nature and reduce the endemic species extinction rate in cropland systems by 50% when cropland expansion is constrained to managed or secondary habitats[18].

As yet, quantitative assessments of dietary change have not accounted for land, climate, and biodiversity co-benefits simultaneously, despite a growing recognition that climate and biodiversity are interconnected and joined-up land-based efforts are needed[24]. Previous work has either focused on co-benefits within cropland systems[16,18] or has included pasture with only climate assessments[22,23]. While a recent study evaluated the impact of a global dietary shift on biodiversity intactness in pasture[25], the impact on global species extinction across agricultural lands has not been mapped at a high resolution.

Generally, there is a strong correlation between environmental benefits and ASF reductions in diets, yet previous work typically assesses one reference diet. As such, it often remains unclear how ASF consumption levels influence agricultural land use and the related carbon and biodiversity impacts. This is especially important when considering ASF intake across different countries, with high-income countries seeing higher current ASF intake than across many middle-income countries. Knowledge of impacts from different dietary patterns in middle-income countries is still lacking[20], yet is critical for providing globally relevant insights into how ASF consumption levels relate to climate and biodiversity targets.

Here, we model three EAT-Lancet-compliant diets: Moderate ASF, Low ASF, and Zero ASF, whose ASF intakes align with the upper bound, mid-point (the reference diet), and lower bound of the recommended levels. We explore the land, climate, and biodiversity outcomes under these dietary scenarios. To achieve this, we build a spatially explicit multi-regional input-output (SMRIO) framework linking high-resolution agricultural land use (cropland and pasture), carbon and biodiversity loss maps with food system data. We calculate carbon loss as the difference between potential and scenario carbon stocks, and biodiversity loss is estimated using the global species loss characterization factors (CFs) for land occupation[8], reflecting the global extinction risk in relative terms.

We simulate land use change under dietary changes at the grid-cell level and explore the different costs and benefits for carbon and biodiversity by food group across country income groups. We apply the diets to high-income countries (HICs), upper-middle-income countries (UMICs), and lower-middle-income countries (LMICs)[26] (Table S1) which combined account for ~90% of the global population, but do not apply them to low-income countries (LICs) given their considerably lower total energy intake than EAT-Lancet recommended calories (Table S11) as well as affordability issues[27]. That is, LICs are excluded from dietary changes, with their diets held constant at current levels across scenarios.

Results

Dietary change and impact overview

Current average energy intake per capita per day (across HICs, UMICs and LMICs, Figure 1a) is 2606 kcal, of which ASF consumption comprises ~18% (472 kcal) and dairy alone accounts for ~7% (186 kcal). Adopting a Moderate ASF diet across these countries increases the ASF consumption to double the current average level (902 kcal), while eating a Low ASF diet means a slightly lower total energy intake from ASF (464 kcal) but with a substantially higher dairy composition (~12%). Note that the 'Moderate' in Moderate ASF is relative to certain high-income diets today, such as the current ASF of EU27 countries (see Figure S2). In a

Zero ASF diet, energy intake from legumes increases more than six-fold, while energy intake from vegetable oils nearly doubles. The Low ASF scenario sees food-related GHG emissions of 6.37 $GtCO_2eq$ per year in total (excl. LICs' consumption, same as below), slightly lower than the current level of 7.18 $GtCO_2eq$. This is because LMIC consumption increases offset most of the decreases across HICs and UMICs. Moderate ASF sees emissions increase to 10.17 $GtCO_2eq$, also mainly driven by LMICs, whereas Zero ASF sees a considerable reduction to 1.87 $GtCO_2eq$ (Figure 1b, Table S15).

