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RESEARCH

Terrestrial biodiversity impacts of replacing beef with alternative-protein burger patties across ten European Union Countries

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Abstract
Alternative-protein patties are increasingly promoted for their lower environmental footprint, yet their impacts on terrestrial biodiversity remain poorly understood. This study compares conventional beef patties with four alternatives — pea, soy, insect, and mycoprotein across ten selected countries. By integrating input–output models with GLAM Life Cycle Impact Assessment with increased impact pathway coverage, this study quantified terrestrial biodiversity impacts driven by land occupation and climate change embedded in food supply chains. Results show that land occupation dominates, accounting for over 96% of the total terrestrial biodiversity impacts. Among the alternative-protein patties, soy patties generally perform the best across the ten countries. Replacing beef with the soy patties in food service could reduce biodiversity impacts by 71–97% per patty and correspond to a 3.6–4.9% reduction in national biodiversity loss associated with beef across the ten countries. Pea and mycoprotein patties exhibit the highest impacts, driven predominantly by coconut oil sourced from biodiversity-sensitive countries, notably the Philippines and Indonesia. In Belgium, the Czech Republic, Germany, and Poland, pea patties' biodiversity impacts even exceed those of beef patties. These findings underscore the dominant role of sourcing from biodiversity-sensitive regions and highlight the importance of substituting high-impact ingredients (e.g., coconut oil) or shifting ingredient sourcing away from high biodiversity-sensitive regions.

Keywords Input–output analysis · Life cycle impact assessment · Industrial ecology · Supply chain · Food system · Meat analogues

1 Introduction

Food production has a profound impact on the global environment. Around 40% of all habitable land is used to produce food, causing 80% of deforestation and 70% of biodiversity loss on land (WWF, 2025). FAO estimated a 60% increase in food production by 2050 (Bruinsma, 2009). The projected rise in global population and higher per capita rates of animal product consumption suggest that livestock production is set to increase (Tilman & Clark, 2014). Livestock production is the most impactful activity in the food production system (Steinfeld and FAO, 2006). It consumes one-third of the global cereal harvest and requires about 40% of global arable land and all of the pastures (Mottet et al., 2017). This extensive demand drives widespread deforestation and converts diverse ecosystems into pastures or monocultures, with serious consequences for biodiversity (Bidoglio et al., 2024; Kastner et al., 2021; Van Huis, 2013).

While land use and associated biodiversity loss are critical concerns, food production also exerts a substantial impact through greenhouse gas (GHG) emissions, contributing to a third of total emissions (Crippa et al., 2021). Land use and land-use change (Friedlingstein et al., 2023; Herrero et al., 2016; Stevanović et al., 2017; Van Loon et al., 2019; Vermeulen et al., 2012), fertilizer use (Herrero et al., 2016; Van Loon et al., 2019), and livestock production (IPCC, 2021; Lamb et al., 2021) are major sources of agricultural GHG emissions. Among these, cattle production emerges as a major contributor (Cheng et al., 2022), as it involves not

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only direct on-farm emissions from enteric fermentation, manure management, and energy use, but also substantial indirect emissions associated with feed production and land-use change from pasture and cropland expansion (Bidoglio et al., 2024; Herrero et al., 2016). These GHG emissions contribute to global climate change, which in turn accelerates biodiversity loss by altering habitats, disrupting migration patterns, and intensifying extreme weather events (John, 2019).

International trade is a major driver of global biodiversity loss, with around 30% of global species threats attributable to internationally traded goods and services (Kastner et al., 2021). A large share of threats is driven by consumption in developed countries and displaced to producing regions in developing countries (Lenzen et al., 2012). Tracing the geographical origin of food products is therefore essential for environmental assessments, as impacts can vary substantially across producing countries (Godar et al., 2015; Vanham et al., 2018) due to differences in production practices, land-use histories and natural resource condition (Sandström et al., 2018). The European Union (EU) is a particularly relevant case in this context. As one of the largest importer of food products globally (FAO, 2025; WTO, 2023), EU sources agricultural products both within and beyond its borders, with substantial environmental impacts embodied in upstream supply chains worldwide (Lenzen et al., 2012; Malik et al., 2023; Pigłowski, 2021).

Dietary shifts towards less animal-based consumption have been widely proposed to reduce environmental pressures from global food systems (European IPCC, 2021; Rockström et al., 2025; Union, 2020), particularly within the EU (European Environment Agency, 2022), although the supply-chain implications are not often explicitly considered (Clark et al., 2022; Saget et al., 2021; Tang et al., 2024). Meat analogues, which are designed to approximate and replace conventional meat (Joshi & Kumar, 2015), have gained increasing attention (Sforza, 2022). In particular, alternative-protein burgers have gained popularity by replacing traditional patties with meat analogues made from plant-based proteins, mycoprotein (MP), or animal-produced alternatives.

Although previous studies indicate that replacing beef with alternative-protein food can substantially reduce environmental pressures (Alexander et al., 2017; Chaudhary & Tremorin, 2020; Ismail et al., 2020; Smetana et al., 2015), existing research is still narrow in scope. Most Life Cycle Assessment (LCA) based studies assume fixed or simplified supply chains, or apply global-average environmental intensity data (Cellura et al., 2022; Clark et al., 2022; Fresán et al., 2019; Mejia et al., 2020; Saerens et al., 2021; Saget et al., 2021; Smetana et al., 2015, 2016, 2021; Tang et al., 2024). Such assumptions overlook regional variation in sourcing, production, processing, and logistics, therefore hindering a more nuanced understanding of how geographic sourcing strategies shape the environmental outcome. Though multi-regional input–output (MRIO) based research has been widely applied to assess dietary shifts (Osei-Owusu et al., 2022; Sun et al., 2022, 2024) and trade-related impacts (Cabernard et al., 2024; Liu et al., 2021), but generally operate at aggregated sectoral levels and rarely resolve impacts for specific processed food products. Moreover, while GHG emissions and land use have been widely assessed, their implications for biodiversity loss remain insufficiently addressed. Life Cycle Impact Assessment (LCIA) methods such as LC-impact (Verones et al., 2020) have advanced in recent years, while climate-related biodiversity models remain limited by taxonomic coverage and rely on generalized characterization factors (CFs), and land-use models lack differentiation of land-use intensity and do not account for habitat fragmentation.

This study addresses these gaps by combining environmentally extended MRIO (EE-MRIO) with GLAM LCIA method (Life Cycle Initiative, 2024). GLAM CFs incorporate spatially and taxonomically explicit species responses for climate-driven biodiversity impacts and account for land-use intensity and habitat fragmentation in land-driven biodiversity assessment. By explicitly accounting for international trade and country-specific consumption patterns, this work enables a comprehensive assessment of terrestrial biodiversity impacts in alternative-protein products driven by land occupation and climate change, providing insights into how product formulation and supply-chain geography shape biodiversity outcomes.

1.1 Research questions and study scope

This study evaluates and compares conventional beef patties with four alternative-protein patties widely available in the European market: pea (Beyond Meat, 2025), soy (Impossible Foods, 2025), insect (ESM, 2017), and mycoprotein (MP) (Quorn, 2025), focusing on terrestrial biodiversity impacts arising from land occupation and climate change of patties consumed in ten selected countries: the Belgium, the Czech Republic, France, Germany, Greece, Italy, the Netherlands, Poland, Romania, and Spain. These countries were selected because they jointly represent the dominant share of beef consumption and associated environmental impacts within the EU, approximately 80% of beef consumption, 72% of land-use footprint and 82% of biodiversity impacts. See Supplementary Information SI3 Table S3-15 for details. These ten countries therefore serve as an analytical sample capturing the majority of EU impacts, but the results should not be interpreted as fully representative of all EU Member States. For the study, a four-year average period was chosen (2015–2018) to reflect typical pre-pandemic conditions and reduce annual fluctuations and uncertainties in the EE-MRIO models. For completeness, additional analyses are provided in Supplementary Information SI1 Sect. 2, including (i) EU Member States (EU-27) average biodiversity impacts and land-use footprints, and (ii) country-specific results for the remaining EU Member States not included in the ten selected countries.

