Quantifying the impact of the food we eat on species extinctions

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Abstract

Agriculturally-driven habitat degradation and destruction is the biggest threat to global biodiversity, yet the impacts on extinctions of different types of food and where they are produced and the mitigation potential of different interventions remain poorly quantified. Here we link the LIFE biodiversity metric – a high-resolution global layer describing the marginal impact of land-use on extinctions of ~30K vertebrate species – with food consumption and production data and provenance modelling. Using an opportunity-cost framing we discover that the impact of what we eat on species extinctions varies widely both across and within foods, in many cases by more than an order of magnitude. Despite marked differences in per-capita impacts across countries, there are consistent patterns that could be leveraged for mitigating harm to biodiversity. We anticipate the approach and results outlined here could inform decision-making across many levels, from national policies to individual dietary choices.

Introduction

The production of food to meet the needs of people is inextricably reliant on and at the same time the most salient threat to nature and biodiversity (IPBES, 2019). Alongside being one of the most significant contributors to anthropogenic greenhouse gas emissions (Crippa 2021), food provision and in particular terrestrial agriculture is the leading driver of recent and projected future losses of biodiversity (IUCN, 2024; Jaureguiberry, 2022; Tilman, 2020; IPBES, 2019). Although agriculture harms biodiversity in many ways, land-use change and habitat destruction are the most damaging mechanisms, with their impacts projected to increase substantially as global demand for food increases (Winkler, 2021; Tilman, 2017). Indeed, almost a third of the global land surface has been altered in the past six decades, and the expansion of arable and grazing land is ongoing, and in some cases accelerating (Potapov, 2022; Williams, 2021; Zalles, 2021).

Halting biodiversity loss and especially extinctions arising from agriculture is thus a key policy concern (Pettorelli, 2021; Scherer, 2020), but effective mitigation hinges on the robust quantification of the impacts of different foods, how these vary spatially, and how they might be reduced by changes in consumption patterns, provenance, or production methods. Spatial layers and summary metrics can inform the efficacy of candidate interventions across diverse scales and actors: from individuals to governments, and from personal dietary choices to national trade policies. Yet to date, there is no agreed-upon method for assessing the biodiversity impacts of food (Damiani, 2023) and despite concerted efforts, attempts to quantify the impacts of agricultural commodities have been limited in spatial and methodological scope. Drawbacks of two important current metrics include prescribed factors based on estimates (Verones, 2022) and the inclusion of only those species which are endemic to ecoregions (Chaudhary, 2019). Green (2019) assessed the impact of soy using state of the art provenance modelling and a pre-cursor to the more comprehensive metric used in this paper (Duran, 2020), but the study was limited to the Brazilian Cerrado.

Schwarzmueller (2022) linked consumption to production impacts via trade and the Species Habitat Index (CBD Secretariat, 2021), but because this uses a year-2000 baseline, only capturing historic damage rather than ongoing impacts and the potential for restoration. Scarborough (2023) links biodiversity and other outcomes on a commodity-specific basis but forgoes any element of spatiality and hence is unable to capture provenance as a lever for mitigation. To address these shortcomings in quantifying the biodiversity impacts of the food system, here we bring together best-available national data on the consumption and provenance of 140 food types with the LIFE (Land-cover change Impacts on Future Extinctions) metric (Eyres, in review). LIFE integrates information on species' habitat preferences and ranges in the absence of people (IUCN, 2024) with estimates of habitat losses to date to map (at 1.8km^2 resolution) the marginal impact of land-cover change on the extinction risk of ~30,000 individually assessed terrestrial vertebrate species (Eyres, in review).

The marginal impact of current food consumption on biodiversity can be viewed as the forgone opportunity to restore biodiversity arising through ongoing agricultural land use. By linking LIFE with spatial crop and pasture distributions (FAO & IIASA, 2024; Klein-Goldewijk, 2017), consumption, production, and trade data (FAO, 2024), and the provenance modelling approach taken by Schwarzmueller et al. (2022), we therefore quantify the opportunity cost to biodiversity of producing or consuming one kilogram of each FAO-aligned food commodity in 174 countries, taking the feed and grazing requirements for animal products into account. We elected to use FAO data, in which post-production food waste and on-farm losses are embedded in consumption and production data respectively. Our analyses are thus based on LIFE 'scores' – changes in the statistically expected number of extinctions (ΔE) summed across all ~30K species – which we estimate for one unit of production of each commodity in each country (see Eyres, in review for more information on LIFE units). Using these data we first quantify the mass specific impact on expected extinctions of producing each commodity and how this varies globally, and then examine per-capita consumption impacts of exemplar countries with disparate trade, production, and consumption profiles. Last, we illustrate the power of our approach for quantifying the mitigation potential of interventions by estimating the potential impact of simple dietary changes.

