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

Supplementary information

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Contents:

1. Supplementary methods

S1.1 Method flowchart

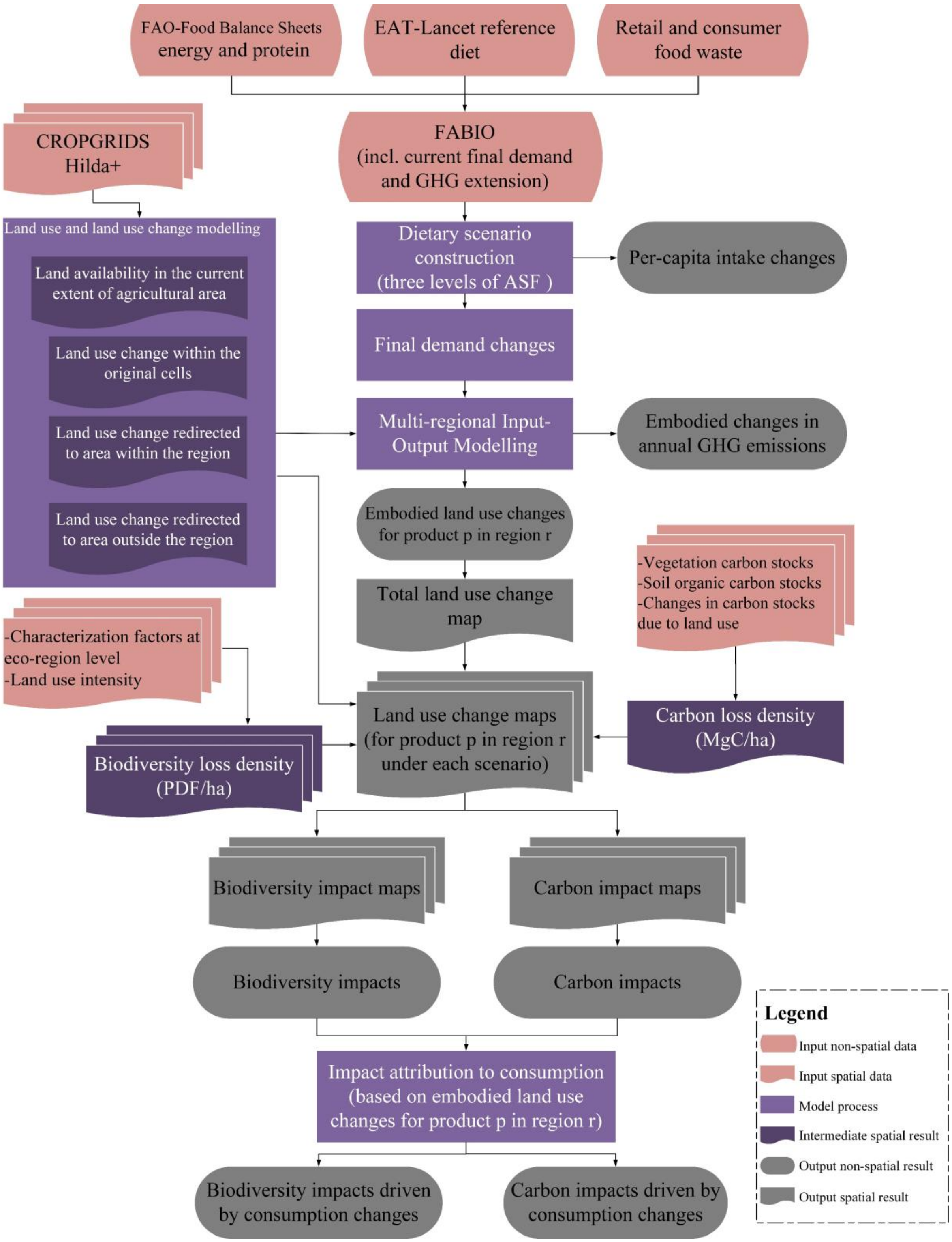

Figure S1. Method flowchart illustrating the analytical framework of this study.

S1.2 Dietary scenario and food consumption changes

We categorize the food types in the EAT-Lancet diet into five major food groups: animal protein, plant protein, vegetable oil, animal fat and other foods. The consumption amounts (in mass) of animal protein, plant protein, vegetable oil and animal fat for each scenario diet are taken from Table S2. In a Moderate ASF diet, ASF (animal protein and animal fat) reaches the upper end of the range for the recommended amount, with plant protein and vegetable oil food groups at the lower end of their ranges to ensure that the protein intake is adequate. Similarly, in a Zero ASF diet where ASF takes the lower end of the range, the plant protein and vegetable oil food groups are at the upper end of their ranges to ensure a generally sufficient protein intake. Given that some countries do not eat all types of legumes or red meat, we allow interchangeability within different legumes (dry beans, lentils, peas, soy foods and peanuts) and different red meats (beef and lamb, and pork). Before making the changes, we sum the amounts (g/day) of different legumes and red meat under each scenario in Table S2 to obtain total intake amounts for legumes and red meat.

For each country, we compile per capita baseline food consumption data (excl. food waste) at the FABIO food item level and then aggregate them to the EAT-Lancet food classification level (Tables S8-11). We calculate the scale ratios at the EAT-Lancet food classification level and apply the ratios to the linked FABIO food items, assuming the changes are at the same rate for all FABIO food items within one EAT-Lancet food classification. With the scale ratios for each food item, for each scenario, we calculate the total direct food consumption changes (in mass, including food waste) for each FABIO food item in each country (Tables S8-11). Comparing the three diet scenarios with baseline average diets across different country groups, the ASF consumption in a Moderate ASF diet is slightly lower than Western ASF (944 kcal, derived from the baseline diet in EU27), whereas the ASF consumption in a Low ASF diet is lower than that in baseline UMICs diet but higher than in baseline LMICs (Figure S2).