We will investigate the following key research questions:

1) How does the terrestrial biodiversity impact of a beef patty consumed in each of the ten selected countries compare to that of each of the four alternative-protein patties (insects, pea, soy, MP)?
2) How do the different alternative-protein patties compare per patty in the ten selected countries, assuming they source the ingredients using their current market mix?
3) For each type of alternative-protein patty in the ten selected countries, where is the largest impact coming from, in terms of geography and ingredients?
4) Assuming 5% of national beef consumption in food service is in the form of burger patties, what is the potential reduction in terrestrial biodiversity impact when shifting all beef burger to alternative-protein burgers in the ten selected countries?

2 Methods

2.1 Data sources, functional unit, and allocation method

For all patties, recipe and electricity usage data were sourced from Smetana et al. (2021), with a cradle-to-gate boundary that covers raw material production, extrusion processing, and patty formation. Soy and pea patties were formulated using soy and pea protein isolates, respectively, as the primary protein sources. For insect and MP patties, process data for insect rearing and MP fermentation were sourced from Smetana et al. (2015), in which the insect patty was modeled with mealworms reared on carrots and a grain mix (barley, wheat, and rye), whereas the MP patty was modeled with sugar-beet molasses, a by-product of sugar production, as the cultivation substrate. Similarly, the beef patty was modelled as a combination of bovine meat and potato starch as in Smetana et al. (2021). Minor additives (e.g., flavoring agents and processing aids, etc.) were excluded due to inconsistent reporting across data sources and the fact that most food additives cannot be explicitly distinguished in FABIO classifications. The final recipes are summarized in Table 1.

As bulk price data for economic allocation were unavailable, a mass-based approach was applied throughout the study. The functional unit (FU) was defined as one raw burger patty (113 g per serving), in line with Smetana et al. (2021). To reflect domestic production with realistic sourcing, ingredient origins were estimated using MRIO trade allocations. Alternative-protein patties are assumed to fully replace beef patties in food service, accounting for 5% of national beef consumption.

2.2 MRIO models

2.2.1 FABIO

FABIO (Food and Agriculture Biomass Input–Output) is a physical MRIO model designed to trace biomass flows and embodied land use across global agrifood supply chains. It covers 191 countries and one rest-of-world region, with 119 processes (e.g., crop cultivation, livestock production, forestry, and fishing) and 123 primary and processed food and agricultural commodities, with the unit of tons per year or 1000 heads per year between 1986 and 2020 (Bruckner et al., 2019). In this study, FABIO (v1.2) is applied to capture the land-driven biodiversity impact and land-use footprint specifically within the agrifood system (Bruckner & Kuschnig, 2020).

To prevent double-counting of land-use footprints, the FABIO land-use extension must be adjusted from harvested area to physical area, acknowledging that the same land can yield multiple harvests within a year (Marquardt et al., 2019). This adjustment is achieved by rescaling FABIO land-use estimates to match the corresponding land-use totals reported in EXIOBASE (Stadler et al., 2018, 2021), while preserving the internal FABIO land-use structure. This adjustment allows both models report identical totals for each land-use category. Methodological details are provided in Supplementary Information SI1 Sect. 1.

2.2.2 FABEXIO

As FABIO does not capture the production of fuels, fertilizers, and other inputs to food production, which are essential to agrifood systems but do not involve direct biomass flows, we employ a tiered hybrid EE-MRIO model that integrates FABIO v1.2 (Bruckner & Kuschnig, 2020) and EXIOBASE v3.8.2 (Stadler et al., 2018, 2021). The integrated framework, referred to as FABEXIO (Rasul et al., 2024), allows for comprehensive environmental accounting by capturing environmental pressures and impact from both within and upstream of the agrifood system. Specifically, the model builds on the commodity structure native to the FABIO and incorporates non-biomass intermediate inputs—such as energy and food processing sectors—from EXIOBASE. In this study, FABEXIO is used to capture the land-driven biodiversity impacts upstream of the agrifood system and the climate-driven biodiversity impact both within and upstream of the agrifood system.

Table 1 Patty recipes (113 g per patty), electricity use, calories, protein content, and mapped MRIO sector names. Note: MP = mycoprotein

	Burger patties					
		Beef	Pea	Soy	Insect	MP
Ingredients *(g per patty)*	FABIO/FABEXIO sector name					
Beef meat	Bovine meat	102.3				
Coconut fat and oil	Coconut oil	/	5.7	/	/	4.5
Egg protein	Eggs	/	/	/	2.3	/
Onion	Onions	/	/	5.7	3.4	/
Pea protein isolate	Peas	/	20.0	/	/	3.8
Pea protein concentrate	Peas	/	/	/	/	11.6
Potato protein	Potatoes and products	/				1.1
Potato starch	Potatoes and products	4.5	1.7	/	1.6	/
Rape oil	Rape and mustard Oil		15.8	11.5	7.1	/
Palm oil	Palm oil	/	/	/	/	3.4
Sunflower oil	Sunflowerseed Oil	/	/	/	/	3.4
Soy protein concentrate	Soyabeans	/	/	/	7.1	/
Soy protein isolate	Soyabeans	/	/	18.0	/	/
Wheat gluten	Wheat and products	/	/	2.3	/	15.4
Wheat starch	Wheat and products	/	/	1.1	/	3.8
Wheat flour	Wheat and products	/	/	/	/	3.8
	Mycoprotein production (Substrate)					
Molasses	Sugar beet	/	/	/	/	339.0
	Insect feeding					
Carrots	Vegetables, other	/	/	/	90.4	/
Grain mix	Barley and products	/	/	/	21.5	/
	Rye and products	/	/	/	21.5	/
	Wheat and products	/	/	/	21.5	/
	Electricity (kWh)					
Electricity mix		0.050	0.0114	0.0106	0.0064	0.0156
	Other information					
Calories *(kcal per patty)*		266	304	191	319	288
Protein content *(g per patty)*		20.3	20.3	15.8	23.7	23.7

The general workflow of the FABEXIO-based calculation is summarized as follows. First, to distinguish between impacts occurring within the agrifood system from those arising in the rest of the economy, the hypothetical extraction method is applied to EXIOBASE. This allows for the decomposition of the total supply-chain impacts into those happening within and upstream of the agrifood system. These impacts calculated using EXIOBASE are then mapped to FABIO as a new set of environmental extensions. The mapping is done using a weighted concordance matrix, using total biomass outputs to allocate from the aggregate EXIOBASE agrifood sectors to the detailed FABIO sectors. FABIO and FABEXIO models are consistent in terms of flow, regional coverage, and sectoral classification. Methodological details see Supplementary Information SI1 Sect. 1.

2.3 LCIA method

Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM), hosted by UN Environment, provides consensus-based characterization factors (CFs) for multiple impact categories (Life Cycle Initiative, 2024). In this study, the GLAM version 1.0.2024.10 is used. For ecosystem quality, GLAM focused on methods that indicate impacts in terms of loss of species richness, using potentially disappeared fraction of species (PDF) as a metric (Verones et al., 2017) and focusing on global species extinction by consistently applying the Global Extinction Probability (GEP) in their models (Verones et al., 2022). GLAM provides models across terrestrial, freshwater, and marine ecosystems. In this paper, we focus on terrestrial ecosystems and only investigate land use and climate change impacts.

For land use, GLAM provides CFs based on Scherer et al.(2023) that are spatially differentiated by ecoregion, land type, and intensity levels. The GLAM CFs advance previous approaches by jointly accounting for land-use intensity and habitat fragmentation within a Species–Habit Relationship framework, while incorporating updated parametrization based on recent global datasets and extend taxonomic coverage to plants and multiple vertebrate groups. As a result, the GLAM CFs are about 9% higher than those from LC-impact (Verones et al., 2020) which based on the Countryside Species–Area Relationship (Kuipers et al., 2021). The GLAM CFs exhibit high variability, reflecting the strong spatial heterogeneity of CFs, which span several orders of magnitude. This is attributable to differences in ecoregion size, land-use type and intensity, species habitat affinities, the degree of landscape connectivity and species dispersal ability, and GEP that account for both threat status and levels of endemism (Scherer et al., 2023).