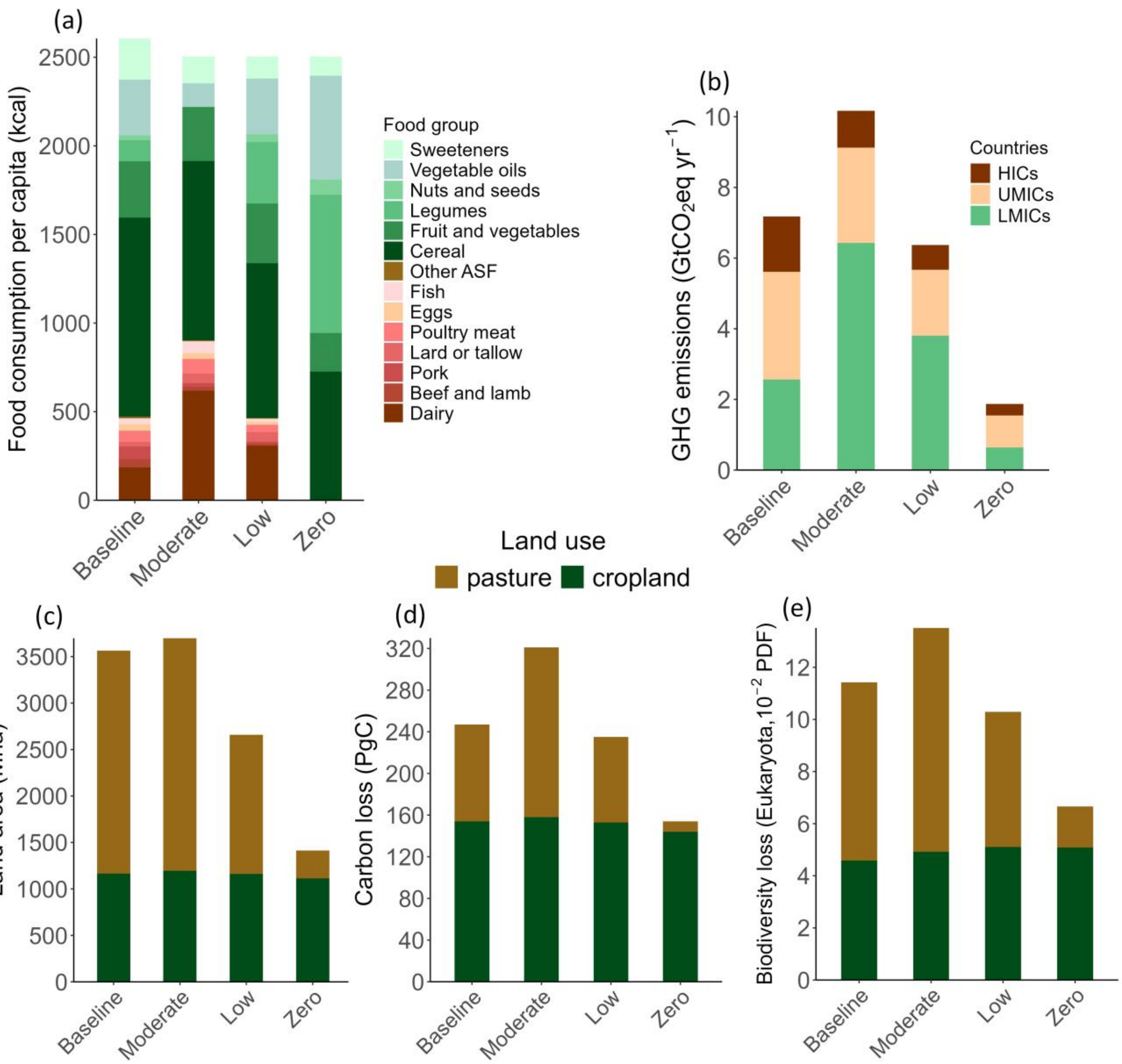

Figure 1. Per-capita food consumption (a) and total GHG emissions (b), land use (c), carbon loss (d) and biodiversity loss (e) for the baseline and scenarios. Results in (a) show the average food energy intake values across HICs, UMICs and LMICs. The per-capita energy intake excludes the energy in food loss and waste in the consumption stage, and does not include food types that are not recommended in the EAT-Lancet diet (e.g., coffee and alcohol). Colours in (b) represent the GHG emissions (excl. land-use change emissions) footprint in food consumption by country income group. HICs, UMICs and LMICs stand for high-income countries, upper-middle-income countries and lower-middle-

income countries. Results in (c-e) are total impacts from land use related to global food consumption. In (c-e), food consumption in low-income countries is included and is assumed to remain at the baseline level in each scenario. Moderate, low and zero in (a-e) stand for Moderate ASF, Low ASF and Zero ASF scenarios. The uncertainty for results in (c-e) are reported in Table S31.

Each dietary scenario has very different consequences on land use, especially for pasture (see Figure 1c-e and Table S32). Under a moderate ASF scenario, we find a net agricultural land expansion of 133 (±394) Mha (3% of the total, current agricultural area), of which pasture expands by 104 (±307) Mha and cropland by 29 (±86) Mha (assuming both pasture and cropland carry the same level of uncertainty as the total agricultural land). Yet despite a generally small change in agricultural land, we find a large negative impact on both carbon and biodiversity (Tables S33-34). Carbon loss from soils, above- and below-ground vegetation totals 74 (±42) PgC, nearly a quarter of the current total cumulative loss in agriculture, and global species extinction risk increases by 15% (±13%) from 2020.

A total 906 (±307) Mha and 2149 (±264) Mha of land are freed in Low and Zero ASF scenarios, respectively, approximately 21% and 50% of the current total agricultural area. Under these two scenarios, most land is spared in pasture, with nearly one-third of the current pasture area in Low ASF and over 70% in Zero ASF. For Low ASF, carbon storage potential increases 11 (±26) PgC (~4% of current cumulative loss in agriculture), and the global species extinction risk drops by 8% (±14%). We see larger benefits in Zero ASF, with a carbon storage potential of 93 (±22) PgC, nearly one-third of the current cumulative loss in agriculture, and a global species extinction risk reduction of 35% (±18%). In terms of food-related carbon and biodiversity impacts, Zero ASF reduces the current carbon impact by ~38% (±12%) and biodiversity loss by ~42% (±17%). We find similar patterns in biodiversity impacts across scenarios when accounting for plant and animal species separately (Figure S5).