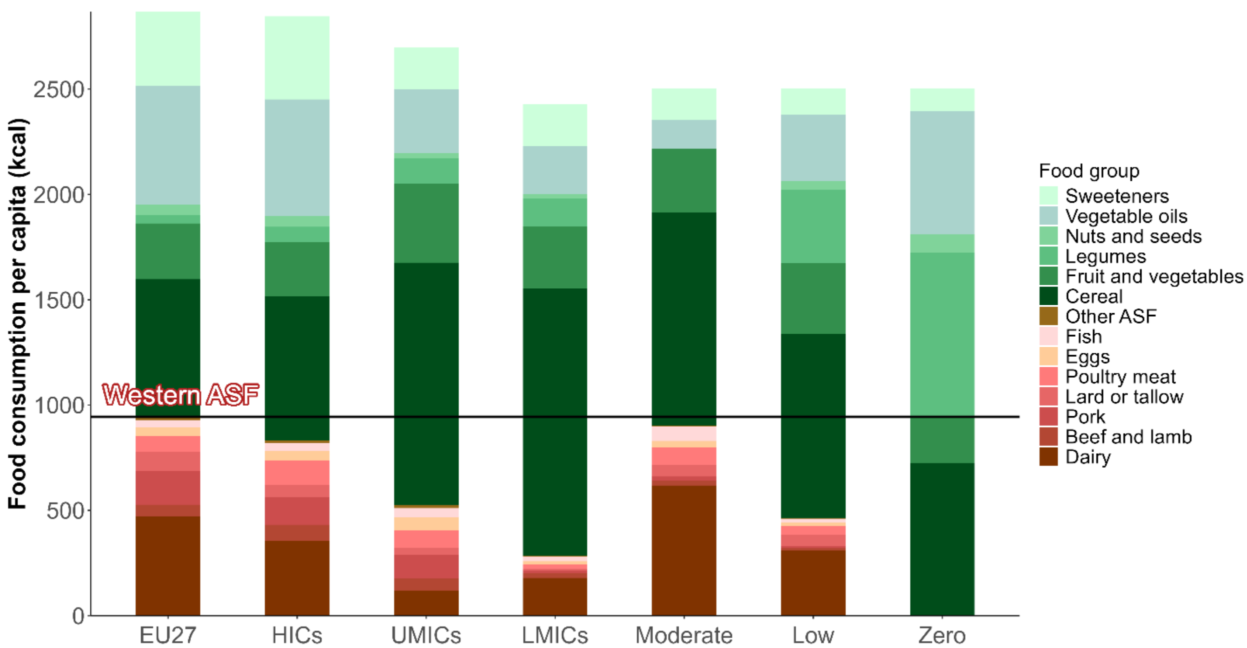

Figure S2. Per-capita food intake for the baseline and scenarios. EU27, HICs, UMICs and LMICs are the average baseline food intake across the country groups. Moderate, low and zero stand for the average food intake of the three income groups (HICs, UMICs and LMICs) under the Moderate ASF, Low ASF and Zero ASF scenarios. The horizontal line marks the average total ASF intake in the average diet in EU27 countries (Western ASF). The per-capita energy intake excludes the energy in food loss and waste in the consumption stage. Calorie intake does not include food groups that are not recommended in the EAT-Lancet diet (e.g., coffee and alcohol).

S1.3 Land use change modelling for each agricultural product in each region

We calculate the final land use change map $\Delta L_{p,r}^{f}$ for each agricultural product p in region r based on the obtained total agricultural land use change map ΔL^{f}. The process is described mathematically with Eq. 1 – 5:

$$\Delta L_{p,r}^{d} = U_{p,r} \times \frac{\Delta L_{p,r}}{L_{p,r}} \tag{1}$$

$$C_{p,r} = \frac{\sum \Delta L_{p,r}^{d,exp\_over}}{\sum \sum_{p} \Delta L_{p,r}^{d,exp\_over}} \tag{2}$$

$$\Delta L_{p,r}^{f,exp\_over} = C_{p,r} \times (L_{r}^{s,a} + \sum_{p} \Delta L_{p,r}^{d,free\_over}) \tag{3}$$

$$\Delta L_{p,r}^{f,exp\_redir} = C_{p,r} \times L^{r} \tag{4}$$

$$\Delta L_{p,r}^{f} = \Delta L_{p,r}^{d,normal} + \Delta L_{p,r}^{d,free\_over} + \Delta L_{p,r}^{f,exp\_over} + \Delta L_{p,r}^{f,exp\_redir} \tag{5}$$

$\Delta L_{p,r}^{d}$ is the land use change demand map (before redirection) for agricultural product p in region r, derived from Eq. 1. In $\Delta L_{p,r}^{d}$, areas are classified into three types, $\Delta L_{p,r}^{d,exp\_over}$, $\Delta L_{p,r}^{d,free\_over}$ and $\Delta L_{p,r}^{d,normal}$. $\Delta L_{p,r}^{d,exp\_over}$ refers to the expansion areas that overlap with L^{s} (the residual area map). $\Delta L_{p,r}^{d,free\_over}$ refers to the spared areas that overlap with L^{s}. The remaining areas are the normal areas $\Delta L_{p,r}^{d,normal}$.

$C_{p,r}$, from Eq. 2, is a scalar representing the contribution of product p to the total redirection area in region r . $\sum \Delta L_{p,r}^{d,exp\_over}$ denotes the total area of map $\Delta L_{p,r}^{d,exp\_over}$ and $\sum \sum_{p} \Delta L_{p,r}^{d,exp\_over}$ denotes the total area of map $\sum_{p} \Delta L_{p,r}^{d,exp\_over}$, which is a singer map aggregated from $\Delta L_{p,r}^{d,exp\_over}$ across all products. The summation symbol without a subscript indicates a sum over all grid cells within a raster, whereas the summation symbol with subscripts denotes aggregation of multiple raster layers across the subscripts, yielding a single raster.

$\Delta L_{p,r}^{f,exp\_over}$ is a map denoting land expansion for product p in region r that finally happens in L^{s}, derived from Eq. 3, in which $L_{r}^{s,a}$ is the available area in region r in L^{a} that overlaps with L^{s}. $\sum_{p} \Delta L_{p,r}^{d,free\_over}$ is a map aggregated from $\Delta L_{p,r}^{d,free\_over}$ across all products. The raster sum of $L_{r}^{s,a}$ and $\sum_{p} \Delta L_{p,r}^{d,free\_over}$ is a map of the total area in region r that can be used for expansion in L^{s}. We disaggregate this map to each agricultural product p based on $C_{p,r}$.

$\Delta L_{p,r}^{f,exp\_redir}$ is a map denoting land expansion for product p in region r that finally happens in L^{r} (the redirected area map), derived from Eq. 4, in which we calculate $\Delta L_{p,r}^{f,exp\_redir}$ from L^{r} also based on $C_{p,r}$.

$\Delta L_{p,r}^{f}$ is the final land use change map for each agricultural product p in region r , by Eq. 5, as the raster sum of $\Delta L_{p,r}^{d,normal}$, $\Delta L_{p,r}^{d,free\_over}$, the land expansion in the residual areas $\Delta L_{p,r}^{f,exp\_over}$ and the land expansion in the redirection areas $\Delta L_{p,r}^{f,exp\_redir}$.

