ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

PAPER • **OPEN ACCESS**

Reducing biodiversity impacts of agricultural production while maintaining food supply—a modelling study of the Swiss food system

To cite this article: Eva Augustiny *et al* 2026 *Environ. Res.: Food Syst.* **3** 035006

ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

PAPER

Check for updates

OPEN ACCESS

RECEIVED
20 December 2025

REVISED
4 June 2026

ACCEPTED FOR PUBLICATION
11 June 2026

PUBLISHED
29 June 2026

Reducing biodiversity impacts of agricultural production while maintaining food supply—a modelling study of the Swiss food system

Eva Augustiny[1,2,*], Adrian Muller[1,*], Ashley Green[2], Alexander Mathys[2], Stephan Pfister[3], Michael Curran[1] and Anita Frehner[1]

[1] Department of Food System Sciences, Research Institute of Organic Agriculture FiBL, Frick 5070, Switzerland
[2] Sustainable Food Processing Laboratory, Institute of Food, Nutrition and Health, ETH Zurich, Zurich 8092, Switzerland
[3] Chair of Ecological Systems Design, Institute of Environmental Engineering, ETH Zurich, Zurich 8093, Switzerland
[*] Authors to whom any correspondence should be addressed.

E-mail: eva.augustiny@fibl.org and adrian.mueller@fibl.org

Keywords: biodiversity impact assessment, food system modelling, sustainable diets, organic agriculture, feed-food competition

Supplementary material for this article is available online

Abstract

Agri-food systems are essential for food security, yet they are major drivers of biodiversity loss through land conversion, intensification, and related emissions, threatening long-term stability of food production. To design food systems that sustain biodiversity while ensuring food provision, biodiversity impacts must be systematically assessed at food system level. This study integrates a food system model (SOLm) with biodiversity characterization factors from the global life cycle impact assessment method (GLAM), enabling consistent biodiversity impact assessment across multiple drivers. The analysis focuses on four drivers of biodiversity loss—land use, eutrophication, acidification, and climate change—and evaluates contributions to biodiversity impacts across alternative production scenarios in Switzerland. Results show that all alternative scenarios reduce biodiversity impacts from domestic production. Scenarios aligning livestock populations with grassland availability and reducing feed-food competition achieved the most substantial reductions, driven by lower pressures from climate change, eutrophication, and acidification, while maintaining calorie and protein supply. Land-use impacts decreased less, particularly in organic systems, due to lower yields, risking externalization of biodiversity impacts through increased imports. Impacts from imports were dominated by products such as coffee and cocoa, which exert substantial external pressures, although biodiversity impacts per unit area were lower for organic production than conventional. Thus, lower yields in organic systems necessitate additional measures, such as reducing feed-food competition and food loss and waste, to improve biodiversity outcomes. Coupling production-side measures with food supply shifts and food loss and waste reductions can lower biodiversity impacts without compromising food availability. The proposed model for integrating biodiversity indicators with food system modelling provides a globally applicable framework for analysing trade-offs between food supply and biodiversity. However, due to lack of data, global biodiversity indicators lack relevant aspects, e.g. related to soil microbiome or eco-toxicity from plant protection means. Assessing significance and potential bias from missing aspects is required to ensure balanced conclusions.

1. Introduction

Agri-food systems are essential for food security, but they are also major drivers of biodiversity loss, which in turn undermines the long-term stability of food production (Hawes *et al* 2021). Land conversion and intensification reduce habitat quality and quantity, causing species loss and ecosystem degradation (Lanz *et al* 2018, IPBES 2019). Pesticide use negatively impacts biodiversity in agricultural landscapes, and also in natural habitats, due to wind drift and runoff (Tang *et al* 2025, Wan *et al* 2025). Fertilizer and manure lead to nutrient surpluses in the environment, causing eutrophication and altering aquatic and terrestrial communities (Isbell *et al* 2013, Knorr *et al* 2023). Emissions of greenhouse gas (GHG) and acidifying substances contribute to climate change and acidification, further threatening biodiversity (Song *et al* 2025). Furthermore, eutrophication and acidification are a form of pollution by nutrients and agriculture is responsible for a large proportion of nutrients in the environment (Liu *et al* 2020). To sustain food security in the long term it is therefore crucial to transition to agri-food systems that decrease the threat to biodiversity, while providing food to the human population.

Alternative farming practices have been increasingly investigated and suggested to produce food with lower environmental impacts (Lampkin *et al* 2016, Tasca *et al* 2017, Rockström *et al* 2020). However, one of the main challenges in transitioning to more sustainable food production is the trade-off between production intensity and environmental impacts. More extensive systems, for example organic farming, are associated with lower inputs of synthetic fertilizers and pesticides, and therefore often lower environmental burdens per hectare (Hashemi *et al* 2024). On the other hand, yields in organic systems are generally lower than in conventional, more intensive systems (Alvarez 2022, de la Cruz *et al* 2023). These yield gaps need to be compensated if food demand remains unchanged, for example by increasing imports to compensate for lower domestic production, thereby shifting environmental impacts to other countries (see e.g. the study on climate change impacts of organic conversion of England and Wales (Smith *et al* 2019)). Another issue are unsustainable livestock production systems with animal numbers too high for the resources of a region or a country, where additional feed needs to be imported from elsewhere. This means external nutrients are added to the system, causing damage to the environment and biodiversity (Karlsson *et al* 2021). Especially in countries such as Switzerland with high amounts of grass resources, limiting ruminant production to the availability of these resources is an option to reduce impacts from livestock systems (Jaisli and Grüter 2024). Lastly, throughout the whole agri-food production system, about a third of the production is lost as food loss or waste. This waste occurs during production, processing, and at household stage. Efforts to reduce any of these losses and wastes result in less overall production needed and therefore less impacts to the environment (Chen *et al* 2020, Kohli *et al* 2024).