Impact hotspots

Under a Moderate ASF scenario, land expansion occurs across much of the world, with the hotspots in Central and East Africa (e.g., Angola, Tanzania) and the Middle East (e.g., Iran). Land is spared in Central Asia (e.g., Kazakhstan and Mongolia), South America, the U.S. and Australia (Figure S6). As diets shift to plant products (Low and Zero ASF scenarios), we see less land expansion and more land sparing.

There is a large variation in the costs and benefits for carbon and biodiversity across different regions (Figure 2). These impacts are a product of land use change area and the loss per unit of area within each grid cell. In the Moderate ASF scenario, we see higher carbon loss in southern Africa (Mozambique) and South and Southeast Asia (India and Myanmar), and higher biodiversity loss in Southeast Asia (Malaysia and Indonesia), Madagascar, Mozambique, Gabon, and Central and South America (Costa Rica, Ecuador). In the Low ASF scenario, the largest carbon benefits are seen in China, and the largest biodiversity benefits in Brazil. The Zero ASF scenario sees carbon and biodiversity benefits worldwide, except for India, Myanmar and Congo (see Tables S20-22 for detailed country-level results).

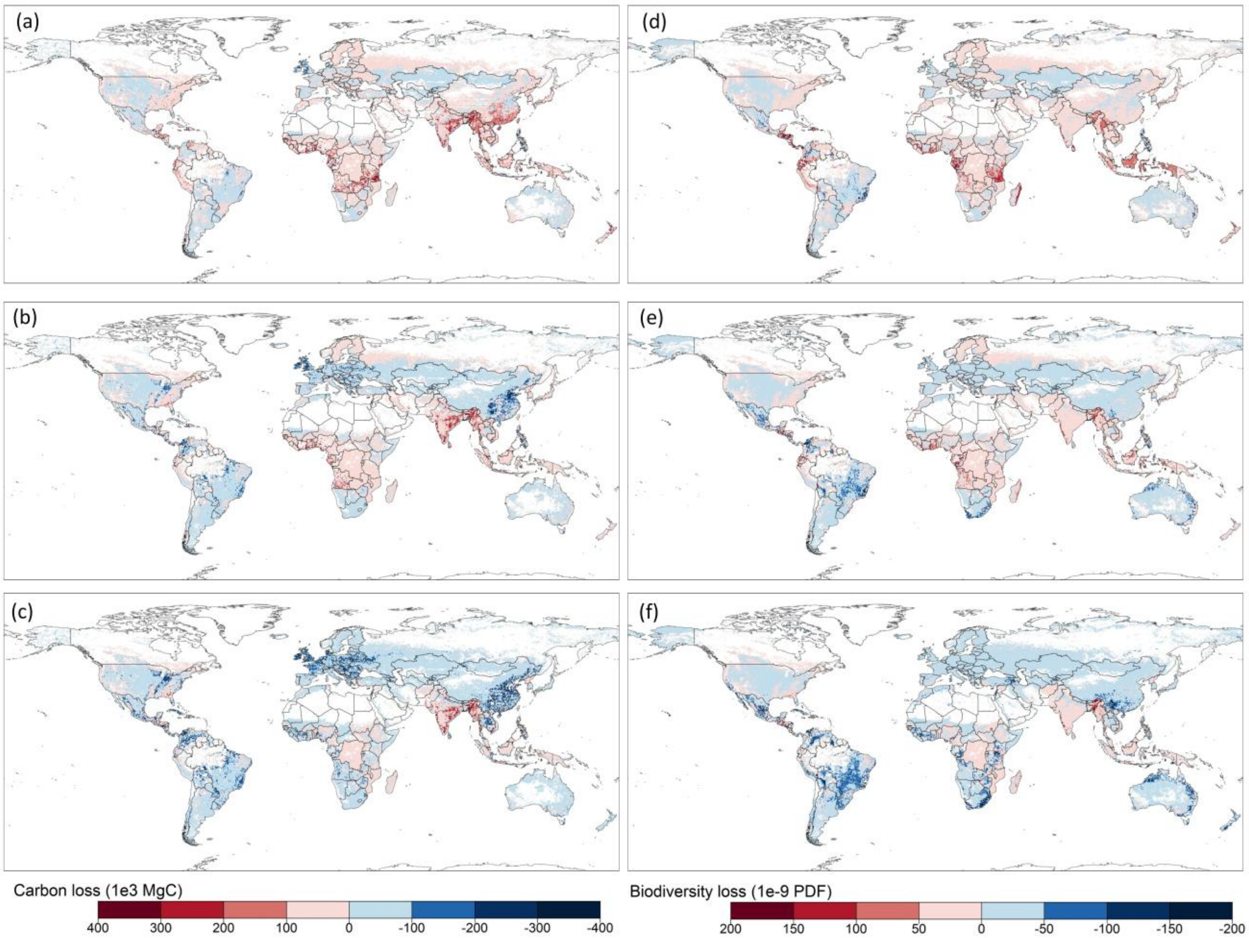

Figure 2. Changes in carbon loss (unit: 1e3 Mg C, a-c) and biodiversity loss (unit: 1e-9 PDF, d-f) under Moderate ASF (a, d), Low ASF (b, e) and Zero ASF (c, f) scenarios. The changes shown are relative to the baseline. Blue colours represent the areas with reduced loss, whereas red colours denote increased loss. Spatial resolution is at 3 arcmin.