Results

Variation in the opportunity cost of food production

Animal products generally have substantially greater impacts on species' extinctions than staple vegetal products (Figure 1). This is a result of the inherently inefficient nature of these products (Halpern, 2022; Poore, 2018): producing a unit of animal product requires grazing land and/or cropland for feed production, which when combined with the intrinsic feed conversion efficiency of animals leads to high land-use and hence extinction impacts. Ruminant meat, for example, thus has a weighted global median opportunity cost on species extinctions ~340 times greater than that of grains. This finding is unsurprising, given that more than three quarters of the human-appropriated land-surface is dedicated to the production of animal products while providing only 17% of global calories (Ritchie, 2019).

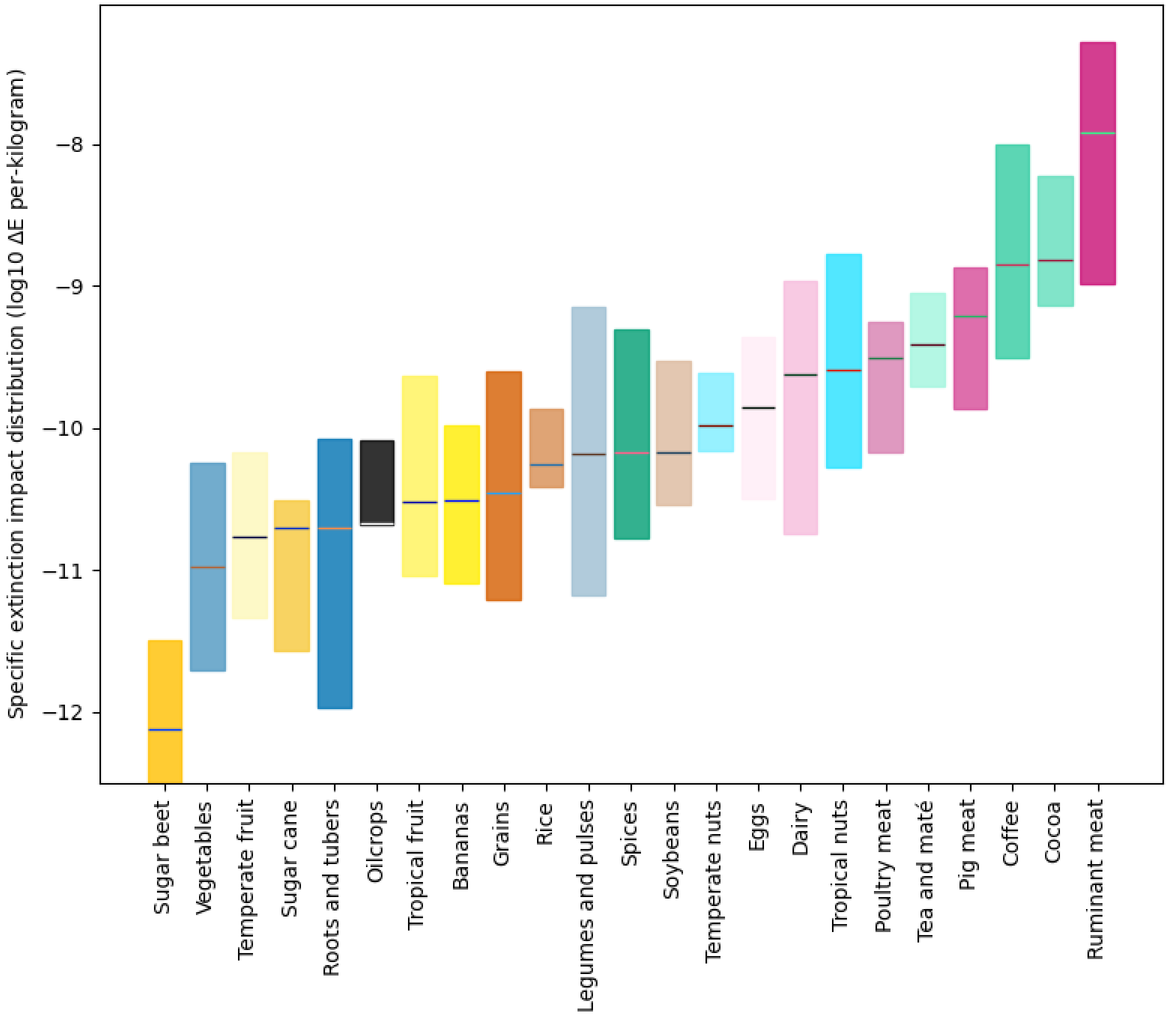

Figure 1. Global variation across and within commodities in the expected extinction impact of producing one kilogram of agricultural commodity or commodity group. The lower and upper boundaries of the boxes represent the production-mass weighted 10th and 90th percentiles respectively. Horizontal lines represent the weighted median (50th percentile). Where commodities are grouped, the per-kilogram extinction risk values of each constituent commodity are weighted by their contribution (by mass) to the total global production of that group.