The links between the global food system and biodiversity loss have already been investigated in literature. Large-scale modelling studies have shown how global land-use and climate scenarios could impact biodiversity in the future, emphasizing the need for ambitious conservation strategies coupled with measures such as lower animal product intake and reduced food waste (Kok *et al* 2023, Pereira *et al* 2024). Other studies have revealed how consumption in high-income countries intensifies biodiversity pressure in developing nations, especially through the import of agricultural commodities (Lenzen *et al* 2012, Hoang *et al* 2023). These studies often identify livestock production and the trade of tropical products like coffee and cocoa as key drivers (Lenzen *et al* 2012). However, while these global analyses reveal crucial global patterns, assessments of how specific nationally implementable production strategies, such as a shift to grass-based feeding or an expansion of organic farming, affect national food security and biodiversity impacts remains a gap. Food system modelling that endogenously models the biomass- and nutrient-flows within agricultural production has predominantly focused on assessing GHG emissions and land use of different systems and scenarios (e.g. Muller *et al* 2017, van Zanten *et al* 2023), while a consolidated set of biodiversity indicators or proxies for such models has been lacking. In contrast, in life cycle impact assessment (LCIA) studies, biodiversity indicators have been developed and applied (Song *et al* 2025) and suggestions such as the global life cycle impact assessment method (GLAM) (*Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM)—Life Cycle Initiative* 2023) aim at harmonizing and improving LCIA methods, including those for biodiversity. LCIA methods translate environmental pressures (e.g. emissions), so-called midpoint indicators, into endpoint damage categories (e.g. damage to the ecosystem) (Souza *et al* 2015). GLAM and other LCIA methods use characterization factors (CFs) for this translation from midpoint to endpoint, i.e. to quantify the impact of specific drivers (e.g. land use, acidification) on biodiversity (*Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM)—Life Cycle Initiative* 2023, Verones *et al* 2022).

In this study, food system modelling was combined with the consistent biodiversity impact assessment method developed in GLAM for the first time. We use Switzerland as a case study to illustrate this methodological development, representing a high-income country with a diverse agricultural sector that combines extensive grassland resources with an already well-developed organic sector, representing one of the highest organic market shares in Europe (Bio Suisse 2022, Willer *et al* 2024). At the same time, Swiss food consumption heavily relies on food imports (Agristat and Schweizer Bauernverband (SBV) 2022, Ritzel *et al* 2024), meaning that a substantial share of the environmental impacts associated therewith, including biodiversity impacts, is effectively externalized to other regions. This combination of domestically available grass resources, a politically relevant policy context for organic and extensive production systems, and diets that are strongly intertwined with global supply chains makes Switzerland an informative case study for studying how large-scale production-side changes influence biodiversity outcomes. To investigate the trade-offs between agricultural production, production intensity, and biodiversity impacts, we modelled three scenarios that focused on (i) grass resources, (ii) organic production, and (iii) a combination thereof.

2. Material and methods

2.1. Model and general assumptions

The calculations were performed using the latest version of the model SOLm (Muller *et al* 2017, Frehner *et al* 2022), coded in R (R Core Team 2025). SOLm is a biophysical mass- and nutrient flow model that can be applied at any spatial scale where aggregate data on production and consumption are available (e.g. countries or NUTS2 regions) to calculate inputs, outputs, and impacts of an agricultural production and food system (s. Figure 1 for a visual overview of the modelling framework). As a primary input to the model, crop areas and yields are needed to derive plant production. Part of the plant production is subsequently used as feed to derive animal numbers and amounts of animal products. Manure and by-products can be used as secondary inputs as fertilizer and feed. Further, some animal (co-)products (e.g. whey from cheese production) are used as feed. Primary outputs of land-based and animal production units are processed into commodities with help of a commodity tree. Imports are added, exports subtracted and stock changes accounted for at each occurring level. This results in the domestically available quantities of all commodities derived from land-based agricultural production. Data on products and their various utilization (e.g. as food, feed, etc) are taken from FAOSTAT supply utility accounts (SUA) and food balance sheets (FBS) (FAO 2022). The FAO commodity trees and information on the technical conversion factors together with the SUA/FBS are used to derive the shares of each commodity that go into various processing chains as well as the respective extraction rates per chain, in the end resulting in the quantities per commodity available for food, feed, waste, etc.

This study focuses on the Swiss food system for the baseline year 2022, especially on land-based agricultural production, while excluding aquaculture and fisheries that are only contributing marginally to food supply in Switzerland. In the baseline runs, SOLm was calibrated with the national GHG inventories (FOEN 2024) as well as the FAO SUA/FBS (FAO 2022). Baseline animal populations were reproduced based on Swiss Federal Office for Agriculture (FOAG) reports (FOAG 2022), and GHG emissions were aligned with the Swiss GHG inventory (FOEN 2024) (cf supplementary section 1.1). Domestic land use data originated from Agristat and the Federal Statistical Office (FSO) (Agristat and Schweizer Bauernverband (SBV) 2022, FSO 2022). Nutrient requirements for crops were derived from Agroscope reports (Richner and Sinaj 2017), energy and feed requirements of animals were based on the default values of the Swiss GHG inventory (FOEN 2024) and the nutrient content (calories, protein, fat) of commodities was sourced from FAO food composition tables. Trade data and land use data in import countries was taken from FAOSTAT 'Detailed Trade Matrix'. A re-export correction was done following the approach by Schwarzmüller and Kastner (Schwarzmueller and Kastner 2022), to derive the country of origin for the main primary product per commodity. Per primary product, the countries that individually were the origin of 10% or more of the import quantity were named explicitly, while all other countries were aggregated as 'rest'. The share of organic import for the baseline was approximated by using data from Bio Suisse (Bio Suisse 2022). The import of organic concentrate feed was adjusted to derive the correct animal numbers given the assumed requirements and feeding rations as well as domestic feed supply.