Impact driven by food and income groups

As of 2020 (excl. LICs' food consumption, same as below), beef and lamb account for the largest land use share at 1370 (±206) Mha or around 44% of food-related land (almost 80% the size of Russia), followed by dairy at 433 (±61) Mha, or around 14% of food-related land (Figure 3a,e; Table S23). Despite their large land-use demands, the two ASF groups generally contribute fewer calories than plant foods, such as cereals, vegetable oils, and fruit and vegetables, which together occupy only 20% of food-related land. In a Moderate ASF scenario (Figure 3b,f), we see a substantial increase in the dairy land footprint to approximately 4 times its 2020 footprint, reaching 1728 (±259) Mha. Meanwhile, dairy's contribution to calories and protein grows to 2.6-2.8 times. In contrast, beef and lamb have a ~60% reduction in their land footprint, dropping to 542 (±92) Mha. In the Low ASF scenario (Figure 3c,g), dairy still doubles its land footprint compared with the baseline, while beef and lamb decrease by ~80%. In Zero ASF (Figure 3d,h), legumes, nuts and seeds, and vegetable oil see expansions of 496 (±54) Mha, which is roughly a quarter of the baseline land footprint of dairy, beef and lamb. However, the increases in calories and protein provided by the three plant-based groups are more than four times the total calories and more than three times the total protein from dairy, beef, and lamb in the baseline (see Table S23 for details).