In general, staple crops have relatively low impacts on species extinctions; grains (excluding rice), vegetables, roots, oil-crops, and fruits all sit between 10^-10 ΔE/kg and 10^-11 ΔE/kg. Conversely 'luxury' crops (those with little to no calorific benefit but generally commanding a high price) such as coffee, cocoa, tea, and spices are all toward the higher end of the impact distribution per-kilogram – although of course these commodities are typically consumed in relatively modest amounts. Sugar beet has an extremely low impact per-kilogram; it is high-yielding compared with most other crops (FAO, 2024), and its production is concentrated in northern and central Europe and northern USA, where the opportunity-cost to biodiversity of agricultural land-use is relatively low.

The extinction impact of one kilogram of production varies within most commodities by nearly an order of magnitude, with some varying significantly more. Exceptions to this general pattern include commodities whose production is dominated by a handful of nations. For example, India and China alone produce around 50% of the world's rice with relatively similar per-kilogram impacts, hence there is relatively low variation in global impacts of rice. The opposite is true of commodity groups that are produced in many different locations – grains, legumes and pulses and dairy products, for example, are produced in significant quantities on every continent and vary in their per-kilogram impacts by almost two orders of magnitude. Likewise impacts vary widely with provenance for coffee. Coffee produced in South America and Sub-Saharan Africa has an impact approximately 10 times greater than that produced in southeast Asia, explained by lower per-area LIFE opportunity-costs and higher yields of *robusta* coffee, which dominates Asian production (Bunn, 2015), compared with *arabica*, which dominates production elsewhere.

Generally, commodities that are produced in tropical or sub-tropical regions have higher per-kilogram impacts than those from temperate regions (evident from the distinction between temperate and tropical fruit and nuts, for example). This is unsurprising, given that tropical regions often house exceptional levels of biodiversity and endemism, greatly increasing the impacts of agriculture on global extinction. In the next section we explore the issue of location in more depth by comparing the extinction impacts of food consumption across six countries with widely differing dietary and sourcing profiles.

Across-country differences in the impacts of food consumption and provenance

We selected six countries as examples for which to compare consumption impacts - the USA, Japan, and the United Kingdom as Global North nations with high, moderate, and low levels of agricultural self-sufficiency, respectively (Beltran-Peña 2020; DEFRA, 2023a); Brazil as a largely self-sufficient, highly productive tropical country which is a globally important producer of many commodities (soy, corn, sugar cane, cattle meat, fruits, and nuts; Valdes, 2022); Uganda as one of several nations in Sub-Saharan Africa that, whilst not reliant on imports, nevertheless faces widespread malnutrition (The Economist, 2022; Development Initiatives, 2018); and India as a largely self-sufficient country and a major exporter of rice, sugarcane, and tea (Beltran-Peña, 2020).

Our results reveal the overwhelming contribution of ruminant meat consumption to the per-capita extinction impact of food consumption in every one of these countries (Figure 2). The impact profiles of the three nations in the global north are driven almost entirely by their ruminant meat intake, suggesting that even small changes to diet composition would have proportionally large consequences (see next section). In the case of the USA, cattle production is concentrated in southern states, where the extinction impact of a unit area of agricultural land-use is much higher than the north (Eyres, in review). While the UK and Japan consume comparable quantities of ruminant meat per-capita, the UK's ruminant footprint arises largely from imported cattle and sheep meat from Australia and New Zealand (approximately 25% of consumption) and soy imported from South America. On the other hand, roughly half of all ruminant meat consumed in Japan is imported from high-impact regions (in particular, the USA, Australia and New Zealand, and Mexico) and so on-average the per-kilogram impact of consumption is far greater. Even in India, where approximately one third of the population are lacto-vegetarian and cattle slaughter is banned in many states (Devi 2014), ruminant meats (mainly sheep and goat meat) contribute of 40% of the impact of people's diets on species extinctions.