S1.4 Carbon and biodiversity loss assessments

The impact of cropland and pastureland use change on carbon sequestration or biodiversity is estimated as the product of land use change maps (in hectares; positive values mean land expansion) and the carbon or biodiversity loss density maps (in Mg C/ha or PDF/ha). This approach assumes that the spared area will fully regenerate into natural vegetation, while the expanded area in each grid cell will experience the carbon or biodiversity loss density as denoted in the density maps described below.

We produce the carbon loss and biodiversity loss density maps following the methods described by Liu et al. [1]. We derive biodiversity loss density maps for cropland and pasture separately. In the cropland (or pasture) map, cells that are not currently cropland (or pasture) but within the extent of current agricultural land have no characterization factors (CFs). In this study, to enable calculations for the situation where cropland or pasture expands to non-cropland or non-pasture areas, we assign the non-cropland (or non-pasture) cells the national average CFs for cropland (or pasture) under light land use intensity (Figure S3). As the source maps cover all current agricultural areas and do not differentiate between cropland and pasture, we use the same carbon loss density map as in Liu et al. [1] (Figure S4).

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 $\Delta L_{p,r}^{f}$ with the biodiversity loss and carbon loss density maps. We calculate 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 the total impacts of agricultural product p in region r to the driving country and food group, we disaggregate it 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 in the main text with food demand changes $\Delta Y_{t,g}$).

There are a few situations where the total carbon and biodiversity impacts of agricultural product p in region r are not zero, but the associated total embodied land use change area across all dietary change countries and food groups is zero. This is caused when rasterizing polygons of very small countries without embodied land use change, as this process can be influenced by surrounding countries which have embodied areas on their boundaries. To ensure this impact is small we quantify the relative percentages of the impacts induced by this spatial mapping error to the total carbon and biodiversity impact estimates for each scenario. We find that for all scenarios, the error-induced impact percentages are well below 0.1% for both carbon and biodiversity estimates. Therefore, we do not include the error-induced impacts in our consumption-based results for carbon and biodiversity.

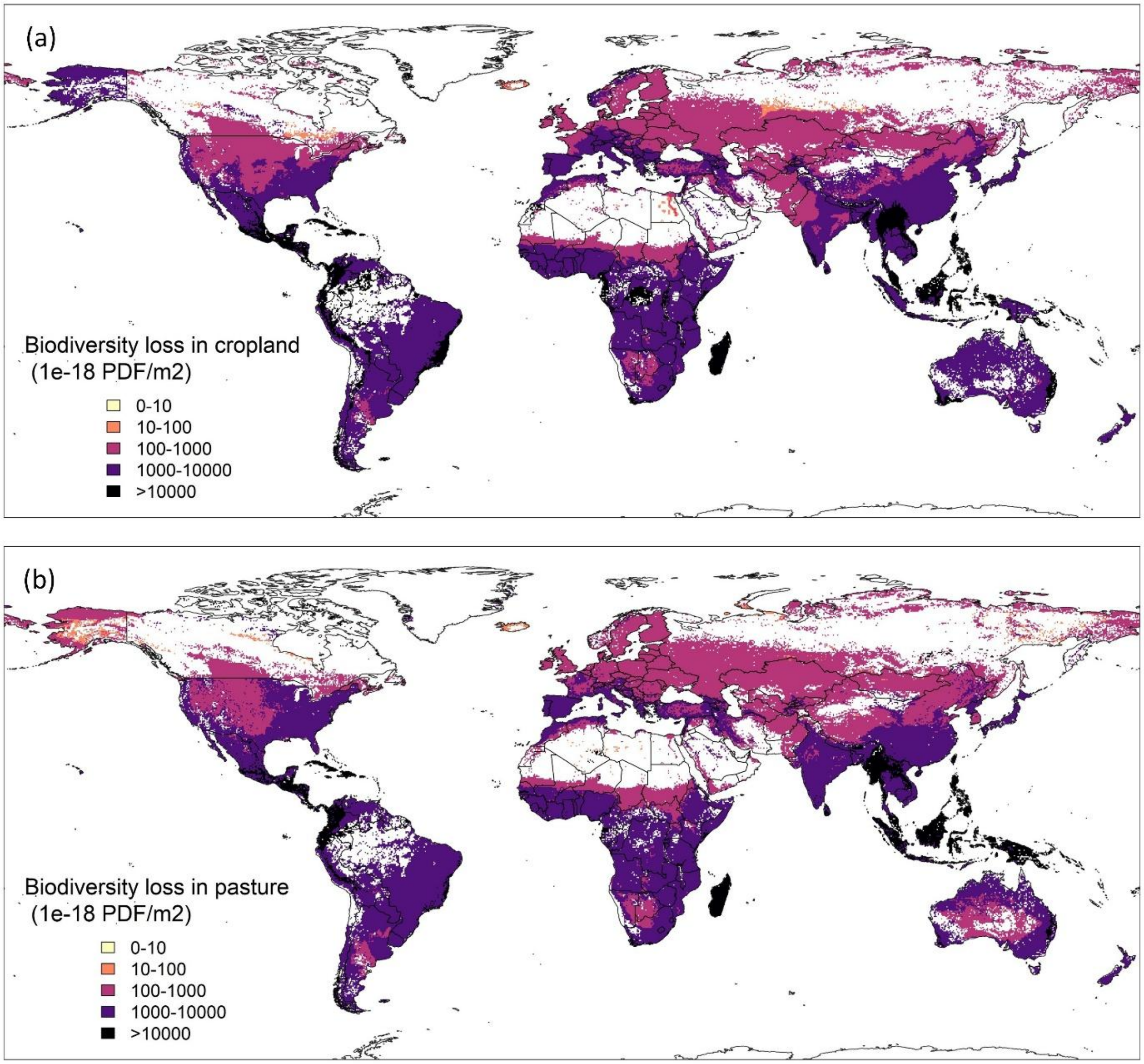

Figure S3. Biodiversity loss in cropland (a) and pasture (b). Loss represents global species loss, including five species groups – plants, amphibians, birds, mammals, and reptiles – at a spatial resolution of 3 arcmin**.**