For climate change, GLAM provides the first climate-change CFs based on spatially and taxonomically explicit model which evaluates the impacts of warming and a subsequent shift in available habitat for species (Iordan et al., 2023). Compared with LC-impact (Verones et al., 2020) with effect factors based on a single PDF / °C value for the entire terrestrial realm obtained from the meta-analysis of Urban (2015), GLAM explicitly models species responses across terrestrial ecosystems with a broader taxonomic coverage at the grid level, and models pixel-based air temperature niche limits for individual species to calculate unsuitable geographic range areas based on climate model projections (Iordan et al., 2023). As a result, the GLAM climate-change CFs are generally about one order of magnitude lower than those obtained with LC-impact (Iordan et al., 2023).

GLAM CFs quantify the biodiversity impact per unit of stressor, hereafter referred to as "biodiversity sensitivity", and are combined with environmental extensions from MRIO models to estimate endpoint-level impacts per functional unit. In this study, GLAM land-occupation CFs were matched to EXIOBASE (Stadler et al., 2018) land-use stressors by land-use type at the country level. As EXIOBASE does not distinguish land-use intensity for cropland and pastures, biodiversity impacts associated with these categories were characterized using intensive CFs, following the worst-case matching rules proposed by Scherer et al. (2021). GLAM global climate-change CFs were matched to EXIOBASE emission stressors by GHG types across all regions (see Supplementary Information SI1 Sect. 1 for details).

2.4 Sensitivity analysis

Sensitivity analyses were performed to test the robustness of results to main assumptions, including (1) allocation method, (2) functional unit, (3) beef patty composition, and (4) coconut oil substitution.

Allocation method: alternative allocation ratios were applied for selected ingredients (incl. soy protein isolate and concentrate, pea protein isolate and concentrate, wheat protein starch, gluten and flour, molasse). These ingredients are processed products without a direct correspondence in MRIO sectors while with obvious impacts contribution in the baseline scenario. Two contrasting scenarios were considered, high-case and low-case scenarios. In the high-case scenario, selected ingredients were assigned higher shares of environmental impact, whereas in the low-case scenario, lower shares were assigned. These scenarios reflect variable processing yields and co-product across alternative production pathways (see Supplementary Information SI3 Table S3-20 for details).

Functional unit: two scenarios were considered: (1) Protein-based FU, defined as 20.3 g protein; and (2) Energy-based FU, defined as 266 kcal, both equivalent to the protein and energy content of a beef patty (see Table 1). Serving sizes were adjusted accordingly for each patty type.

Beef patty composition: in the baseline scenario, the beef patty was modelled as a mixture of bovine meat and potato starch, whereas in this sensitivity scenario it was assumed to be composed of 100% bovine meat.

Coconut oil substitution: In this scenario, coconut oil was replaced by rapes oil on a mass-equivalent basis in pea and MP patties. Rape oil was selected, as it offers comparable functional properties as coconut oil and is widely used in novel food products (Zahari et al., 2022).

3 Results

3.1 Terrestrial biodiversity comparison

The analysis reveals substantial geographical variation in biodiversity sensitivity, resulting in contrasting patterns between land-driven biodiversity impacts and land-use footprints. As illustrated in Fig. 1, land occupation is the predominant driver of terrestrial biodiversity loss across all patty types, consistently surpassing the contribution of climate change. For all patties and countries, land-driven biodiversity impacts account for more than 96% of total biodiversity impact. Contributions from non-food sectors are minor, remaining below 16% (see Supplementary Information SI3 Table S3-14). The results are substantially influenced by the updated GLAM LCIA method (see Section 2.3 for a detailed comparison with the LC-Impact).

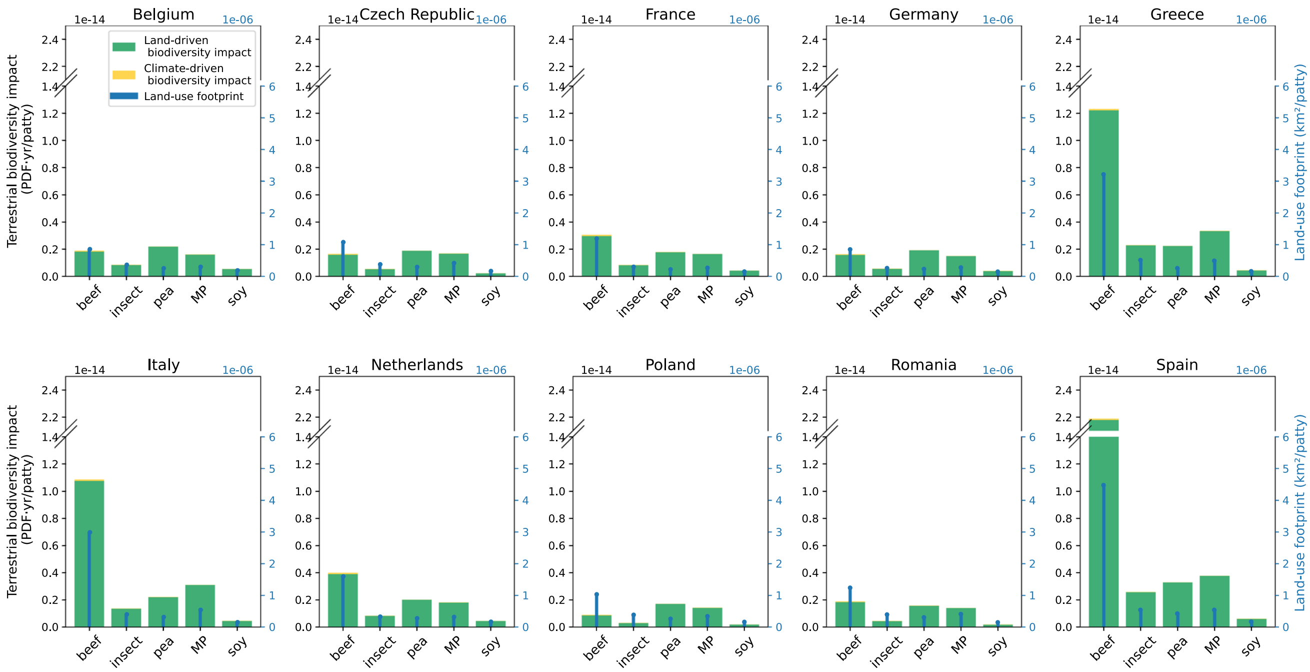


Fig. 1 Terrestrial biodiversity impact and land-use footprint per patty (113 g) driven by land occupation and climate change across all patty types and selected countries (averaged over the period 2015–2018). The blue line indicates the land-use footprint, while the bars represent terrestrial biodiversity impacts driven by land occupation and climate change, respectively. The underlying data for this figure are provided in Supplementary Information SI3 Table S3-4. Note: MP—mycoprotein

Regarding land-use footprint, beef patties exhibit the highest values compared to the alternative-protein patties across the selected countries, with Greece, Italy, and Spain showing the largest. Among alternative-protein patties, insect or MP patties show the highest footprint, whereas soy patties consistently show the lowest.

Land-driven biodiversity reveals a different pattern. As shown in Figs. 1 and 2, beef patties generally exhibit the highest land-driven biodiversity impacts, while in Belgium, the Czech Republic, Germany, and Poland, pea patty unexpectedly surpasses beef. This counterintuitive outcome arises from pea patties' sourcing of ingredients from the Philippines and Indonesia (see Sect. 3.4), both are highly biodiversity-sensitive countries, with cropland CFs reaching up to 2.2×10^{-14} PDF/m2. In contrast, beef patties consumed in these countries show comparatively lower impacts, as their supply chains are highly diversified, relying primarily on domestic production with a small share of imports from sourcing countries such as Australia, India, and Italy, all of which exhibit relatively lower CFs for both pastures and cropland (e.g., Poland cropland CF = 4.6×10^{-16} PDF/m^2, see Supplementary Information SI2 Table S2-2). Among the alternative-protein patties, pea patties consistently yield the highest land-driven biodiversity impact, except in Greece, Italy, and Spain, where MP patties dominate due to their greater reliance on ingredients sourced from biodiversity-sensitive local countries (see Sect. 3.4). Soy patties again demonstrate the lowest impacts, positioning them as the most preferable alternatives.