To ensure transparency regarding system boundaries and methodological choices, domestic production and imported commodities were treated distinctly throughout the analysis. For domestic production, impacts were calculated endogenously within SOLm using a cradle-to-farmgate system boundary, covering all primary agricultural processes in Switzerland, including the use of imported feed for domestic livestock production. Impact calculations focused on biophysical mass flows of relatively unprocessed commodities, therefore, processing stages (e.g. energy required for industrial transformation) and transportation were excluded. Commodities produced in Switzerland were included irrespective of

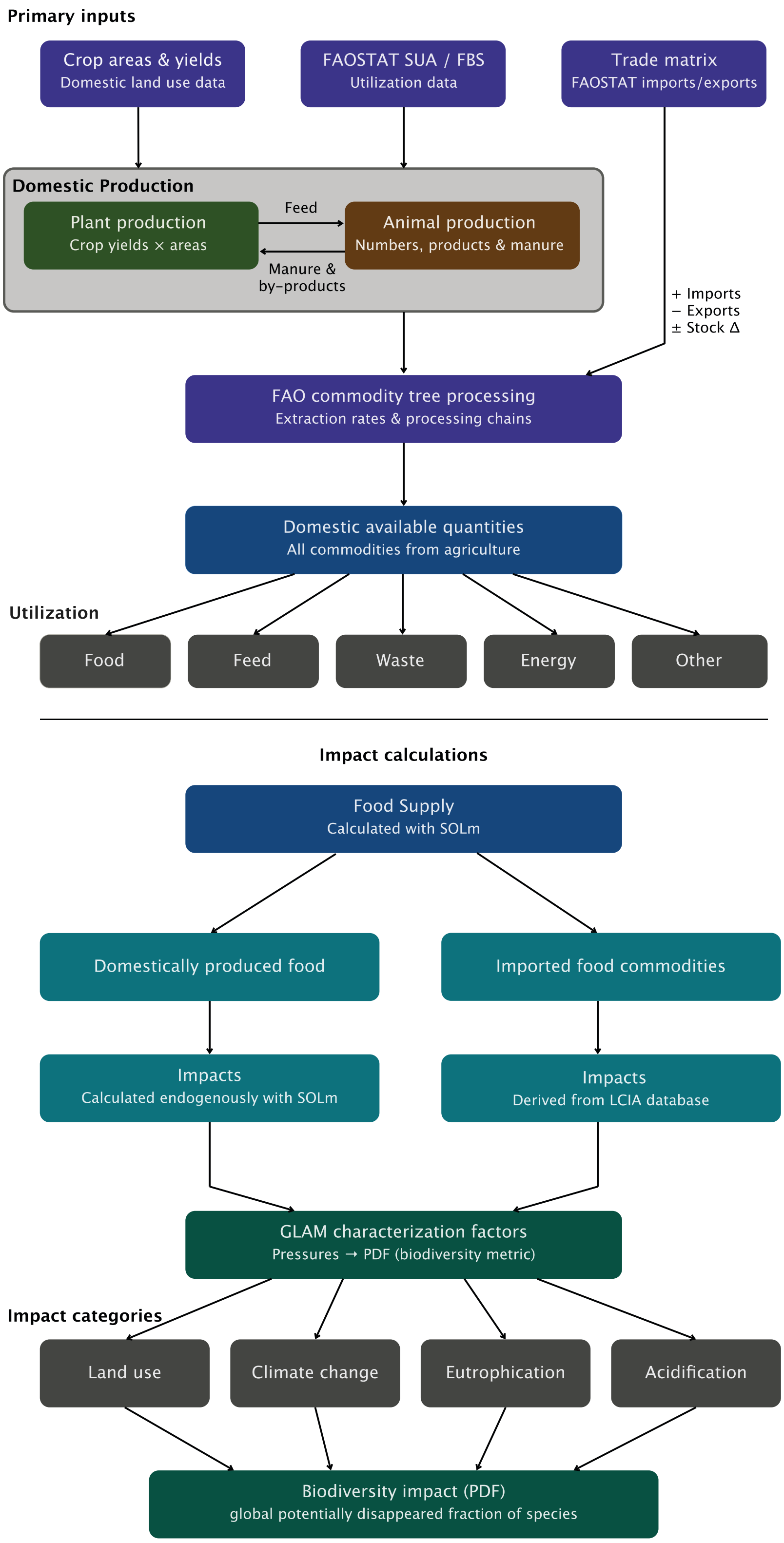

Figure 1. Overview of the modelling framework. Primary data are used to derive plant and animal production, which are processed into available quantities. Biodiversity impacts of domestic production and imports are calculated and translated into the PDF indicator using GLAM characterization factors.

whether they are consumed domestically or exported, whereas commodities produced abroad, merely processed in Switzerland, and subsequently re-exported were excluded (e.g. chocolate products for export). For imported commodities, system boundaries followed the specifications of the underlying LCIA database (Poore and Nemecek 2018, Clark *et al* 2022) used for impact calculation. As a consequence, system boundaries and levels of detail were not fully harmonized between domestic production and imports, and the study did not aim to directly compare the environmental performance of domestic production vs imports. Rather, imports were included to provide system-level context, while the primary focus remained on comparing changes across domestic production scenarios.

The analysis focuses on calculating paradigmatic scenarios designed to capture substantially different future states of the Swiss agricultural production system with respect to a number of key indicators (cf supplementary section 1.3.). We chose to report scenario results without uncertainty ranges and compare the scenarios to gain indications of the biophysical performance of considerably different futures. This approach allows the identification of potential trade-offs, leverage points and the evaluation of how different scenarios perform relative to each other. Thereby, the values are to be understood as directional indications of results, and small differences are unlikely to indicate meaningful differences.