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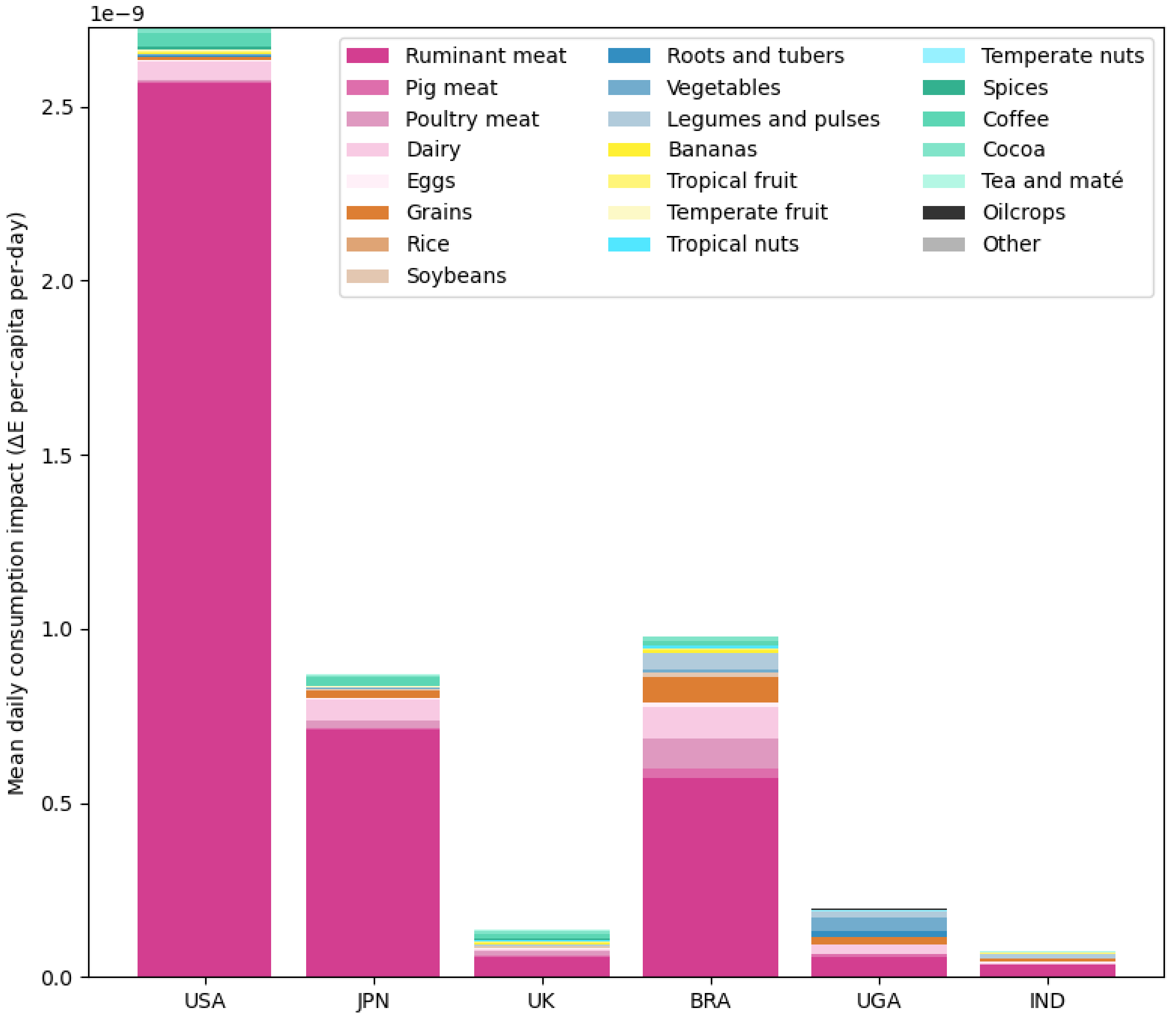

Figure 2. The mean daily specific extinction impact for consumption within the USA, Japan (JPN), the United Kingdom (UK), Brazil (BRA), Uganda (UGA), and India (IND). Note that due to complex and opaque supply chains, sugar impacts have been excluded from these consumption analyses.

Unpacking the issue of provenance further, Figure 3 shows the proportion of the impact of consuming one kilogram of a commodity that arises from imported food. The extinction impacts of food consumption within the United Kingdom and Japan are both driven almost entirely by imports. Although these countries produce 60% and 38% of their food domestically (DEFRA, 2023a; MAFF 2023), 95% and 98% of their impacts respectively come from imported commodities. In terms of species extinctions, for both nations almost all of the impacts of food they consume are accrued in other nations. Given their size and population densities, some reliance on imported food is inevitable, but this result suggests that sustainably intensifying domestic production and investment into less damaging production overseas should be key policy concerns for these countries. Conversely, current trends in both countries towards promoting low-yielding domestic agriculture (DEFRA, 2023b; USDA, 2021) – which may increase reliance on imports from higher-impact regions – are a cause for concern. In addition, for the UK, the effects of post-Brexit trade deals on the extent to which they increase imports of ruminant products from Australia and New Zealand should also be carefully scrutinised (Roberts, 2024; Bateman, 2023; Fuchs, 2020).