Land-driven biodiversity impacts from beef patties are jointly driven by pastures and cropland, with pastures dominating in Spain, Greece and Italy. Alternative-protein patties are primarily influenced by cropland (Fig. 2a). Contributions from 'Forest' and 'Other land' are limited for all patty types, lower than 13% for 'Forest', and 2% for 'Other land' across all selected countries. Similar patterns are observed for land-use footprints, although beef patties consistently exhibit higher footprint than alternative-protein patties due to greater cropland and pastures use. As for climate-driven biodiversity impact, beef ranks the highest across all countries, primarily due to CH_4 emissions (Fig. 2b). Alternative-protein patties are primarily driven by N_2O, CO_2, and CH_4. Among them, insect patties consistently exhibit the highest impacts, whereas soy patties show the lowest (see Supplementary Information SI3 Table S3-3).

3.2 Potentially avoided impact

Figure 3 illustrates that replacing beef patties with the best alternative-protein patties (soy) can considerably reduce the land-driven biodiversity impact across countries. Assuming beef patties in food service represent approximately 5% of national beef consumption, their substitution with soy patties would lower land-driven biodiversity impacts

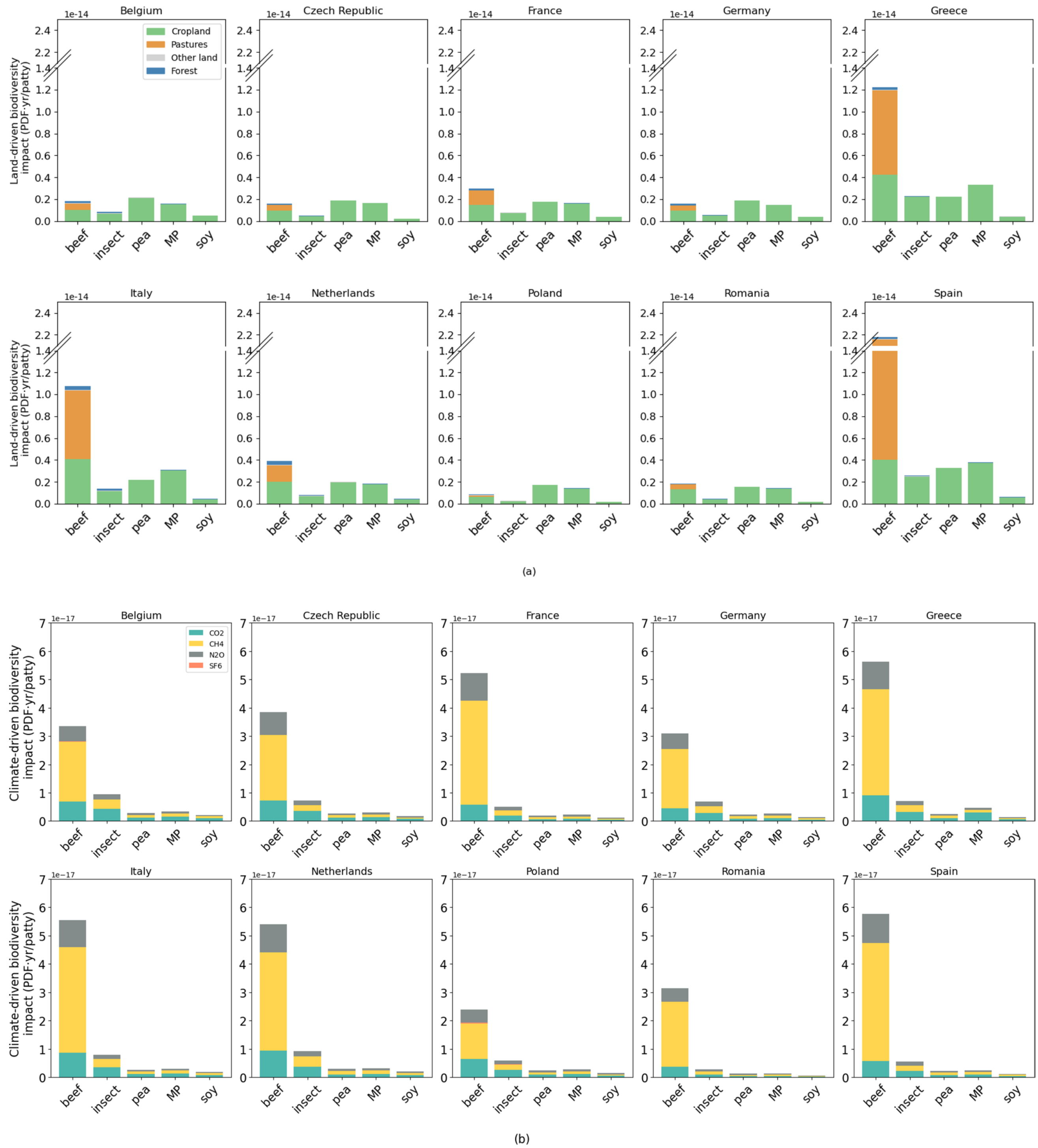


Fig. 2 Terrestrial biodiversity impact per patty (113 g) for all patty types across selected countries **a** Land-driven biodiversity impact **b** Climate-driven biodiversity impact (averaged over the period 2015–2018). The underlying data for this figure are provided in Supplementary Information SI3 Table S3-2 and S3-3. Note: MP—mycoprotein

by 71–97% compared with an equivalent quantity of beef patties, corresponding to an estimated 3.6–4.9% reduction in national biodiversity loss associated with beef across the selected countries. The reduction potential broadly reflects the biodiversity impacts of beef patties across countries: with Spain, Greece and Italy showing the largest reduction (~96–97%), and Belgium showing markedly smaller reductions (71%) (see Supplementary