2.2. Scenario design and specifications

SOLm is based on a ceteris paribus framework; all parameters remain at baseline values unless explicitly changed by a scenario assumption. For the present study, three agricultural scenarios have been calculated and compared to the baseline in 2022 (i.e. grass-based, organic, and a combination of both).

In all scenarios, the total cropland areas and areas for temporary and permanent grassland were the same as in the baseline. Areas per crop rotations and management however changed depending on the scenario. Data on conventional and organic crop yields was derived from several sources (Agridea and FiBL 2022, FSO 2022, Schweizer Obstverband 2022). For crops where no specific organic yield could be found, they were assumed to be 20% lower than conventional yield. For more information on the specific changes in the scenarios compared to the baseline cf supplementary section 1.3.

The three scenarios are the following:

<u>Grass-based</u>

In the scenario representing a grass-based agricultural system, ruminant feed was limited to grass resources. Therefore, no more crops used as forage feed (e.g. forage maize) were cultivated in Switzerland or imported. Production quantity of main concentrate feed crops was reduced by the amount required for ruminants in the baseline (38% for conventional and 34% for organic sub-system), to keep monogastric numbers constant. Concentrate feed imports were reduced by the same shares. Freed-up areas from reduced concentrate production within Switzerland were cultivated with crop rotations with a focus on food production (cf supplementary section 1.2 and table S4).

<u>Organic</u>

For the organic scenario, 50% of the areas per crop were cultivated organically, where 50% has been chosen to represent an ambitious target. Yields for these 50% were adjusted according to available data of organic yields in Switzerland (Agridea and FiBL 2022, FSO 2022, Schweizer Obstverband 2022) and ruminants derived from the organically cultivated feed were fed according to Swiss organic regulations, limiting concentrate feed to 5% (Notz 2021, Schneider and Helbing 2024). The number of organically produced animals was driven by the availability of organic animal feed and the yields of animal products were adapted considering lower productivity of organic livestock and longer fattening durations (Agridea and FiBL 2022). Since organic domestic production was increased 2.5 times from the baseline (20%) to the organic scenario (50%), organic import shares were also increased by multiplying by 2.5. Thus, overall, import quantity remained the same, however the share of organic products was increased by 2.5x over all commodities, whereas the shares of conventional imports were decreased accordingly. Similarly, the quantity of synthetic fertilizer was reduced by 30% since the area of conventional agriculture decreased by 30%.

<u>Combination</u>

In the combination scenario, production and trade maintained the same organic shares as in the organic scenario. Further, ruminants were fed as in the grass-based scenario, thus limiting their feed to grass resources and reducing concentrate production and import accordingly, by 32% in conventional and 21% in organic sub-system. On the freed-up areas, crop rotations with a focus on food production, including cereals and legumes, were cultivated (table S4). Additionally, food loss and waste shares based on FAOSTAT SUA (FAO 2022) per commodity were reduced by 50%, as this percentage has been shown to be a potentially avoidable share of food loss and waste (Beretta *et al* 2013, Bundesrat 2022). Food loss and waste was considered along the whole value chain excluding waste at household level for products produced in Switzerland. Loss and waste of imported products was only considered once they entered Switzerland, since this is the part that could be influenced by the domestic agri-food system.

Table 1. Biodiversity loss drivers included in this study, their midpoint indicator, the environmental consequences and realm/species groups considered by the characterization factors of these drivers of the GLAM framework. Midpoint results are calculated by the model or for imports derived from a LCIA database and then multiplied by the corresponding characterization factors to get the biodiversity indicator PDF. The characterization factors are based on a relationship between the environmental consequences and the species richness of the considered species groups. The references indicate the publications the GLAM characterization factors are based on.

Driver	Midpoint		Environmental Consequences	Realm/species groups
	Domestic	Import		
Land use (Scherer *et al* 2023)	Occupied and transformed area per crop (m^2) incl. grazing areas	Occupied and transformed area per food item (m^2) incl. grazing areas	Changed habitat availability	Terrestrial plants, amphibians, reptiles, birds, mammals
Climate change (de Visser *et al* 2023, Iordan *et al* 2023)	GHGs (CO_2, CH_4, N_2O) emitted per crop and from animal production per animal	GHGs in CO_2-eq per food item (kg)	Change in surface and water temperature	Terrestrial mammals, birds, reptiles and amphibians; marine mammals, reptiles, fish, invertebrates, corals and seagrasses
Freshwater eutrophication (Zhou *et al* 2024)	N budget in soil per crop Occupied area per crop item for eutrophication due to erosion (m^2)	N and P emissions as PO_4^{3-}eq per food item (kg) Occupied area per food item for eutrophication due to erosion (m^2)	Change in nutrient concentration in freshwater bodies	Freshwater fish
Terrestrial acidification (Lebrun *et al* 2025)	NH_3 and NO_x per crop and from animal production per animal	SO_2-eq per food item (kg)	Atmospheric deposition leading to pH change in soil	Terrestrial vascular plants