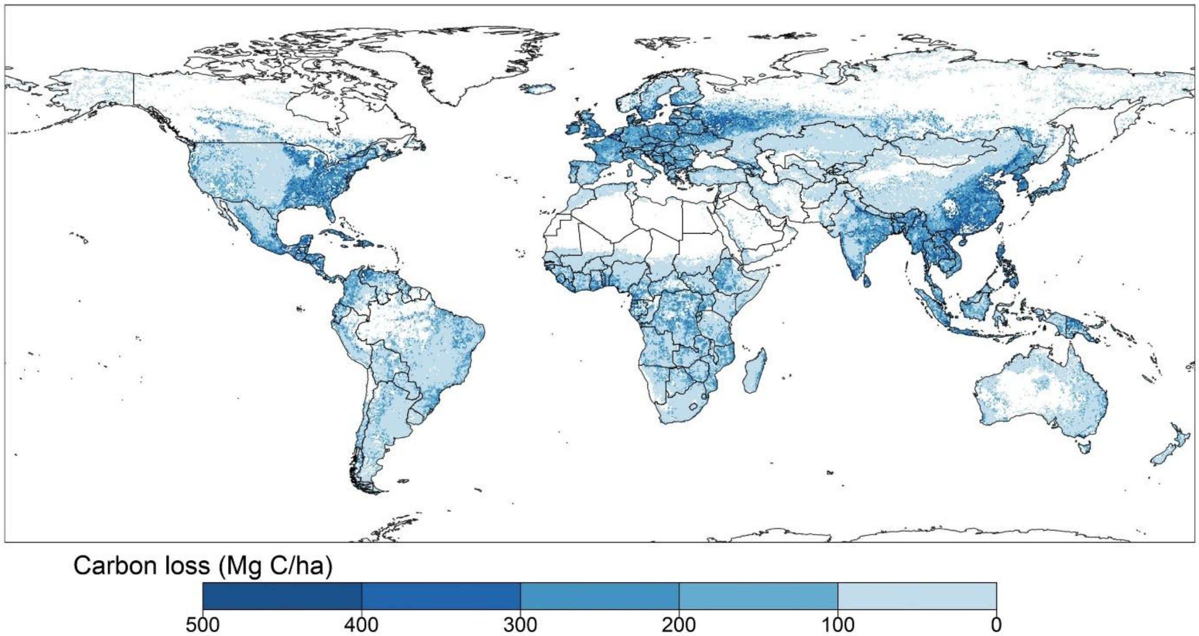

Figure S4. Carbon loss in total carbon pool (including biomass and soil) at a spatial resolution of 3 arcmin.

S1.5 Methods comparison

Here, we assess carbon and biodiversity impacts based on the simulated land use changes at the grid-cell level. We consider the land availability within each cell and redirect residual areas to other agriculture-related cells proportionally. Our approach is referred to as the grid-based method. An alternative method is using a standard Leontief consumption-driven model linking baseline carbon and biodiversity impacts to each agricultural product p in each region r (see Eq. 1 in the main text). This approach is referred to as the extension-based method. It assumes that the impact intensity for each agricultural product p in each region r remains the same as the baseline under the scenarios. It does not capture spatial constraints at the grid-cell level or actual land use change at finer scales.

To quantify how methodological differences influence carbon and biodiversity impacts, we compare the results from the two methods (see Table S29). Although the two methods yield consistent patterns across the scenarios, the grid-based method shows a larger net loss in both carbon and biodiversity under the Moderate ASF scenario, and a smaller net gain in both under the Low ASF and Zero ASF scenarios. This suggests that methods with finer spatial resolution tend to provide more conservative (more pessimistic in both gains and losses) and potentially more realistic estimates for carbon and biodiversity impacts.

S1.6 Uncertainty analysis

We perform an uncertainty analysis by approximating the propagated uncertainty for our main results from input data. Following the method in Liu et al. [1], we weigh the country-level uncertainty of land use, carbon loss, and biodiversity loss with food-related land use across production countries to estimate the uncertainty for consumption-based results for 16 food groups. For the baseline results, we use the current food-related land use across production countries; for the scenarios investigated in this study, we use the scenario-associated land use across production countries. The computed uncertainties for each food group under each scenario are shown in Table S30.

Based on the food-group level uncertainty, we calculate the uncertainty for aggregated results across multiple food groups for each scenario, using the uncertainty propagation equation:

$$\sigma_{agg} = \frac{\sqrt{\sum_g (W_g \times U_g)^2}}{\sum_g W_g} \quad (6)$$

where σ_{agg} is the estimated uncertainty for the aggregated result (e.g., food-related), W_g is the global impact (land use, carbon loss or biodiversity loss) of food group g, and U_g is the associated relative uncertainty of food group g, presented in Table S30. The calculated uncertainties of aggregated food-related results (across all 16 food groups) are reported in Table S31.

For each scenario, the change C in food-related results is calculated as the difference between the scenario result S and the baseline result B. To estimate the relative uncertainty of C, we assume S and B are independent, and use the uncertainty propagation equation:

$$U_c = \frac{\sqrt{(S \times U_s)^2 + (B \times U_b)^2}}{|C|} \quad (7)$$

where $C=S-B$, and U_s, U_b and U_c represent the relative uncertainty of S, B and C, respectively.

For relative results that are compared to baseline food-related results (e.g., in terms of food-related carbon and biodiversity impacts, Zero ASF reduces the current carbon impact by **~38%** and biodiversity loss by **~42%**), as the numerator and the denominator are dependent and likely strongly and positively correlated, we thus assume the correlation between these two variables is 1. We use the R package *propagate*[2] to perform the calculation.

The calculated uncertainties of the aforementioned two types of results, derived from aggregated food-related results, are reported in Table S31.

For relative results that are compared to the agricultural total under baseline (e.g., global species extinction risk increases by **15%** from 2020 under a moderate ASF scenario), we make the same assumption that the correlation between the numerator and the denominator is 1. The uncertainties for the denominators (the total biodiversity loss and carbon loss in agricultural land) are from Liu et al. [1], as ±21% and ±15%, respectively. Using the R package *propagate*[2], we calculate the propagated uncertainties for those results and report them in the main text. For example, under a moderate ASF scenario, the increase in global species extinction is 0.02 PDF, with an uncertainty of 108% (see Table S31). Meanwhile, the total global species extinction in agricultural land under baseline is 0.14 PDF, with an uncertainty of 21%. The calculated standard deviation for this relative change result is 13%. Therefore, we report that the global species extinction risk increases by 15% (±13%).