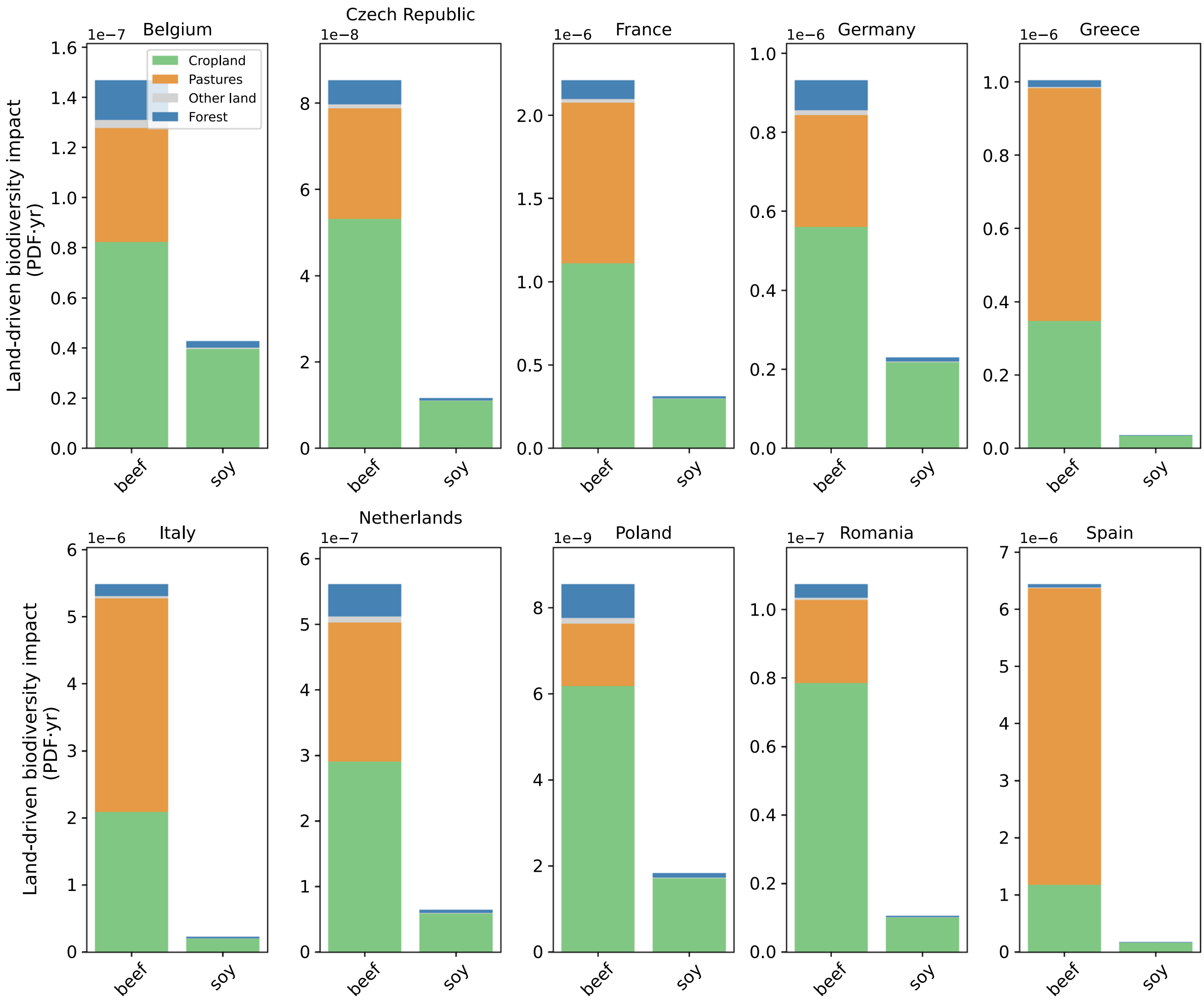


Fig. 3 Comparison of the annual land-driven biodiversity impacts of beef burgers served in food services and their replacement by the best-performing alternative-protein burger patty across selected ten countries, averaged over the period 2015–2018. The underlying data for this figure are provided in Supplementary Information SI3 Table S3-11

Information SI3 Table S3-11). Similar trends are observed for land-use footprints, where soy patties again perform best, achieving 78–96% lower footprint relative to beef patties and contributing to an estimated 3.9–4.8% reduction in national land-use footprint across the selected countries. The largest reductions again occur in Spain, Greece and Italy, while the smallest reduction is observed in Belgium. (see Supplementary Information SI1 Sect. 2 for details).

3.3 Ingredient analysis

Given the dominance of land-driven biodiversity impacts within terrestrial biodiversity impacts, the ingredient-level analysis focuses on this driver, with cross-country variability assessed using the coefficient of variation (CV) (see Supplementary Information SI3 Tables S3-4 and S3-6 for details).

As illustrated in Fig. 4, land-driven biodiversity impacts of patties are largely driven by a small number of ingredients sourced from biodiversity-sensitive countries, particularly outside the EU. Ingredients sourced within the EU generally contribute less, except when sourced from biodiversity-sensitive Southern EU countries (e.g., Greece, Spain, and Italy), where cropland CFs are relatively high (e.g., Spain cropland CF = 6.0 × 10⁻15 PDF/m2; see Supplementary Information SI2 Table S2-2). This pattern is most evident for coconut oil in pea and MP patties. Despite its small amount in the recipe (5.7 and 4.5 g per patty, respectively), coconut oil, largely sourced from biodiversity-sensitive Extra-EU countries, including the Philippines, Indonesia,

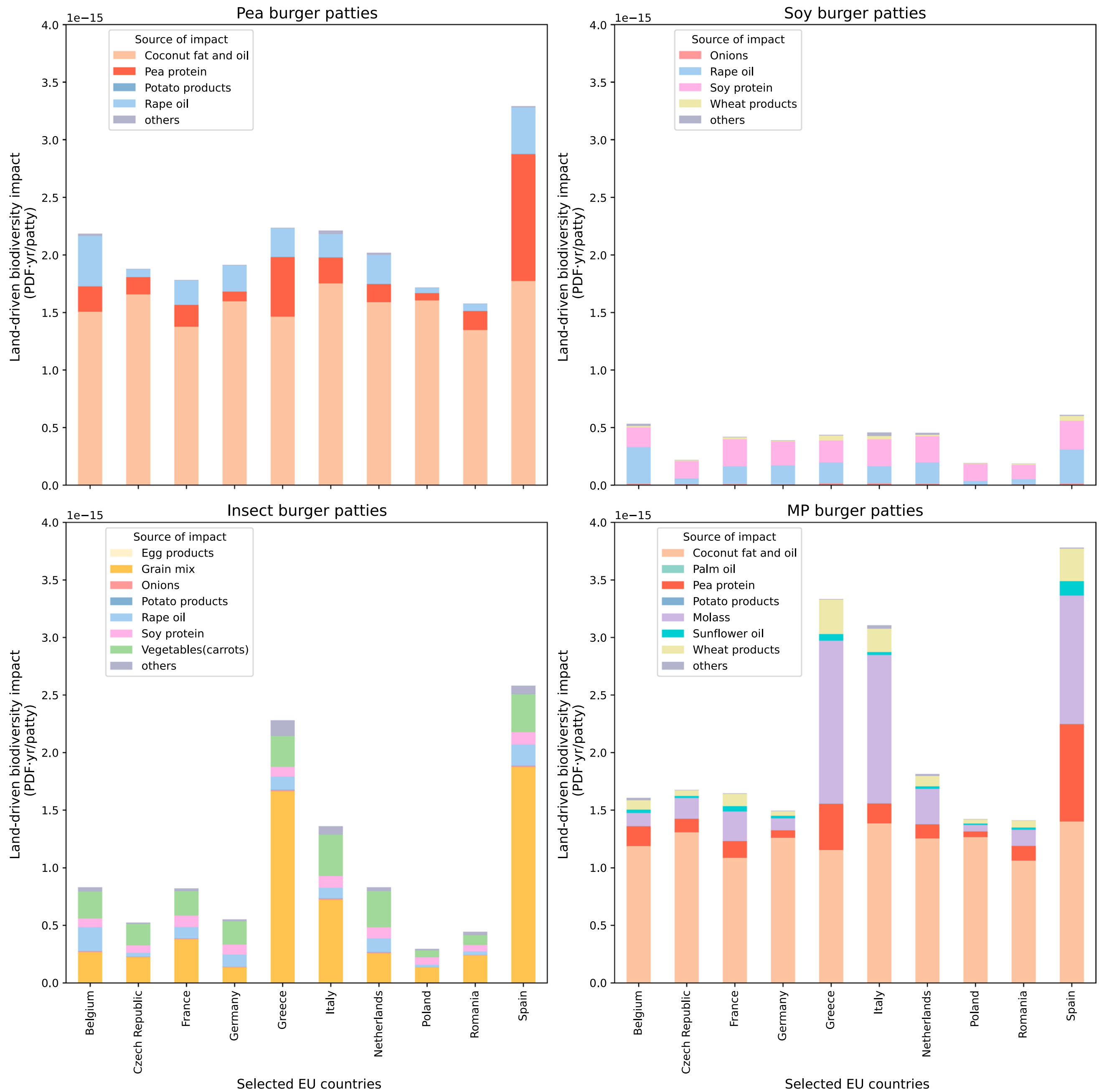
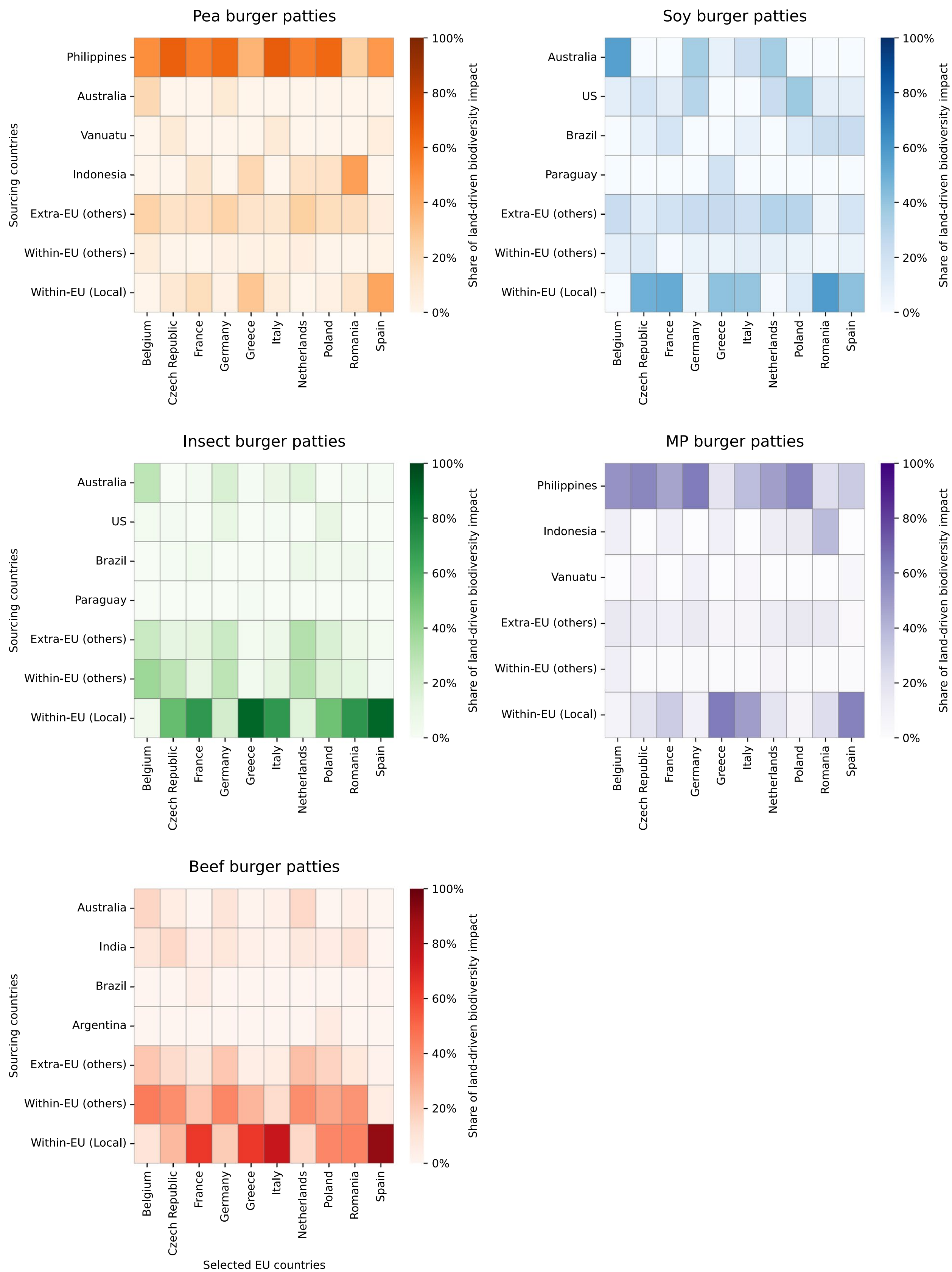