2.3. Biodiversity and environmental impact calculations

The core calculations of SOLm result in available commodities and animal numbers. Impacts for domestic production were calculated per crop and animal number and then attributed to the individual commodities using a mass-based allocation approach to get the impacts per total amount of available commodity. Impacts per animal number included impacts of imported feed. While impacts from domestic production were calculated endogenously using the model, impacts from imports were taken from the LCIA database (Poore and Nemecek 2018, Clark *et al* 2022). As a result, not all impact pathways were consistent between the domestic production and import (e.g. terrestrial acidification includes NH_3 and NO_x for domestic production but uses SO_2-equivalent values from the database for imports; see table 1 for details). Because of these divergent data sources and modelling approaches, domestic and import impacts are not directly comparable. The import data were intended to provide system-level context regarding externalized impacts rather than a direct comparative analysis against domestic production and the primary focus of this study was on the comparison of the impact of domestic production in different scenarios. Additionally, the commodities present in the model were much finer than the categories in the LCIA database used for impacts from import, therefore the values that matched best were chosen (e.g. all tomato products present in SOLm, e.g. peeled tomatoes, or tomato sauce, were matched to the category 'Tomatoes' of the LCIA database, cf supplementary data file for more information on matching). The differences between organic and conventional import impacts were approximated by the values of a recent meta-analysis (Hashemi *et al* 2024), where only the mass-based impact of land use changed significantly between conventional and organic. Therefore, land use impacts attributed to organic imports were increased per food group by the values provided by Hashemi *et al* (2024) and for all food groups that do not have a specific value, the average increase of 64% was taken.

GHG

GHG emissions from domestic production due to enteric fermentation, manure management and managed soils were calculated following the Swiss GHG inventory (FOEN 2024). Fertilizer was distributed by crop requirements and once these were fulfilled, the remaining fertilizer was allocated by area.

Biodiversity

To assess the impact on biodiversity, the proposed methods from the GLAM framework were used (*Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM)—Life Cycle Initiative* 2023). Calculated outputs from the model or midpoint impact values from the LCIA database (Poore

Table 2. Domestically available energy, protein and fat supply per scenario in total and relative numbers compared to the baseline.

Scenario	Kcal	Relative kcal (%)	Protein (g)	Relative protein (%)	Fat (g)	Relative fat (%)
Baseline	1.08×10^{13}	100	3.02×10^{11}	100	5.06×10^{11}	100
50% organic	1.01×10^{13}	94	2.84×10^{11}	94	4.82×10^{11}	95
Grass-based	1.06×10^{13}	99	3.05×10^{11}	100	4.85×10^{11}	96
Combination	1.06×10^{13}	99	3.01×10^{11}	99	4.75×10^{11}	94

and Nemecek 2018, Clark *et al* 2022) were multiplied by CFs from GLAM to derive the impact on biodiversity through the different environmental pressures (e.g. emissions, land use) (cf supplementary section 1.5. For more information on CF selection). Impact categories were selected according to importance regarding agricultural systems and their impacts on the environment. The main drivers of biodiversity loss through agriculture are land use, climate change and pollution (Sanyé-Mengual *et al* 2023). Therefore, we chose to assess impacts through land use, GHG emissions, freshwater eutrophication (from emissions and erosion due to agricultural land use) and terrestrial acidification. Due to lack of data, ecotoxicity from pesticide use could not be covered (cf supplementary section 3). Table 1 gives an overview of the included drivers in this study. For each driver, CFs have been selected and multiplied with the model outputs or database values. Where available, country-specific CFs were used. The impact of GHG emissions is global and therefore also the CFs are global average values. Due to the differences in domestic, calculated and database-based import impacts, the used CFs may also differ (e.g. for GHG for domestic impacts CFs for the individual gasses were used, for import impacts only the CF for CO2-equivalents was used).

The individual CFs are based on relationships between species and environmental conditions, and they translated the model outputs/pressures into a biodiversity metric, namely the potentially disappeared fraction (PDF) of species at the global scale, which describes the fraction of species that potentially can go globally extinct due to the environmental changes (e.g. temperature changes due to GHG emissions). By providing these CFs, the GLAM framework makes it possible to convert different environmental pressures into a common biodiversity endpoint (global PDF), and thus to quantify the potential global species loss attributable to a food system scenario (Verones *et al* 2022).

These indicators provide coverage of species groups where such global data is available. Awareness of missing aspects is central for the interpretation of the results. Here, for example, the soil microbiome is not covered, as impacts on soil invertebrates, fungi, bacteria etc are missing. Those species groups are however central in agriculture, as the soil microbiome is the basis for fertile soils and as impacts of agriculture and differences in management practices and intensity in particular, most directly affect the soil microbiome (Peltoniemi *et al* 2021, Tripathi *et al* 2025).

3. Results

3.1. Food supply

The grass-based scenario and the combination scenario were able to supply the same amount of calories and protein as the baseline, without increasing import quantities (table 2). The organic scenario reached up to 94% of the calories and of protein of the baseline. Fat supply was lower than in the baseline in all three scenarios (94% for combination, 95% for organic scenario and 96% for grass-based). The food supply values refer to the domestically available quantities, meaning imported commodities were included and quantities produced for export subtracted.

The amount of calories per food group was lower than in the baseline for most food groups in the combination and grass-based scenario, which was compensated with a larger number of calories from cereal and legumes, such that overall, the two scenarios supplied almost the same number of calories as the baseline (figures 2, figure S1). The reason for the higher production of cereals and legumes for human consumption in the combination and grass-based scenario is that less area was needed for concentrate feed production (107 629 ha in the combination and 86 838 ha in the grass-based scenario area), these were instead used for crop rotations including cereal and legumes. Missing calories and protein from reduced animal production were therefore compensated by increased area for cereal and legume production. However, the lower fat supply due to the lower quantity of animal-sourced foods could not be offset by the additional cereal and legume production (figure S3). Thus, with increased