Our estimated uncertainties do not account for those from FABIO due to the lack of quantitative uncertainty information. However, FABIO can be a major source of uncertainty for our final results. As discussed in Liu et al. [1], we expect that our results for animal-sourced foods (probably particularly ruminant-based foods) likely carry larger uncertainty than those for plant-based foods across all scenarios.

2. Supplementary results

Table S32. Land use change in pasture and cropland under each scenario (unit: Mha). Positive values indicate land use expansion, and negative ones mean land sparing.

Scenario	Cropland			Pasture			Agricultural					
	change	baseline	total	change	baseline	total	change	baseline	total	change to baseline	baseline (food use)	change to food use baseline
Moderate ASF	29		1418	104		3036	133		4454	3%		4%
Low ASF	-2	1389	1387	-904	2932	2028	-906	4321	3415	-21%	3562	-25%
Zero ASF	-51		1338	-2098		834	-2149		2171	-50%		-60%

Table S33 Carbon loss baseline and changes under each scenario (unit: PgC). Positive values indicate carbon loss (cost), and negative ones mean enhanced carbon stock (benefit).

Scenario	Cropland			Pasture			Agricultural					
	change	baseline	total	change	baseline	total	change	baseline	total	change to baseline	baseline (food use)	change to food use baseline
Moderate ASF	3.69		188.46	70.10		181.27	73.79		369.73	24.94%		29.95%
Low ASF	-0.87	184.77	183.90	-10.37	111.17	100.80	-11.24	295.94	284.7	-3.80%	246.40	-4.56%
Zero ASF	-10.13		174.64	-82.40		28.77	-92.53		203.41	-31.27%		-37.55%

Table S34. Biodiversity loss baseline and changes under each scenario (unit: PDF). Positive values mean more loss (cost), and negative ones less (benefit). The biodiversity impact is based on the aggregated global species loss potential, which includes five species groups: plants, amphibians, birds, mammals, and reptiles.

Scenario	Cropland			Pasture			Agricultural					
	change	baseline	total	change	baseline	total	change	baseline	total	change to baseline	baseline (food use)	change to food use baseline
Moderate ASF	0.0032		0.0597	0.0176		0.0987	0.0208		0.1584	15.15%		18.25%
Low ASF	0.0051	0.0565	0.0616	-0.0163	0.0811	0.0648	-0.0112	0.1376	0.1264	-8.14%	0.1142	-9.80%
Zero ASF	0.0049		0.0614	-0.0525		0.0286	-0.0476		0.0900	-34.57%		-41.65%

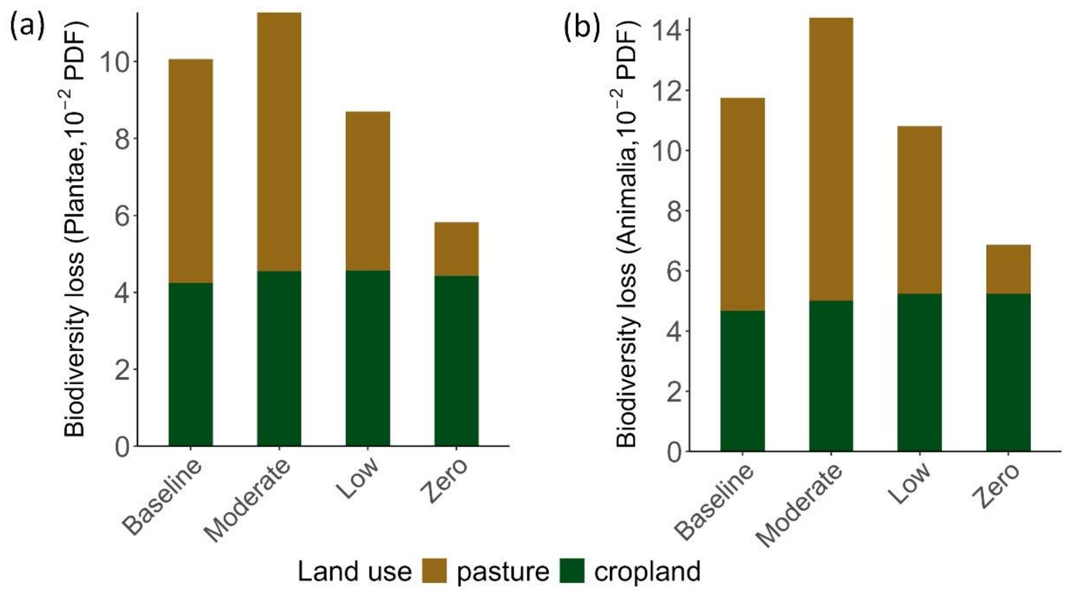

Figure S5. Total impacts on biodiversity using global plant species CFs (a) and global animal species CFs (b) for the baseline and three scenarios. Results are the total impacts from land use related to global food consumption. Consumption in low-income countries is included and is assumed to remain at the baseline level in each scenario. Moderate, low and zero stand for Moderate ASF, Low ASF and Zero ASF scenarios.