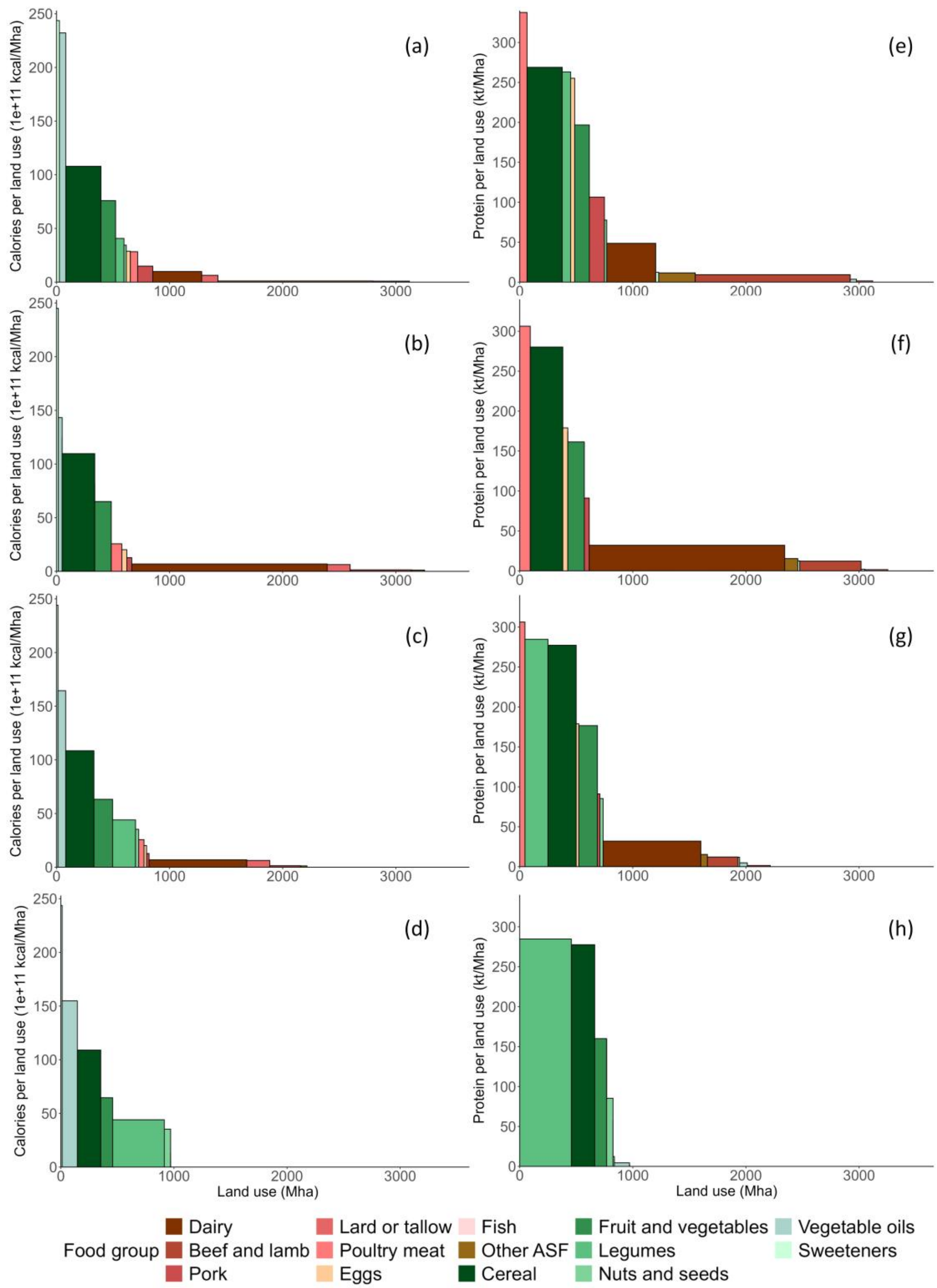

Figure 3. Land use footprint, calories per land use (a-d) and protein per land use (e-h) by food groups under the baseline (a, e), Moderate ASF (b, f), Low ASF (c, g) and Zero ASF (d, h) scenarios. Results are based on food

consumption amounts that include food loss and waste at the retail or consumption stage, and the food consumption in low-income countries is excluded. The global average energy and protein contents derived from the FAO Food Balance Sheets are used to convert food consumption into food energy and protein.

Consumption changes in dairy in Moderate ASF lead to substantial costs for carbon (150 ± 36 PgC) and biodiversity ($4.92 \cdot 10^{-2} \pm 1.69 \cdot 10^{-2}$ PDF), outweighing all the benefits from consumption change in other food groups (Figure 4, Table S28). Under the Low ASF scenario, dairy still drives costs for carbon (45 ± 16 PgC) and biodiversity ($1.65 \cdot 10^{-2} \pm 0.92 \cdot 10^{-2}$ PDF), but its costs are offset by benefits from other groups, achieving the overall benefit in this scenario. Under Zero ASF scenarios, although the increased consumption of legumes exerts costs on carbon and biodiversity by 50.8 ± 10.3 PgC and $1.76 \cdot 10^{-2} \pm 0.48 \cdot 10^{-2}$ PDF, the costs are compensated by much larger benefits from reduced ASF, which offers 135 ± 15 PgC carbon benefits and $6.42 \cdot 10^{-2} \pm 1.27 \cdot 10^{-2}$ PDF biodiversity benefits.