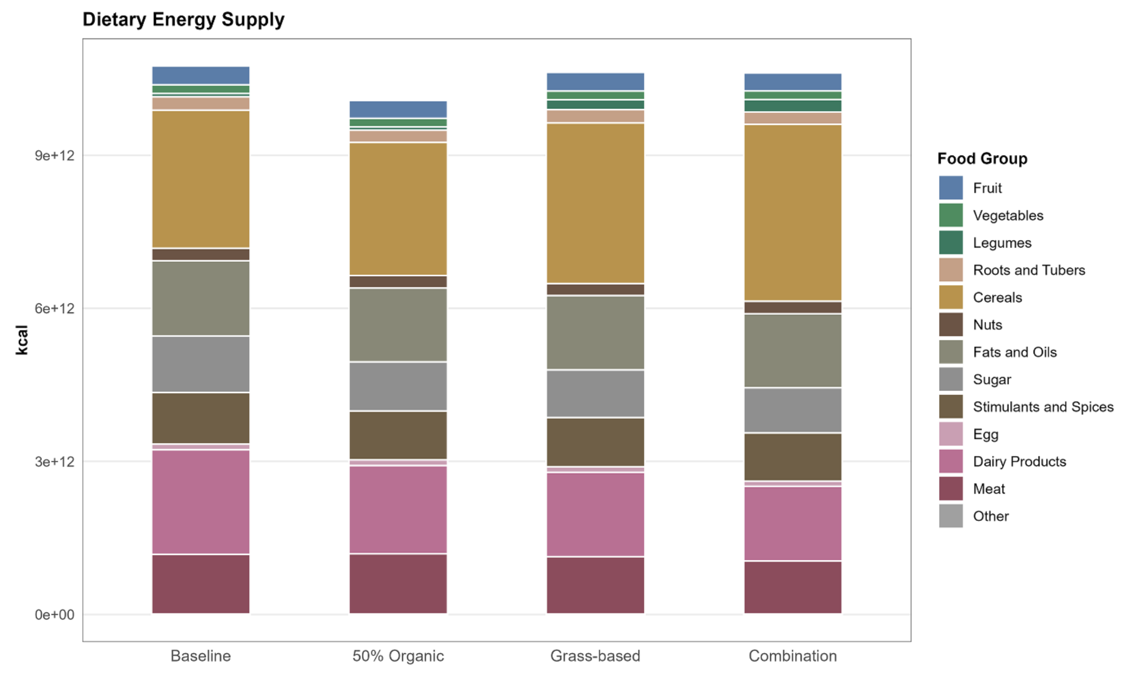

Figure 2. Domestically available food supply per scenario in kcal, divided into different food groups.

plant-based production, keeping fat supply constant is a challenge. The quantity of imported food commodities was kept constant and is 3.55×10^{12} kcal, which corresponds to between 33% and 35% of the total dietary energy supply.

3.2. Biodiversity

Domestic production

The impact on biodiversity of the agricultural production in Switzerland (incl. imported feed) was lower in all scenarios as compared to the baseline (figure 3). Compared to the baseline, the PDF from domestic production decreased by 21% in the combination scenario, 18% in the grass-based scenario, and 10% in the organic scenario. However, when the per calorie PDF is considered, the difference between the organic scenario and baseline decreases to 3%, as the organic scenario provided a lower number of calories compared to the baseline. The lower impact on biodiversity of the scenarios can mainly be attributed to a lower impact from dairy and beef (figure 3), a direct result of decreased ruminant numbers.

The biodiversity impact in the combination and grass-based scenario was lower for climate change (decrease of 31% and 30% for combination and grass-based scenario, respectively), freshwater eutrophication (27% and 28% for combination and grass-based scenario, respectively) and terrestrial acidification (32% and 36% for combination and grass-based scenario, respectively), due to lower impacts from animal products (figures 4(a)–(c)). The biodiversity impact from land use did not decrease as much, 15% for the combination scenario, 9% for the grass-based scenario and 9% for the organic scenario when the lower number of calories was accounted for (figure 4(d)).

Compared to the midpoint results (supplementary section 2.2 and figure S4), the endpoint biodiversity impact results were even more dominated by the impacts of animal sourced products (figures 4(a)–(d)). The reason for this is, that biodiversity impacts from imported feed are relatively high, due to the differences in magnitude of the used CFs. For example, the Switzerland specific CFs for acidifying emissions were approximately 10^{-16}, whereas CFs from origin countries of the feed and the global average CF were around 10^{-13}. Therefore, the biodiversity impact per tonne of emissions was higher for imported feed than for the emissions occurring within Switzerland. Additionally, the midpoint impacts attributed to imported feed, derived from the LCIA database (Poore and Nemecek 2018, Clark *et al* 2022), e.g. GHG emissions, were relatively high. Therefore, overall the biodiversity impacts of animal sourced foods were much higher than plant sourced foods (cf supplementary section 2.2.).

The impact from land use contributed over 50% to the PDF from domestic production and the share increased for the scenarios with grass-based ruminants. The impact from freshwater eutrophication was