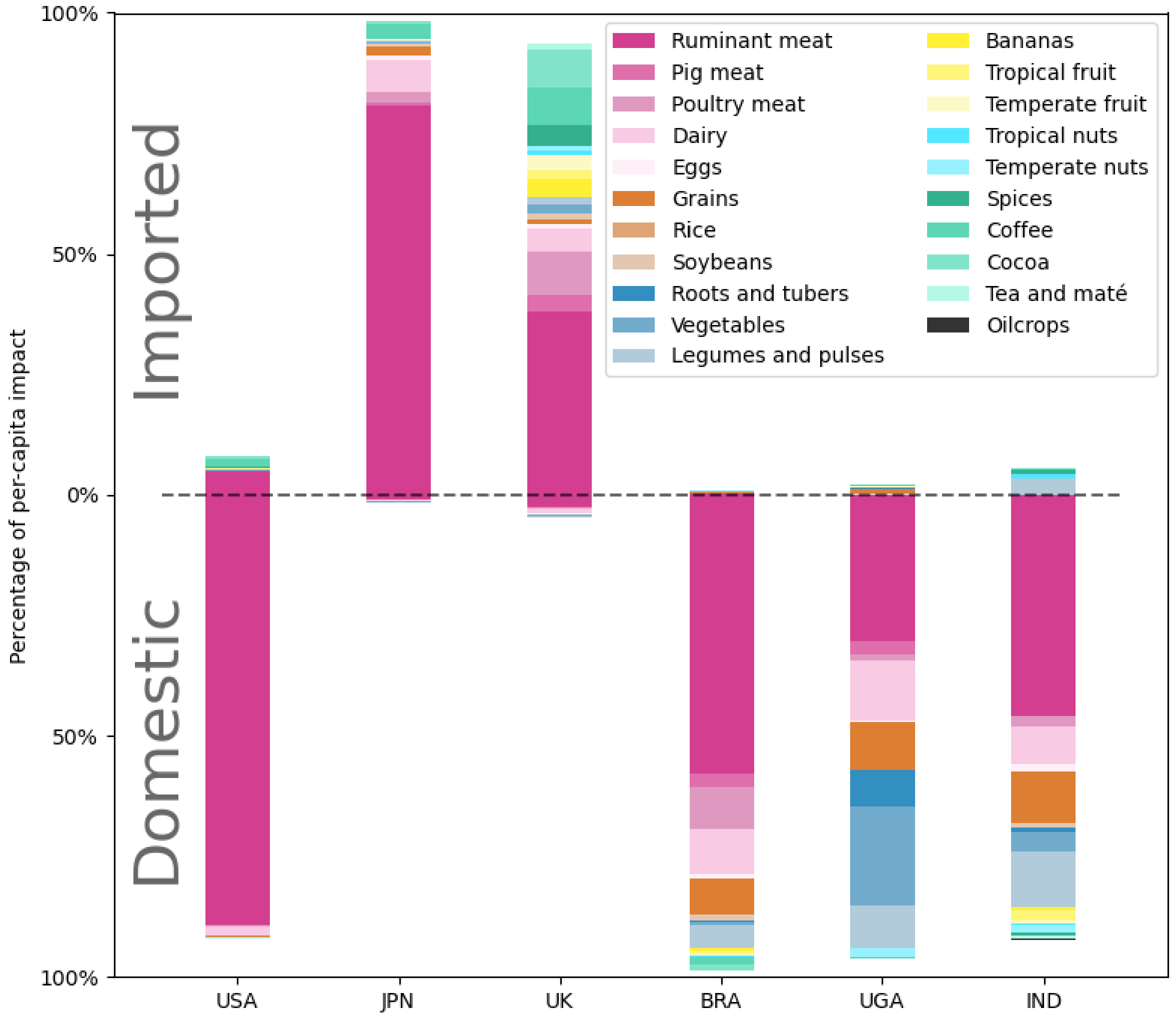

Figure 3. The percentage of per-capita consumption-driven extinctions arising from imported (above the dashed line) and domestically produced (below the dashed line) food commodities, estimated for USA, Japan (JPN), the United Kingdom (UK), Brazil (BRA), Uganda (UGA), and India (IND). Once again sugar is excluded from these analyses.