Fig. 4 Land-driven biodiversity impact per patty (113 g) for alternative-protein patties across selected countries. Impacts are split by ingredient (averaged over the period 2015–2018). The underlying data for this figure are provided in Supplementary Information SI3 Table S3-6. Note: MP—mycoprotein

and Vanuatu, dominates the biodiversity impacts of both patties (~75 and ~58%, respectively). In contrast, ingredients sourced from countries with lower biodiversity sensitivity contribute less to total impacts despite larger mass inputs and dominant roles in land-use footprints. For example, pea protein, the primary protein source (20 g per patty) and the dominant contributor of land-use footprints (~46%) for pea patties, accounts for only ~14% of total biodiversity impacts on average across ten consuming countries. Similarly, molasses, the main substrate for MP patties (339 g per patty), dominates land-use footprints (~40%) but contributes only ~23% of total biodiversity impacts on average. Both pea protein and molasses are primarily sourced within the EU (see Supplementary Information SI3 Table S3-13). An exception is observed for MP patties consumed in biodiversity-sensitive Southern EU countries, where higher cropland CFs in these countries increase the biodiversity impact of locally produced molasses, accounting for ~40%


Pea burger patties
Philippines
Australia
Vanuatu
Indonesia
Extra-EU (others)
Within-EU (others)
Within-EU (Local)
Sourcing countries
Belgium
Czech Republic
France
Germany
Greece
Italy
Netherlands
Poland
Romania
Spain
Share of land-driven biodiversity impact
100%
80%
60%
40%
20%
0%
Soy burger patties
Australia
US
Brazil
Paraguay
Extra-EU (others)
Within-EU (others)
Within-EU (Local)
Insect burger patties
Australia
US
Brazil
Paraguay
Extra-EU (others)
Within-EU (others)
Within-EU (Local)
MP burger patties
Philippines
Indonesia
Vanuatu
Extra-EU (others)
Within-EU (others)
Within-EU (Local)
Beef burger patties
Australia
India
Brazil
Argentina
Extra-EU (others)
Within-EU (others)
Within-EU (Local)
Selected EU countries

◂**Fig. 5** Heatmaps showing land-driven biodiversity impacts per patty (113 g) across selected EU countries for all patty types. Impacts are disaggregated into Within-EU (local and other EU countries) and Extra-EU regions, with the latter further disaggregated into the top two Extra-EU sourcing countries for each consuming country and other Extra-EU countries. Values represent percentage shares of land-driven biodiversity impacts (PDF·yr per patty). 'Within-EU (Local)' denotes sourcing from the country of consumption, while 'Within-EU (others)' and 'Extra-EU (others)' represent aggregated contributions from the remaining Within-EU and Extra-EU countries, respectively. Data are averaged over 2015–2018. Underlying data are provided in Supplementary Information SI3 Table S3-9. Note: MP – mycoprotein; US – United States

of total impacts in Greece and Italy and ~ 30% in Spain. This leads MP patties consumed in these countries to exceed pea patties in total impacts and become the worst-performing alternative.

Biodiversity impacts for soy patties are largely driven by soy protein and rape oil (~ 50 and ~ 40%), broadly consistent with their land-use footprint contributions (~ 55 and ~ 36%) but showing greater cross-country variability (CV = 0.4 vs. 0.1). This notable variation is mainly driven by differences in rape oil sourcing. Specifically, higher impacts observed in Belgium, France, Germany, Italy, and the Netherlands are driven by rape oil sourcing from biodiversity-sensitive countries, notably Australia (cropland CF = 9.1×10^{-15} PDF/m2), and in Greece and Spain by elevated local biodiversity sensitivity. In contrast, lower impacts observed in the Czech Republic, Poland, and Romania are mainly due to predominantly domestic sourcing of rape oil and lower local biodiversity sensitivity (see Supplementary Information SI2 Table S2-2 for CFs). For insect patties, biodiversity impacts are predominantly driven by feed inputs (grain mix and carrots; ~ 56 and ~ 21%) which are largely sourced within the EU. Impacts from grain mix are substantially high in insect patties consumed in Southern EU countries like Greece and Spain, due to predominantly domestic sourcing and elevated local cropland CFs. Carrots, despite their large quantity (90.4 g per patty), contribute relatively little to total impacts across all consuming countries due to lower land-use intensity and their predominantly within-EU sourcing (see Supplementary Information SI3 Table S3-12 and S3-13 for details). Similar to soy patties, land-use footprints of insect patties follow similar contribution patterns to biodiversity impacts but show much lower cross-country variability (CV = 0.2 vs. 0.7), reflecting their limited ability to capture spatial variation in biodiversity impacts (see Supplementary Information SI1 Sect. 2).