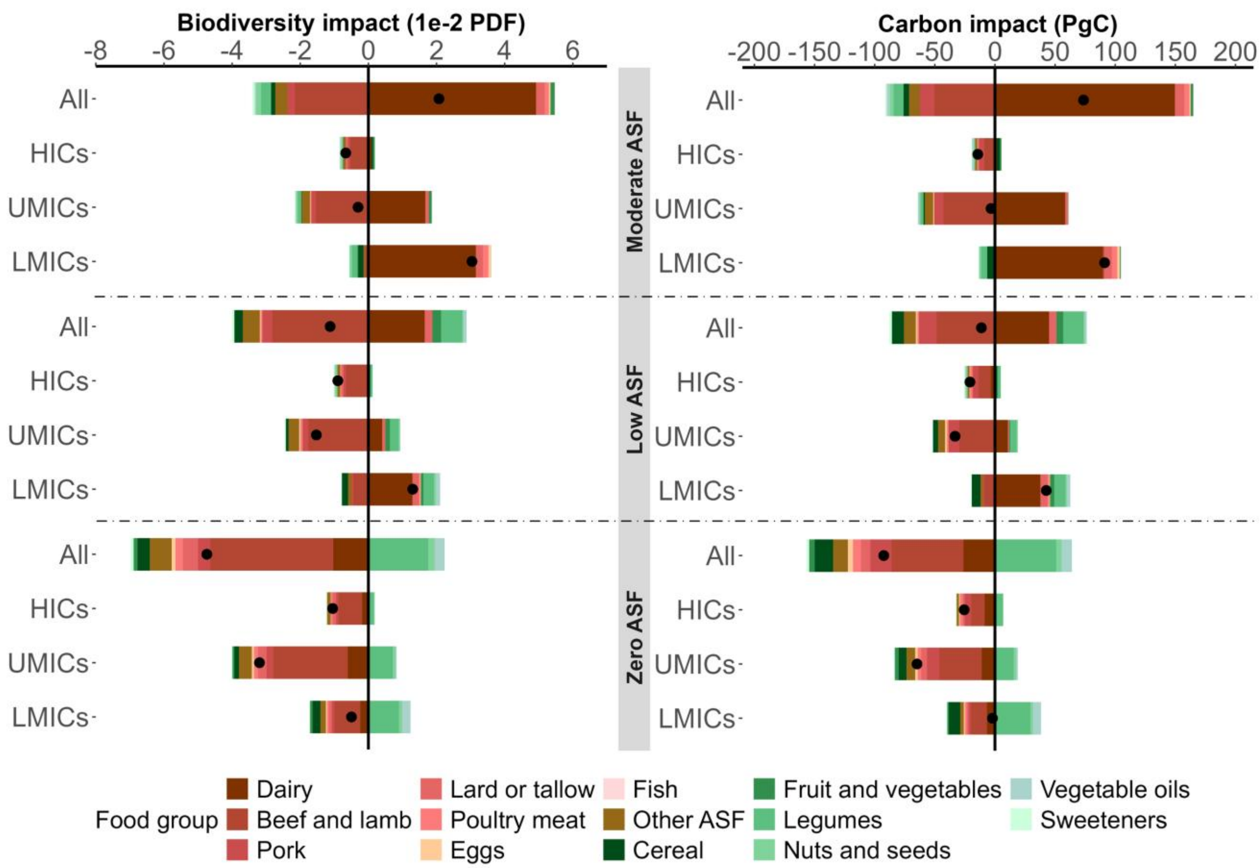

Figure 4. Changes in biodiversity and carbon loss driven by food groups and country income groups under dietary scenarios (Moderate ASF, Low ASF, and Zero ASF). HICs, UMCs and LMICs stand for high-income countries, upper-middle-income countries and lower-middle-income countries. Bars labelled "All" represent the aggregated changes across HICs, UMICs and LMICs. Positive values mean more loss (cost), and negative ones less (benefit). The dot within each bar represents the net change. The uncertainties of the net change for "All" results are reported in Table S31.

Impacts from dietary change differ across income groups. For a Moderate ASF scenario, HICs see a net land sparing of 326 Mha, a net biodiversity benefit of $0.66{\cdot}10^{-2}$ PDF and a net carbon benefit of 14.3 PgC, largely driven by reductions in beef, lamb and pork consumption. HICs also see net benefits for land, carbon and biodiversity in Low and Zero ASF scenarios. Results are similar for UMICs, but usually with a much larger benefit for land, carbon and biodiversity. However, LMICs only see net benefits in the Zero ASF scenario (see Tables S24-26 for details).

We find that a small share of impacts from dietary change in HICs occur in other country groups through the global food supply chain (Figures S7-10). For example, changes in beef and lamb consumption in HICs across all three scenarios result in land, carbon and biodiversity benefits in UMICs, with a carbon benefit of 1.14-1.46 PgC and a biodiversity benefit of $0.09\text{-}0.12{\cdot}10^{-2}$ PDF. Similarly, shifts in nuts and seeds consumption in HICs under the Low ASF scenario result in a carbon benefit of 1.23 PgC and a biodiversity benefit of $0.06{\cdot}10^{-2}$ PDF in LMICs. In contrast, dietary changes in UMICs and LMICs have limited impacts in HICs (see Table S27 for details).

Discussion

We find that a Moderate ASF diet – at the highest end of ASF intake in the EAT-Lancet diet – for HICs, UMICs, and LMICs results in a small increase in agricultural land but large climate and biodiversity costs. In Low ASF (the EAT-Lancet reference diet) and Zero ASF (the lowest of EAT-Lancet diet ranges for ASF) scenarios, approximately 21% and 50% of the current total agricultural land is released, with a carbon sequestration potential of reversing approximately 4% and 31% of cumulative agricultural carbon loss, while reducing global species extinction risk by 8% and 35%, respectively. In combination, our results suggest that shifting toward more plant-based diets considerably improves land use efficiency, offering substantial benefits for both climate and biodiversity.

Under a Moderate ASF scenario, global annual food-related GHG emissions increase by nearly 40%, adding ~3 $GtCO_2eq$ per year. Although land expansion is relatively small, it is concentrated in carbon-rich tropical regions and incurs a large carbon loss of 74±42 PgC (272±154 $GtCO_2eq$ or 2-8 years of global GHG emissions). Given remaining global carbon budgets (as of 2023) of approximately 250 $GtCO_2$ for a 50% chance of keeping warming to 1.5°C and 1220 $GtCO_2$ for 2°C[28], a Moderate ASF diet would most likely exceed the 1.5°C threshold and consume 10-35% of the remaining 2°C budget. Under a Low ASF scenario, annual GHG emissions will be similar to the baseline, but it offers long-term carbon sequestration benefits of 11±26 PgC (~40±95 $GtCO_2eq$), equivalent to 16±38% of the remaining budget associated with 1.5°C. A Zero ASF diet will see an even greater increase in carbon sequestration potential (93±22 PgC, ~341±81 $GtCO_2eq$, a similar magnitude to Hayek et al.[23]), equivalent to 20-35% of the 1.5°C budget. Additionally, annual GHG emissions under this scenario are heavily reduced.

A Moderate ASF diet is also incompatible with biodiversity targets. Such a diet further intensifies land competition for food (especially in several LMICs where the nationwide land availability is insufficient, see Table S16), increasing the global species extinction risk by 15%±13%. In our land use change modelling, the land expansion is constrained within agriculture-related grid cells. However, agricultural expansion often encroaches on more natural ecosystems with higher conservation value, threatening the integrity of existing protected areas and key biodiversity areas. As such, the actual species extinction risk is likely greater than our estimate. A Low ASF diet, despite its general alignment with the climate target, still falls short of biodiversity ambitions. However, a Zero ASF diet frees up half of all agricultural land, offering very large opportunities to restore habitats, aligning well with the half-Earth proposal[29,30] and the restoration target and the reduced species extinction target outlined in the Kunming-Montreal Global Biodiversity Framework[31].