In contrast, the extinction impact of food consumed in Brazil, Uganda, and India arises very largely from domestic production, with the impact of imports being just 2%, 9%, and 4% respectively. We suggest reducing the impacts of the food people need in these countries will often best be addressed by sustainably increasing yields and thus increasing production to meet rising demand without clearing remaining areas of natural habitat (Bateman, 2023; Balmford, 2021). The USA also has a low proportion of import-driven impacts (~10%) - it produces the bulk of its food domestically, although it is nevertheless reliant on imports of commodities such as coffee and bananas – however, yields in the USA are already relatively high (at least, for vegetal products), so conservation policies may be more effective if directed at dietary shifts (Williams, 2021), as we explore in the next section.

Dietary shift in the USA

Last, turning from consumption and provenance, we illustrate for the USA how our approach can be used to investigate the potential impact of various broad changes in people's diets. We constructed simple scenarios which modify the relative consumption of food groups based on vegetarian and plant-based Eatwell guides (PBHP.UK, 2023; NHS, 2022a, 2022b; Sustain, 2018), and a no-ruminant scenario in which poultry and pig meat replace ruminant calories (Table 1). The total calorific contribution of the modified groups was scaled to meet the calorific value of the products that are replaced such. In reality, vegetarian

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and plant-based consumers are likely to have lower total calorific intakes, so we probably underestimate the mitigation effects of shifting to such diets (Scarborough, 2023). Stimulants and spices do not meaningfully contribute to calorific intake, so we elected to set them as constant.

Table 1. Contributions to total calories of different food groups in the basic dietary scenarios. Each scenario has the same overall calorific intake as the baseline.

	Fruit and vegetables	Legumes, beans, nuts	Grains, roots, starchy carbohydrates	Dairy	Eggs	Ruminant meat	Poultry and pig meat
No-ruminant	Baseline	Baseline	Baseline	Baseline	Baseline	None	Replaces ruminant
Vegetarian (Eatwell)	40%	10%	35%	10%	5%	None	None
ePlant-based (Eatwell)	40%	25%	35%	None	None	None	None