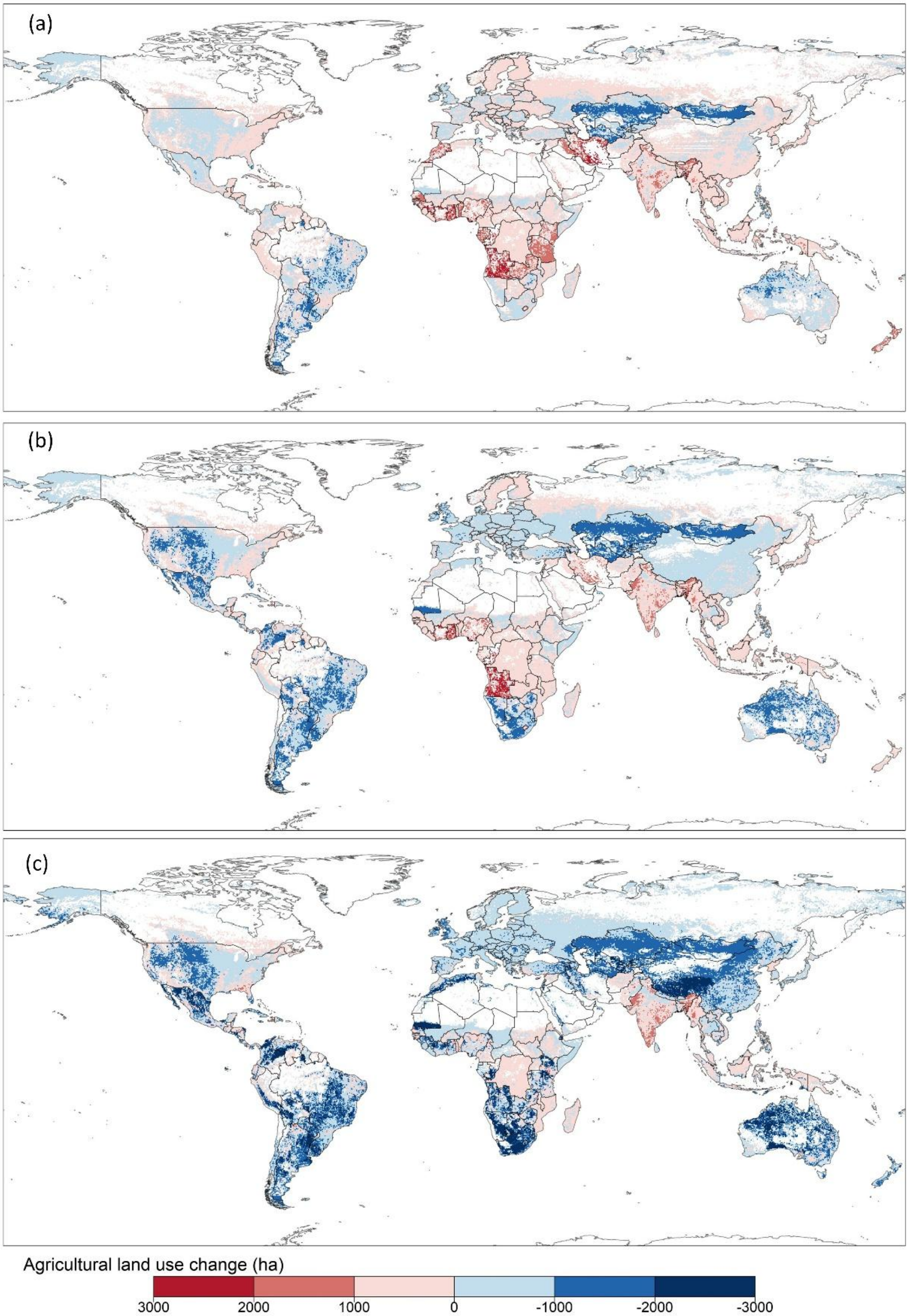

Figure S6. Agricultural land use change under Moderate ASF (a), Low ASF (b) and Zero ASF (c). Blue colours represent land sparing, whereas red colours denote land expansion. Spatial resolution is 3 arcmin.

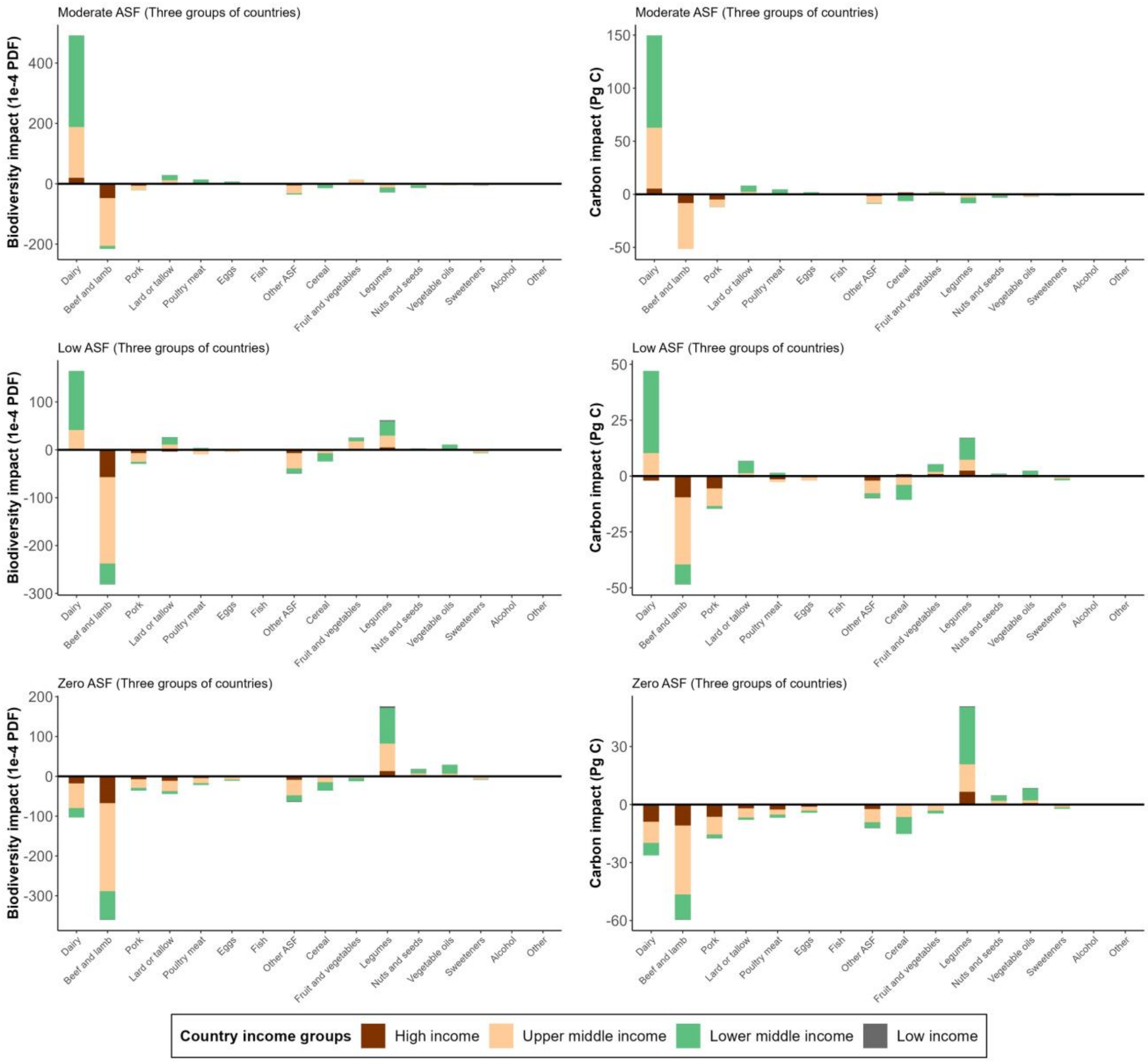

Figure S7. Costs and benefits for carbon and biodiversity in country income groups due to dietary change in three income groups. Each bar corresponds to the impacts driven by the consumption changes of each food group. The color represents where the impact occurs. Positive values mean more loss, and negative ones less.