More ambitious ASF reductions also require greater attention to high-impact food groups and the thoughtful development of food-specific policies. Beef, lamb and dairy, which currently occupy 56% of the food-related land, play a major role in the dietary transition but need different levels of reduction to achieve carbon and biodiversity gains. We find that the upper range of the EAT-Lancet beef and lamb recommendation would free up land across all three income groups, delivering substantial benefits for carbon and biodiversity, whereas the upper end of the dairy recommendation drives further negative impacts. Adopting the higher bound of dairy recommendations would require extra land across HICs and middle-income countries (MICs), causing considerable carbon and biodiversity loss, especially across MICs. While the midpoint of dairy intake adopted in HICs alone can offer improvements, it still demands more land in MICs.

Throughout this analysis, we exclude LIC for reasons mentioned previously, assume a constant population, assume current agricultural yields and the structure of the global food supply chain. As we exclude LICs and keep population static, our results may underestimate the costs under the Moderate ASF scenario. Future studies could include potential dietary changes in LICs and population growth. We account for the land suitability for agricultural production by constraining the land use change in agriculture-related cells, while we do not consider the yield difference during land use redirection. Food production improvements (e.g., yield improvements and agricultural technologies) may reduce the need for regional and global redirection. However, extreme weather events that reduce agricultural yields could be a countervailing factor[32]. We also do not optimize international trade, land expansion, nor land-sparing strategies which could improve carbon and biodiversity benefits for the same level of shifts. Although optimization strategies could improve outcomes, they alone are unlikely to be sufficient without substantial dietary change.

Dietary changes have different implications for land, carbon, and biodiversity for different country income groups. Divergent environmental outcomes across LMICs, UMICs, and HICs, are due to large disparities in current food consumption across country income groups. Given that meat and dairy consumption typically increases with income, the expected increase in ASF demand across MICs and LICs would put greater pressure on land and further threaten global climate and biodiversity targets. As such, global-level benefit would be only achieved when HICs take deeper cuts in their ASF consumption, in line with moral reasons[33] and broad expert opinions[34]. This also aligns with the concept of ‘shared but differentiated responsibilities’ in the United Nations Framework Convention on Climate Change, UNFCCC.

Methods

We model the impact of three EAT-Lancet dietary scenarios with decreasing levels of ASF consumption for GHG emissions, land use, carbon sequestration, and biodiversity loss. We link these scenarios to the 2020 Food and Agriculture Biomass Input-Output (FABIO) database[35] and quantify GHG emissions and potential land use change at the grid-cell level for each scenario. We account for grid-cell-level land availability. We then assess carbon and biodiversity impact related to land use change using carbon and biodiversity loss density maps and attribute food production impacts to food consumption by country and product (see Figure S1 for the method flowchart).

Dietary scenario construction

We investigate three dietary scenarios based on the EAT-Lancet planetary health diet[18] using different levels of ASF consumption. EAT-Lancet gives ranges of ASF levels (in mass) for each food type in the diet, which we use to derive a Moderate, Low, and Zero ASF diet. The Moderate ASF scenario represents a situation where ASF is at the top end of the range provided by EAT-Lancet, and the Zero ASF scenario at the bottom (the lowest recommended is zero across all ASFs). The midpoint of the ranges is taken for the Low ASF scenario (which is commonly referred to as the reference diet). In each scenario, other foods are added by scaling up or down to make all the scenarios isocaloric (at a total of 2503 kcal, the same as the EAT-Lancet reference diet) (see Table S2 and Supplementary methods S1.2 for further information).

Direct food consumption changes in target countries

Direct food consumption changes are calculated for each country as the difference between its baseline national food use (from FABIO) and consumption under each dietary scenario. We link FABIO food items to EAT-Lancet food classifications (see Table S3 for mapping relationship). To convert between mass and calories, we use the country-item specific energy content based on mass data from FABIO and food supply energy data from FAO Food Balance Sheets. For some items for which we are unable to derive energy contents, we use an income-group or global average value (see Tables S4-7 for compiled energy content). We account for food loss and waste at the retail or consumer level using Coudard et al.[36] (see Tables S4-7). We use population for 2020 from the UN[37] (Table S1) throughout the analyses (see Tables S8-11 for more). We follow food consumption changes in countries to producers via food supply structures (domestic production, import and export) as represented in FABIO (see Tables S12-14 for the food use final demand changes for all the scenarios, and Supplementary methods S1.2 for more details).

Embodied changes in GHG emissions and land use area

We assess environmental impacts following a standard Leontief consumption-driven model:

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

where ΔF is the environmental impact (in our analysis, GHG emissions and land use) driven by the final demand changes (ΔY). $diag(\quad)$ 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 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), which is derived from $f = e \times (x)^{-1}$ where e is the total environmental pressure or impact. Z and x are from FABIO.