3.4 Supply-chain analysis

This section examines the geographic origin of land-driven biodiversity impacts embodied in patties consumed in the selected countries. Although impacts are attributed to the consuming countries, they occur along international supply chains. As illustrated in Fig. 5, Pea, MP, and soy patties are predominantly associated with Extra-EU sourcing (~ 62–85% of total impacts), whereas insect and beef patties rely more on Within-EU sourcing (~ 73% of total impacts for both), reflecting the largely Within-EU sourcing of feed inputs (e.g., grains).

Extra-EU sourcing of all patties is largely driven by a limited number of Extra-EU biodiversity-sensitive countries. These include tropical countries (e.g., the Philippines, Indonesia, and Vanuatu) and non-tropical countries (e.g., Brazil, Australia, the United States, Paraguay, India, and Argentina; see Supplementary Information SI2 Table S2-2 for CFs). The top two Extra-EU sourcing countries for pea and MP patties are predominantly tropical, most commonly the Philippines together with another tropical country (e.g., Indonesia and Vanuatu), accounting for ~ 68 and ~ 56% of total biodiversity impacts, respectively, due to coconut oil sourcing (see Sect. 3.3). This reflects elevated cropland CFs associated with high GEP, small ecoregion sizes, and fragmented land-use patterns in tropical ecosystems. In contrast, soy patties are primarily driven by non-tropical countries, most commonly Brazil, the United States, and Australia, with the top two Extra-EU contributors accounting for ~ 42% of total impacts. For beef and insect patties, impact contributions from the top two Extra-EU sourcing countries are much lower (~ 13%), consistent with the relatively small impact share of total Extra-EU sourcing (~ 27%) in both patties. Beef patties are primarily associated with non-tropical countries such as Australia and India, while insect patties are largely associated with Brazil, the United States, and Australia. In contrast, some Extra-EU sourcing countries with lower biodiversity sensitivity (e.g., Russia, Ukraine, and Canada; see Supplementary Information SI2 Table S2-2 for CFs) contribute marginally to biodiversity impacts despite being among the top contributors to land-use footprints across many patties and consuming countries (see Supplementary Information SI1 Sect. 2).

Within-EU sourcing is consistently dominated by domestic sourcing across all patties. For pea, MP, and soy patties, impacts from Within-EU contributions are modest (~ 15, 32, and 38%, respectively), but largely reflect domestic sourcing (~ 12, 29, and 30%). For insect and beef patties, Within-EU shares increase to around 73% on average, with domestic sourcing accounting for ~ 49%. This pattern is most pronounced in insect and beef patties consumed in Southern EU countries (Spain, Greece, and Italy), where biodiversity impacts embodied in these patties are largely from domestic sourcing and amplified by high local biodiversity sensitivity. As a result, Within-EU shares reach around 90% for insect and beef patties in these countries, with ~ 80% of total impacts arising from domestic sourcing, leading to substantially higher total biodiversity impacts. In contrast, some Within-EU countries with lower biodiversity sensitivity serve as major sourcing countries while contributing little to total biodiversity impacts. For example, France supplies most of the grain mix, the major feed component for insect patties, in Belgium and the Netherlands. However, due to its relatively low biodiversity sensitivity (cropland CF = 2.6×10^{-15} PDF/m2), biodiversity impacts from grain mix remain modest in both countries (see Fig. 4), with France's contribution to total impacts remaining limited (22 and 14%, respectively).

Unlike biodiversity impacts, land-use footprints of patties are dominated by Within-EU sourcing across all patty types, with Within-EU sourcing accounting for ~ 75–83% of total footprints on average for beef, insect, and MP patties and ~ 44–54% for soy and pea patties. Within this, domestic sourcing constitutes a substantial share, contributing ~ 52–64% of total footprints for beef, insect, and MP patties and ~ 32–38% for soy and pea patties. In contrast, the top two Extra-EU sourcing countries contribute relatively little to land-use footprints (~ 14–30% for pea, MP, and soy, and ~ 3–7% for beef and insect patties), far below their contributions to biodiversity impacts (see Supplementary Information SI1 Sect. 2). This highlights a decoupling between land-use footprints and biodiversity impacts, driven by spatial differences in biodiversity sensitivity.

3.5 Sensitivity to modelling assumptions

The sensitivity analyses indicate that the identification of the best- and worst-performing patties remains largely robust to variations in allocation ratios, functional units, and beef patty composition. As shown in Table 2, varying allocation ratios under high- and low-case scenarios results in a + 5 to + 31% increase and a − 4 to − 15% decrease in biodiversity impacts, respectively; however, the best- or worst patties results remain unchanged relative to baseline scenario. Similarly, under the protein-based FU, the relative ranking among patties remains, as differences in protein content across patties are minor (as shown in Table 1). Under the energy-based FU, soy patties are no longer the best-performing option in Belgium, Germany, and Poland due to their relatively low energy content (191 kcal/patty) compared to other alternatives (266–319 kcal/patty), while the worst-performing patties remain unchanged. Under the beef patty composition scenario, assuming a 100% bovine meat patty increases total biodiversity impacts for beef by approximately 10%, without altering the overall conclusions relative to the baseline scenario.

However, under the coconut oil substitution scenario, the results deviate markedly from the baseline. Replacing coconut oil with rape oil reduces biodiversity impacts by approximately 74% for pea patties and 62% for MP patties, leading to changes in patties relative performance across selected countries. Specifically, MP and pea patties replace soy patties as the best-performing alternatives in Germany and Poland, respectively, while insect patties become the worst-performing alternative-protein option in most countries. Under this scenario, beef patties consistently exhibit the highest biodiversity impacts across all countries, in contrast to the baseline and other scenarios results where pea patties exceeded beef in some cases. Overall, substituting high-impact ingredients like coconut oil—can substantially reduce biodiversity impacts of pea and MP patties and shift the relative performance of alternative-protein patties across countries (see Supplementary Information SI3 Table S3-20 and Table S3-21 for details).

4 Discussion

4.1 Ingredients and their sourcing countries as a key lever for reducing biodiversity loss

This study reveals that terrestrial biodiversity impacts for patties are primarily driven by land-driven biodiversity impacts, with climate-driven biodiversity impacts remaining minor (< 4%) across all patties (see Sect. 3.1). Although climate-driven impacts vary across patties and decline substantially when shifting from beef to all alternative-protein patties, they have limited influence on overall terrestrial biodiversity impacts and the magnitude of avoided impacts from dietary shifts (see Sect. 3.1). This finding is consistent with the IPBES report which identifies land-use change as the leading cause of terrestrial biodiversity loss (Díaz et al., 2019). However, previous LCA case studies applying LC-Impact (Verones et al., 2020) identified climate change as the dominant driver, reflecting differences in impact pathway modeling between LC-Impact and GLAM (see Sect. 2.3).

Land-use footprints often reflect the proportional mass share of ingredients in a product, while land-driven biodiversity impacts are disproportionately shaped by ingredient characteristics and sourcing origins. Coconut oil illustrates this point well. Despite its small proportion in recipes, it contributes notably to land-use footprint yet dominates the biodiversity impacts of pea and MP patties (Sect. 3.3). This is consistent with previous studies showing that, despite its minor formulation share, coconut oil can contribute land-use footprints comparable to those of primary protein ingredients in plant-based meat (The Good Food Institute, 2024) and is linked to disproportionately high biodiversity loss per unit produced (AAAS, 2025; NMBU, 2022; Oilcocos, 2024). This reveals a broader limitation of conventional mass-based LCA approaches, demonstrating that such methods may systematically overlook high-impact, low-mass components (e.g., coconut oil in this study) in supply chains where biodiversity sensitivity is spatially heterogeneous. In this context, neither mass-based LCA method nor land-use footprints adequately capture the spatial variation in biodiversity sensitivity. These underscore the methodological implication of recipe-level resolution, comprehensive representation of global supply chains (e.g., MRIO-based approaches), and the explicit integration of biodiversity metrics in food system assessments.