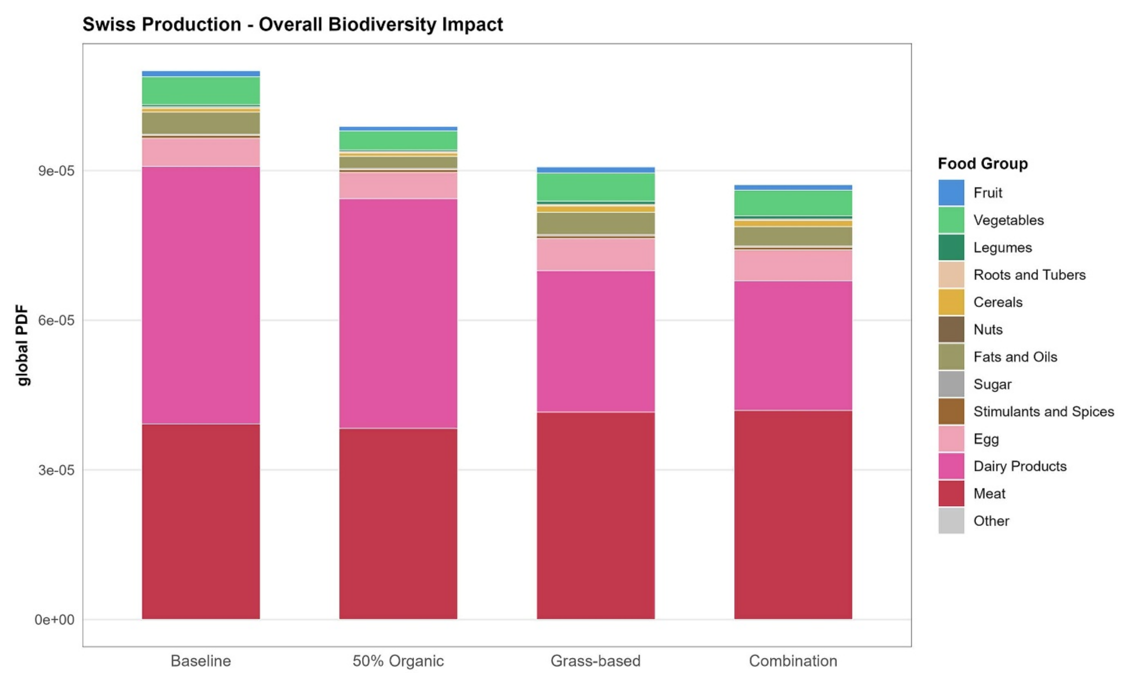

Figure 3. PDF of domestic production per scenario and food group. Impacts of imported feed were included (in animal products) but no other import.

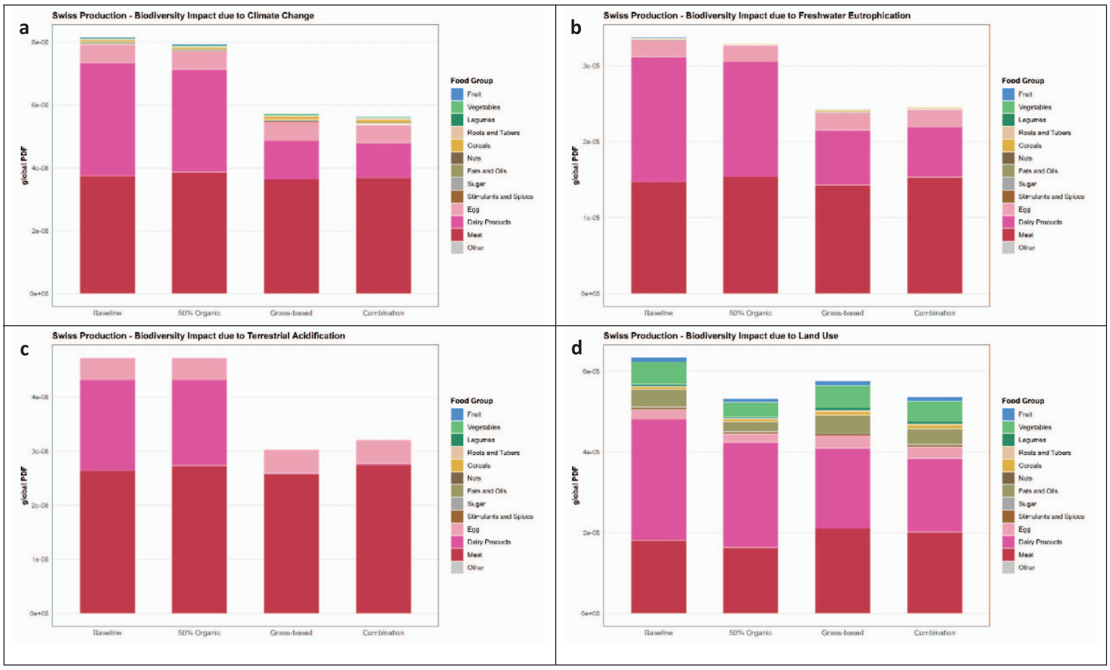

Figure 4. Biodiversity impacts, expressed as PDF, from domestic production per food group shown for (a) climate change, (b) freshwater eutrophication, (c) terrestrial acidification and (d) land use.

responsible for around 30% of the PDF from domestic production, while here the share decreased for the scenarios with grass-based ruminants (figure 5).

Domestic production and import

The PDF, considering domestic production and imported food was largely driven by the impacts of the imports, in particular of the food group stimulants and spices, including e.g. coffee, chocolate, as well as tea, alcohols, and various spices (figure 6). Coffee and cocoa are usually grown in biodiversity rich ecosystems (Toledo and Moguel 2012, de Lima *et al* 2014, Chain-Guadarrama *et al* 2019) and the amounts of chocolate and coffee consumed in Switzerland are relatively high (Rochat *et al* 2020, Samanta