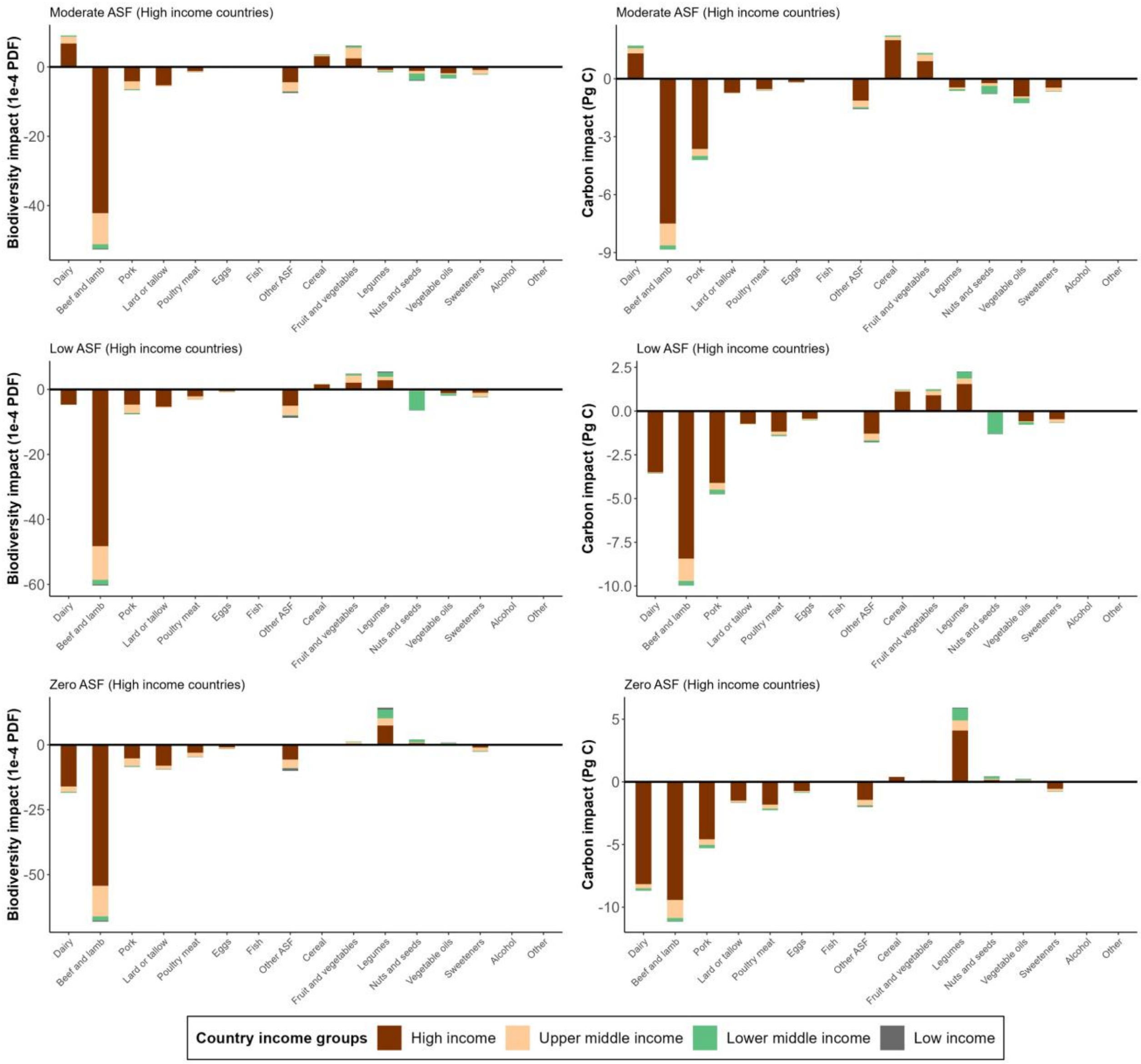

Figure S8. Costs and benefits for carbon and biodiversity in country income groups due to dietary change in high-income countries. Each bar corresponds to the impacts driven by the consumption changes of each food group. The color represents where the impact occurs. Positive values mean more loss, and negative ones less.