4.2 Potential and condition of shifting to alternative-protein patties

This study shows that all selected alternative-protein patties have substantially lower land-use footprints than beef. While the near elimination of pastures is a major driver of this, the beef production also involves higher footprint from cropland than selected alternative-protein patties (see Sect. 3.1). This indicates that, even without converting current pastures to cropland, existing cropland used for cattle feed could sufficiently meet the additional requirements of alternative-protein patties. This finding aligns with previous studies, which shows that plant-based diets typically require less cropland (Gerbens-Leenes & Nonhebel, 2002; Heller & Gregory, 2018; Smith et al., 2014; The Good Food Institute, 2024).

However, the biodiversity benefits of shifting from beef to alternative-protein patties are neither universal nor unconditional. The magnitude of the benefits depends both on the type of alternative-protein patty and the baseline impact of beef in the corresponding country (see Sect. 3.2). Sourcing ingredients from biodiversity-sensitive countries may substantially reduce the expected benefits of alternative-protein patties and, in some cases, even lead to higher impacts than beef (see Sect. 3.1). Such spatially uneven pressures echo the concept of biodiversity leakage, defined as the displacement of activities that harm biodiversity from one region to another through trade or consumption shifts (Balmford et al., 2025). In this context, local environmental gains may be offset by displaced impacts in other, often more biodiversity-sensitive regions. Therefore, achieving biodiversity impact reductions from dietary shifts requires not only replacing animal-based products, but also careful consideration of ingredient composition and sourcing for alternative-protein products, and the regional biodiversity condition.

This study challenges the assumption that alternative-protein patties are always environmentally superior, as most prior assessments focus on GHG emissions, land use, or water use (Heller & Gregory, 2018; Mazac et al., 2022; Smetana et al., 2021; Sofia Khan et al., 2019; The Good Food Institute, 2024), while overlooking biodiversity impacts. Moreover, it is important to note that the lower biodiversity impact achieved by the dietary transition does not guarantee ecological restoration. Spared land may be abandoned or returned to nature, but it can also be reoccupied for other uses, such as urban expansion, alternative

Table 2 Summary of best-and worst-performing burger patties across countries under baseline and sensitivity analysis scenarios

Scenario		Ranking category	Belgium	Czech Republic	France	Germany	Greece	Italy	Netherlands	Poland	Romania	Spain
Baseline		Best all	soy	soy	soy	soy	soy	soy	soy	soy	soy	soy
		Worst all	pea	pea	beef	pea	beef	beef	beef	pea	beef	beef
		Worst (non-beef)	pea	pea	pea	pea	MP	MP	pea	pea	pea	MP
Allocation method	High-case	Best all	soy	soy	soy	soy	soy	soy	soy	soy	soy	soy
		Worst all	pea	pea	beef	pea	beef	beef	beef	pea	beef	beef
		Worst (non-beef)	pea	pea	pea	pea	MP	MP	pea	pea	pea	MP
	Low-case	Best all	soy	soy	soy	soy	soy	soy	soy	soy	soy	soy
		Worst all	pea	pea	beef	pea	beef	beef	beef	pea	beef	beef
		Worst (non-beef)	pea	pea	pea	pea	MP	MP	pea	pea	pea	MP
Functional unit	Protein-based	Best all	soy	soy	soy	soy	soy	soy	soy	soy	soy	soy
		Worst all	pea	pea	beef	pea	beef	beef	beef	pea	beef	beef
		Worst (non-beef)	pea	pea	pea	pea	MP	MP	pea	pea	pea	MP
	Energy-based	Best all	insect	soy	soy	Insect	soy	soy	soy	insect	soy	soy
		Worst all	pea	pea	beef	pea	beef	beef	beef	pea	beef	beef
		Worst (non-beef)	pea	pea	pea	pea	MP	MP	pea	pea	pea	MP
Burger patty composition		Best all	soy	soy	soy	soy	soy	soy	soy	soy	soy	soy
		Worst all	pea	pea	beef	pea	beef	beef	beef	pea	beef	beef
		Worst (non-beef)	pea	pea	pea	pea	MP	MP	pea	pea	pea	MP
Coconut oil substitution		Best all	soy	soy	soy	MP	soy	soy	soy	pea	soy	soy
		Worst all	beef	beef	beef	beef	beef	beef	beef	beef	beef	beef
		Worst (non-beef)	pea	insect	insect	insect	insect	MP	insect	insect	insect	insect

"Best all" and "Worst all" refer to rankings among all patties, including beef patty. "Worst (non-beef)" refers to rankings among alternative-protein patties only (excluding beef patty)

Cell colors indicate patty type: green = pea patty; light yellow = soy patty; purple = insect patty; light blue = MP patty; grey = beef patty.

MP mycoprotein

agriculture, or biofuel production (Lambin and Meyfroidt, 2011). In this context, avoided biodiversity impact refers to preventing further habitat occupation, rather than restoring degraded terrestrial ecosystems.

Additional analyses for the remaining EU Member States and the EU-27 average confirm that the key patterns identified in the ten selected countries are robust across the EU countries (see Supplementary Information SI1 Sect. 2), particularly the dominant role of biodiversity-sensitive sourcing, the potential for reducing biodiversity impacts by replacing beef with alternative-protein patties, and the divergence between land-use footprints and land-driven biodiversity impacts.

4.3 Recommendations

Building on the preceding discussion, the following recommendations are proposed for industry stakeholders and policymakers. For industry, biodiversity impact assessments beyond conventional mass-based LCA approaches, with high recipe granularity and comprehensive representation of global supply chains, are essential to identify disproportionately high-impact ingredients. Reformulation through reduction, substitution with lower-impact alternatives, or sourcing from less biodiversity-sensitive regions represent an immediate mitigation option. Integrating biodiversity-informed sourcing into product development is also critical, as impacts associated with the same ingredient may vary substantially across sourcing regions. Product-level environmental disclosures should extend beyond conventional indicators to incorporate biodiversity metrics.

For policymakers, dietary transitions should consider regional biodiversity conditions and require region-specific substitution and supply-chain strategies, as replacing meat with alternative-protein products does not consistently reduce impacts. Sustainability standards, public procurement, and labelling schemes for alternative-protein products should incorporate biodiversity metrics, while policies that enhance supply-chain traceability and incentivize sourcing from lower-impact regions can further support biodiversity-aligned dietary transitions.

4.4 Uncertainties and limitations

These implications should be interpreted considering several sources of uncertainty and limitation, primarily arising from the MRIO models, GLAM CFs, and recipe data. In particular, spatial aggregation in MRIO models and the application of country-level land-occupation CFs with intensive land-use intensity assumptions mask heterogeneity in production systems and ecosystem damage. In addition, the results are specific to the modeled recipes and do not capture land transformation dynamics or recent changes in alternative protein markets and agricultural trade patterns. As alternative protein markets and agricultural trade patterns evolve, the results cannot reflect current conditions, future research should therefore incorporate more recent data. Further discussion of limitation and uncertainties is provided in Supplementary Information SI1 Sect. 3.

5 Summaries

Supplementary Information SI1: This supplementary information provides supplementary methods, visual analyses of biodiversity impacts and land-use footprints across selected and remaining EU countries, and a detailed discussion of uncertainties and limitations.

Supplementary Information SI2: This supplementary information provides concordance tables linking the FABIO and FABEXIO models with the GLAM method.

Supplementary Information SI3: This supplementary information provides summary statistics, analytical results, and detailed sensitivity analysis assumptions and results.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44498-026-00120-1.

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Data availability The data that supports the findings of this study are available in the Supplementary Information of this article. The Python scripts and supplementary code used in this study are publicly available at GitHub: https://github.com/Cathy-zyq/burger-patty-biodiversity.

Declarations

Conflict of interest The authors declare no competing interests.

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