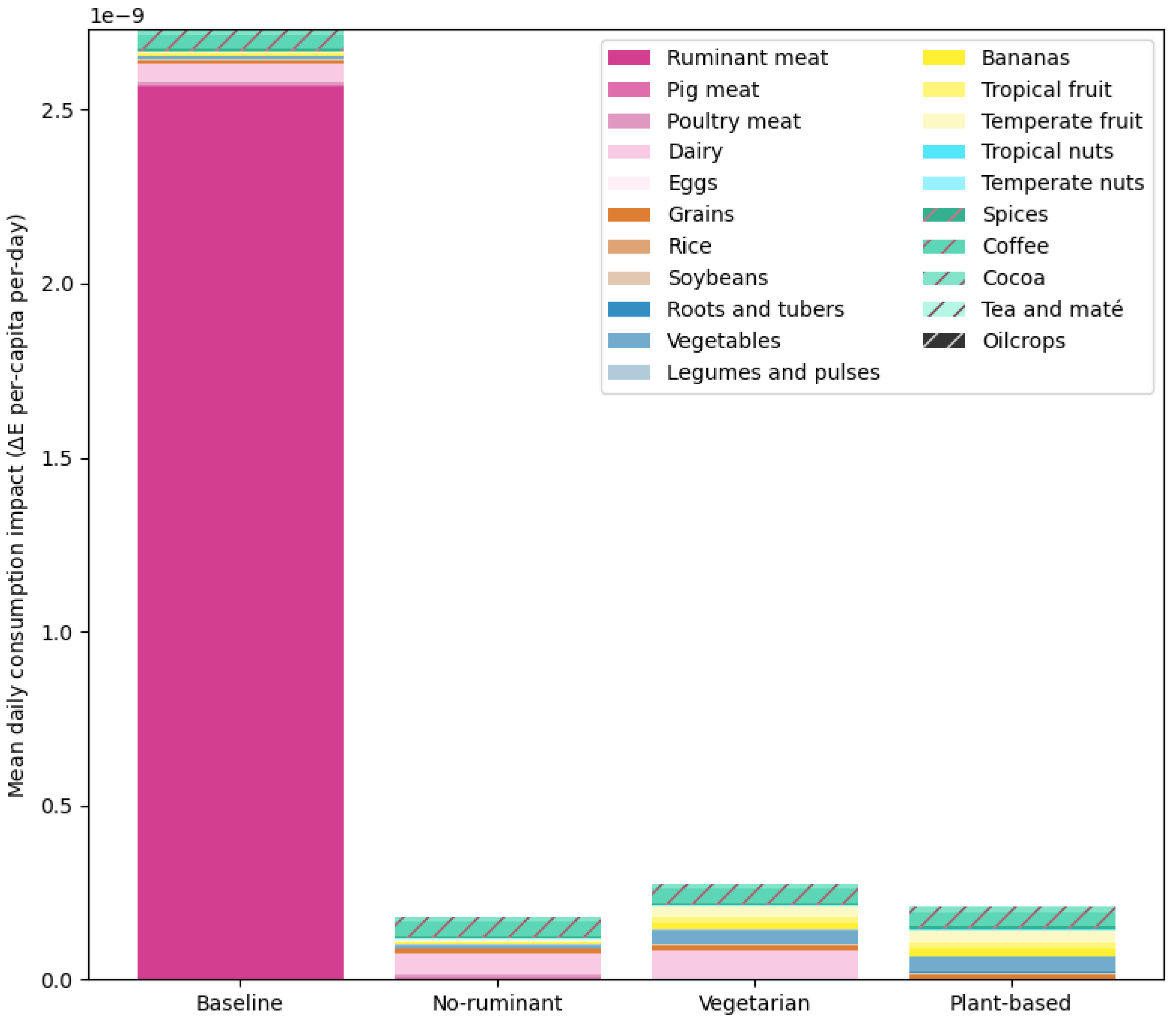

Figure 4. The extinction impacts of average daily per-capita food consumption in the USA for consumption in 2021 (FAO, 2024) and three basic individual dietary scenarios (see Table 1). Spices, coffee, cocoa, tea and maté are hatched since their intake remains constant across scenarios. The no-ruminant diet has ruminant meat calories replaced with poultry and pig meat calories in the ratio that they are currently consumed. The vegetarian and vegan diets are based on 'Eatwell' plates, with constituent commodities

consumed in the same ratios that they currently are within each group (PBHP.UK, 2023; NHS, 2022a, 2022b; Sustain, 2018).

Our results underscore the greatly disproportionate extinction impacts of eating animal products, especially ruminant meat. Replacing ruminant calories like-for-like with poultry and pig meat leads to a dramatic decrease of 90% in overall extinction impact of people's diets. The vegetarian and plant-based diets have impacts slightly higher than the no-ruminant scenario (50% and 10% respectively) due to the approximately 4-fold increase in the intake of fruits and vegetables in those scenarios compared to the baseline. Clearly, there is significant scope for reducing the harm to nature by changing consumption patterns given the prominence of ruminant meat impacts in the USA, but mitigating impacts in a healthy way beyond reducing ruminant consumption is likely to be more complex, and subject to location and sourcing.

It is important to note that due to economic and other non-linear effects which will be discussed in the next section, these results are not reflective of a scenario in which *everyone* in the USA changes diet at once. We also conducted this analysis for the United Kingdom (see supplementary materials), finding that replacing animal-derived calories with entirely plant-based calories leads to just over 50% reduction in impact – notably a similar finding to that of Scarborough (2023), assuming that baseline consumption is comparable with the medium meat-eater group in that study.

Discussion and caveats

The impact on species extinctions of producing food varies dramatically, in many cases 10-100 times per kilogram, both within and between commodities. Unsurprisingly, the per-capita impact of consumption also varies significantly between countries, again by over an order of magnitude. Animal products, in-particular ruminant meat and 'luxury' commodities like coffee and cocoa have consistently high extinction impacts, with median per-kilogram values being over 100 times greater than those of grains and roots. Indeed, together they form the majority of per-capita consumption impacts for all countries assessed in this study. Given that agriculture is and will continue to cause greater harm to biodiversity than any other sector, recognising, understanding, and addressing these patterns will be critical in informing decisions at national, subnational, and individual scales aimed at curbing the global extinction crisis.

The combination of methodologies used in this paper have furnished us with a powerful apparatus for further research, with the capacity to explore the effects of several levers to effect change. Future work might examine the effects of reducing food waste and losses, of intensifying agricultural production and hence reducing land-use, or of shifting trade policy toward sourcing from less-impactful regions.

Our analyses are subject to three important sets of caveats. First, they exclude aquatic foods, and in part sugar. The LIFE metric is driven by the conversion of terrestrial habitat types, and thus any assessment of the impact of fish production or consumption on species extinctions would be limited to the cropland used for aquaculture feed. It might in future be possible to derive estimates of the impacts of habitat damage or bycatch from fisheries, to facilitate comparison of fish with terrestrial products, although terrestrial impacts generally outweigh those in aquatic systems (Halpern, 2022). Importantly, sugar is only partly included in our analyses. Sugar, beet and cane have very different per-kilogram extinction impacts (Fig. 1) but supply chain data do not distinguish which of them traded sugar is derived from, so we were unable to include sugar reliably in our consumption analyses.