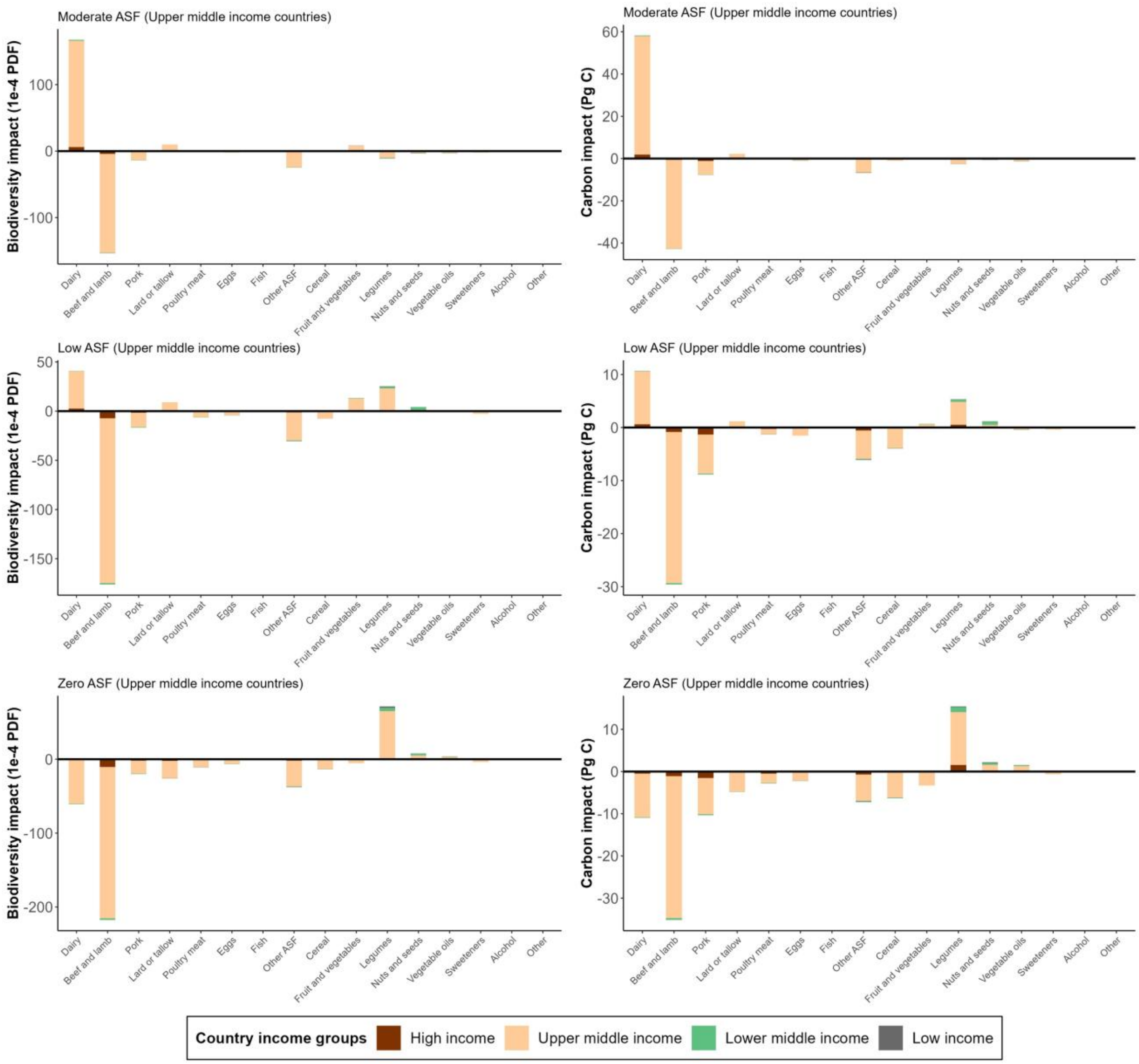

Figure S9. Costs and benefits for carbon and biodiversity in country income groups due to dietary change in upper-middle-income countries. Each bar corresponds to the impacts driven by the consumption changes of each food group. The color represents where the impact occurs. Positive values mean more loss, and negative ones less.

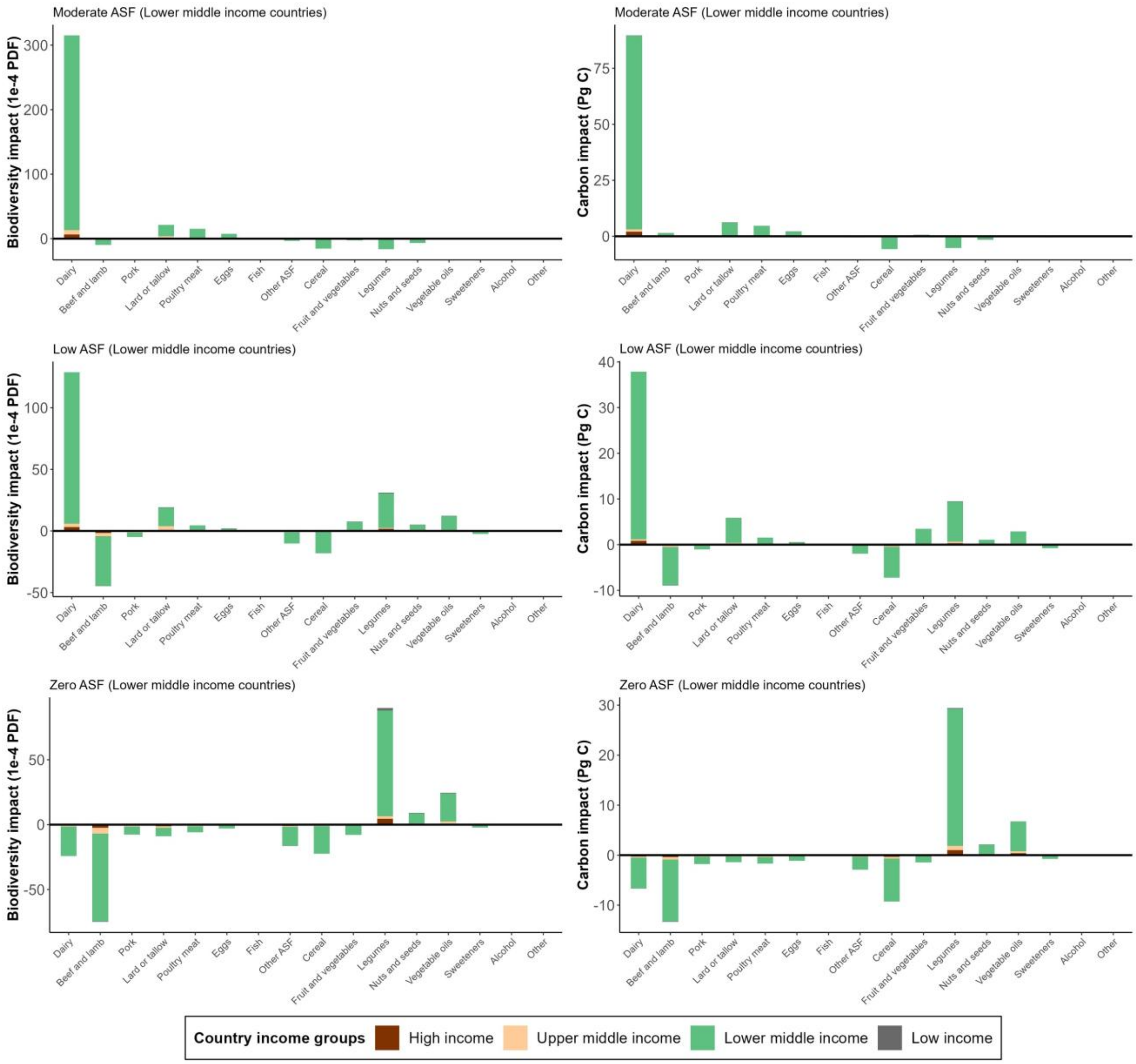

Figure S10. Costs and benefits for carbon and biodiversity in country income groups due to dietary change in lower-middle-income countries. Each bar corresponds to the impacts driven by the consumption changes of each food group. The color represents where the impact occurs. Positive values mean more loss, and negative ones less.

3. References

1. Liu, B., Behrens, P., Sun, Z. & Scherer, L. Two-thirds of agricultural carbon and biodiversity loss occurs on one-third of the agricultural area. *PREPRINT (Version 1) available at Research Square* (2025) doi:10.21203/rs.3.rs-5527595/v1.

2. Spiess, A.-N. Package 'propagate': Propagation of Uncertainty. Preprint at https://cran.r-project.org/web/packages/propagate/propagate.pdf (2025).