Total environmental pressures or impacts, e, for GHG emissions derived from FABIO, which includes 26 emission types (Table S15) and does not include land use change emissions. We calculate e for land use by linking map-based and country-specific land use areas to associated items in FABIO. This coupling enables us to map the embodied land use changes to grid cells for each scenario. We include cropland and pasture in this analysis using 173 crop area maps circa 2020 from CROPGRIDS[38] and the HILDA+ 2019 pasture/rangeland map[39] (See Liu et al.[40] for more details).

Land use change modelling

Specific land use locations are essential for calculating carbon sequestration and biodiversity impacts. We map the embodied land use change from dietary changes to the grid-cell level, considering both the theoretical land use change and the land availability in each grid cell. The total agricultural land use demand map ΔL^d is given by:

$$\Delta L^d = \sum_{p,r} (U_{p,r} \times \frac{\Delta L_{p,r}}{L_{p,r}}) \qquad (2)$$

Where $U_{p,r}$ is the current agricultural land use map for agricultural product p (crop cultivation and grazing) in region r . $\Delta L_{p,r}$ is a scalar of the total land use footprint in region r for agricultural product p driven by food consumption change under scenarios (derived from ΔF in Eq. 1). $L_{p,r}$ is a scalar of the current total land use area for agricultural product p in region r. The summation symbol with subscripts denotes aggregation of multiple raster layers across the subscripts, yielding a single raster.

There are a few situations where the total land use demand after a dietary shift is larger than the area available in a grid cell. For these situations, we redirect the production above the availability in that cell using Eq. 3 – 4. We calculate a map of the residual area as $L^s = \Delta L^d - L^a$ where L^a is the available area map for land expansion:

$$L^a = U^{max} - \sum_{p,r} U_{p,r} \qquad (3)$$

Where U^{max} is a map of values showing the cell size of each grid, and it is constrained to the same extent as $\sum_{p,r} U_{p,r}$. That is, we assume the available area can only be in the cells where crop cultivation or grazing has already occurred, avoiding land expansion into other areas (e.g., natural intact areas). The final, total agricultural land use change map ΔL^f is given by:

$$\Delta L^f = \Delta L^d - L^s + L^r \qquad (4)$$

Where L^r is a map denoting the redirected area. We make a two-step redirection for each region, regional redirection and global redirection if necessary. In a regional step, we proportionally distribute the residual area to each grid cell in L^a (excluding L^s) within each region. When the region cannot fully meet the redirection demand, we further redirect the remaining demand area globally and proportionally (see Tables S16-18 for further details). With Eq. 2-4, we assume that: (1) land use change in each grid cell takes place proportionally across product p in region r [22,41] ; (2) the spared area from one agricultural product can be used for the expansion of another agricultural product in each grid cell; (3) the yield of agricultural product p in the redirected area remains the same as in its original cells (the redirected area comprises approximately 3% of the original areas for each product p on average, see Table S19). We further calculate the final land use change map $\Delta L^f_{p,r}$ for each agricultural product p in region r (see Supplementary methods S1.3 for more details).

Carbon and biodiversity impacts, and impact attribution to consumption

For each scenario, we generate the biodiversity and carbon storage impact maps $\Delta M_{p,r}$ for agricultural product p in region r by multiplying the final land use change map $\Delta L^f_{p,r}$ with the biodiversity loss and carbon loss density maps (Figures S3-4). Biodiversity loss is estimated using characterization factors (CFs) in potentially disappeared fractions (PDF) of species per unit of land use. We use the global species loss CFs (including five species groups: plants, amphibians, birds, mammals, and reptiles) for land occupation from Scherer et al.[8]. Carbon loss is calculated as the difference between potential and actual carbon stocks for both biomass and top 1 m soil carbon, based on Xu et al.[42], Erb et al.[11] and Sanderman et al.[12]

We calculate the total carbon and biodiversity impacts of agricultural product p in region r for each scenario by aggregating all cell values in $\Delta M_{p,r}$. To attribute these map-based total impacts to the driving country and food group, we disaggregate them based on the non-spatial embodied land use change area $\Delta F_{t,g}$ of dietary change country t and food group g (derived from ΔF in Eq. 1 with food demand changes $\Delta Y_{t,g}$; see Supplementary method S1.4 for further details).

Methods comparison and uncertainty analysis

To improve the robustness of our results and better understand how our data and methodological choices affect the final results, we conduct further analyses on methods comparison and propagated uncertainty. Specifically, we compare our results with those based on an alternative method (see Supplementary method S1.5 and Table S29). We approximate the propagated uncertainty for our main results from input data (see Supplementary method S1.6). The calculated uncertainties are reported in Tables S30-31 and are also presented alongside key results in the main text.

Data Availability

The code and results underlying this study are available in Code Ocean (TBA). 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

All authors provided inputs in the final manuscript. B.L., P.B. and H.H. designed the study. B.L., P.B. and L.S. developed the methodologies. B.L. performed the analysis, and A.J.K. contributed to the dietary scenarios. 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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