Second the results presence here rely on best-available but still relatively coarse species and agricultural data: the crop and livestock distributions from GAEZ and Gridded Livestock of the World have resolutions of 5 arcminutes (or ~9km at the equator), which may fail to capture nuances in more heterogenous landscapes. The representation of grazing livestock is also limited by the quality and availability of data: global, spatial grazing productivity data (i.e. 'yield' for pasture at the commodity level) does not to our knowledge currently exist, but would be invaluable in improving our results. LIFE is also fairly coarse in its current iteration – it relies on species distribution and habitat preference data from the IUCN, subject to varying degrees of estimation. However, LIFE has been designed around an incremental pipeline, so, as better resolution data become available, LIFE values can easily be recalculated, and analyses updated.

A third caveat is around marginality. The production and trade data can be used to indicate the opportunity cost of producing a unit of production of a commodity, but clearly economic factors such as price effects and substitution mean such values cannot be extrapolated to estimate overall impacts at national or global scales. The LIFE metric itself also of necessity takes a marginal approach: it is based on the understanding that extinction risk changes with the fraction of a species' potential area of habitat which is currently available to it in a convex, non-linear fashion (Eyres et al. in review). This non-linearity means that the aggregate impact of global food production and consumption cannot be estimated by extrapolating from marginal effects. Moreover, the LIFE metric has significant scope for improvement – in particular through the introduction of habitat quality and conversely degradation: habitats are treated as either suitable or not, hence not capturing the nuances of land-use and production intensity. Nonetheless, ceteris paribus the individual and per-kilogram scale results presented in this paper are valuable and provide a robust approach for further research and development.

Despite these limitations, we believe that this study represents a significant improvement on previous efforts to link food production and consumption with global extinctions at the national and commodity level. Two findings in particular stand out. Clearly governments, corporations, individuals, and others concerned with averting the extinction crisis cannot do so without taking steps to dramatically reduce consumption of animal products, especially ruminant meat. Significant reductions in the impacts of animal products might be achieved through intensification and hence land-use reduction – but often this comes at the cost of animal welfare (Broom, 2019). Second, great care should be taken by countries to avoid increasing their already out-sized impacts by adopting land-use and trade policies which will increase the offshoring of production of the food they eat to more biodiverse parts of the world. It seems implausible that these core findings will change as better data become available.

Methods

Our approach allows us to estimate the extinction impact of both the production and consumption of food commodities in terms of the forgone opportunity to reduce extinctions through habitat restoration because of continued agricultural land-use. In the case of production of vegetal products, impact values are derived from the weighted median national LIFE score (per unit area) for the spatially explicit locations in which that commodity is produced. To derive these estimates, we intersect a partially modified version of the LIFE 'restore' layer (Eyres in review, see supplementary information) with crop production layers from the Global Agro-Ecological Zones (GAEZ) project (FAO & IIASA, 2024). For animal products, the impacts depend firstly on the LIFE scores associated with grazing land, which we obtain by following Alexander (2017) and using Gridded Livestock of the World data (Gilbert, 2018) to weight cell contributions; and secondly cropland used to produce any feed consumed by the animal. This feed may is often imported, so our framing allows us to capture the impact of South American soy used in the production of animal products in northern Europe, for example.

Note that LIFE is a metric of marginal change – the certainty of results reduces as cell values are aggregated – however, modelling analysis conducted in Eyres (in review) finds that this deviation remains very low (<10%) for land-cover changes up to around 1000km^2, larger than per-kilogram or per-capita analyses would precipitate.

The global distribution of impacts for each commodity is calculated as a production mass-weighted distribution of the median values for each commodity across all countries. This means that, for example, if country *a* produces 100 bananas, and country *b* produces 3 bananas, the weighted median (50th percentile) impact of bananas would be much closer to that of *a* than of *b*. To calculate the consumption-side impacts of countries, we use the method described by Schwarzmueller (2022) to estimate the provenance portfolio of commodities consumed within each country, the distribution of which we use to weight the previously calculated impact values for that commodity in that country. See the supplementary information for more detail on these calculations.

For our simple representation of the impacts of in the USA, we used a baseline mean daily caloric intake of 3911 kcal per capita (FAO, 2024). For the no-ruminant scenario, calories derived from ruminant meat in the baseline were replaced with poultry and pig meat calories in the same ratio that they are consumed in the baseline. For the vegetarian and vegan dietary scenarios, the total calories available in the baseline were allocated to each of the food groups via the proportions derived from vegetarian and vegan 'Eatwell' plates from the Vegetarian Society and Public Health England respectively (PBHP.UK, 2023; Sustain, 2018).

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