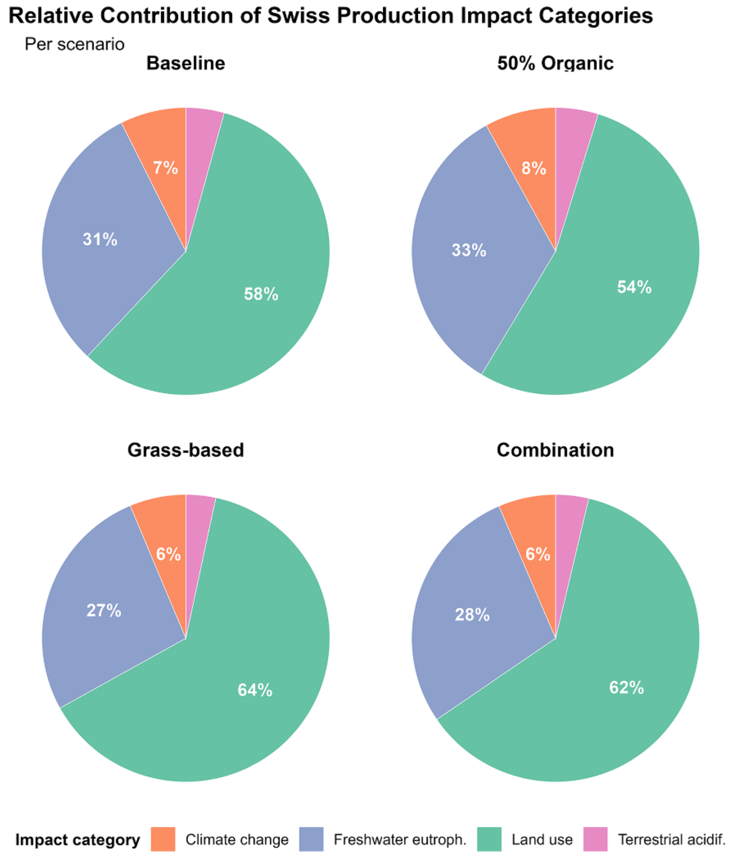

Figure 5. Relative contribution of the individual PDFs to the total PDF per scenario.

et al 2022). This is reflected in their substantial contribution to biodiversity impacts: in the baseline, 18% of the PDF was attributed to coffee and 22% to cocoa products. Within the stimulants and spices category, coffee dominated several impact categories, contributing, for example, 72% of eutrophying and 65% of GHG emissions, while cocoa powder contributed 30% of land area within the food group stimulants and spices. Cocoa butter was included in the fats and oils category and accounted for a large share of impacts within this group (e.g. 51% of land use and 72% of GHG emissions), explaining the high biodiversity impacts attributed to this category (cf supplementary section 2.3 for detailed results). To provide a complete view of the Swiss food system's environmental impact, we included the impacts of imported food. This allowed for the identification of central commodities at total systems level, such as coffee and cocoa, while, due to the differing data basis, we do not provide a direct detailed comparison between the domestic versus foreign production systems (cf methods section).

Germany, Italy, Spain and France were the most important countries of origin for Swiss food imports when considering the origin of primary products, both mass and calorie wise. The largest imported PDF came from the countries Ecuador, Colombia, Brazil, Vietnam and Ghana (figure 7), mainly due to imports of coffee and cocoa commodities.

3.3. Animal production

The grass-based scenario had around 20% less ruminants and all other animals mostly relying on grass-based feed (e.g. equids). There was also a decrease (around 5%) of animals based on concentrates. The organic scenario showed a decrease in animal numbers that are driven by grass yields between 11% (cattle, equids) and 23% (goats). Only animals relying on concentrate feed showed an increase (13% more pigs, 3% more chicken), this was due to the concentrate quantities no longer used by ruminants due to their reduced numbers and thus being freed up for use by monogastrics. The steeper increase of pigs compared to poultry can be explained with the proportionally larger increase in concentrate ratio going to pigs. For the combination scenario there was a decrease of all animal numbers: cattle decreased by 25%, chicken by 12% and pigs by 4%.

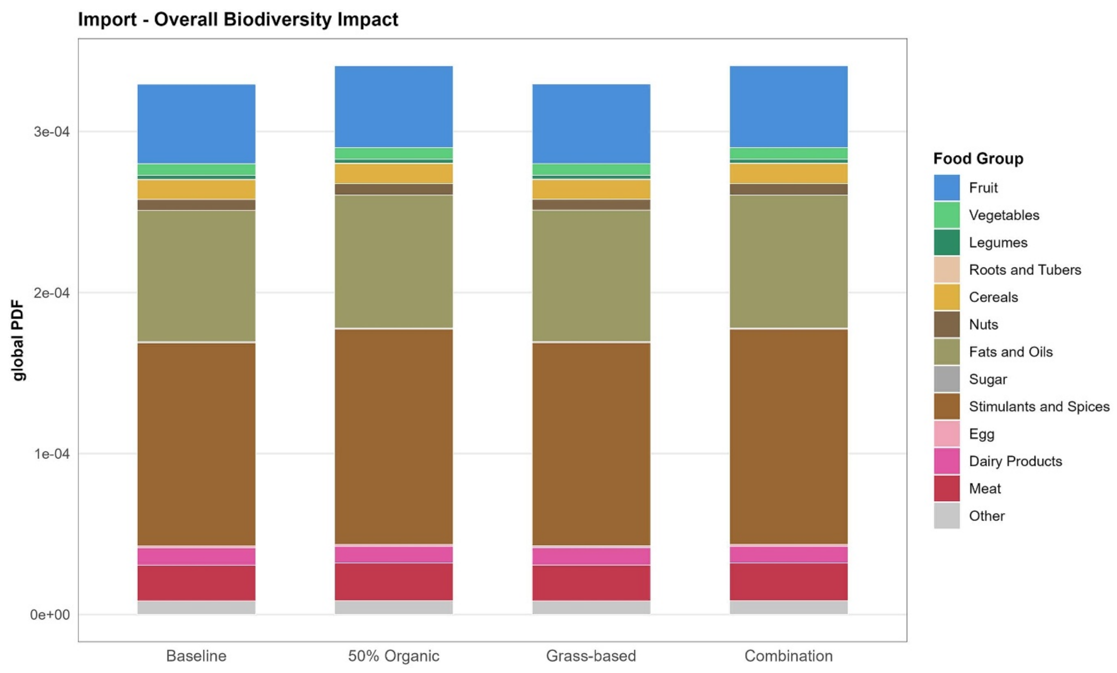

Figure 6. PDF of imported food commodities.

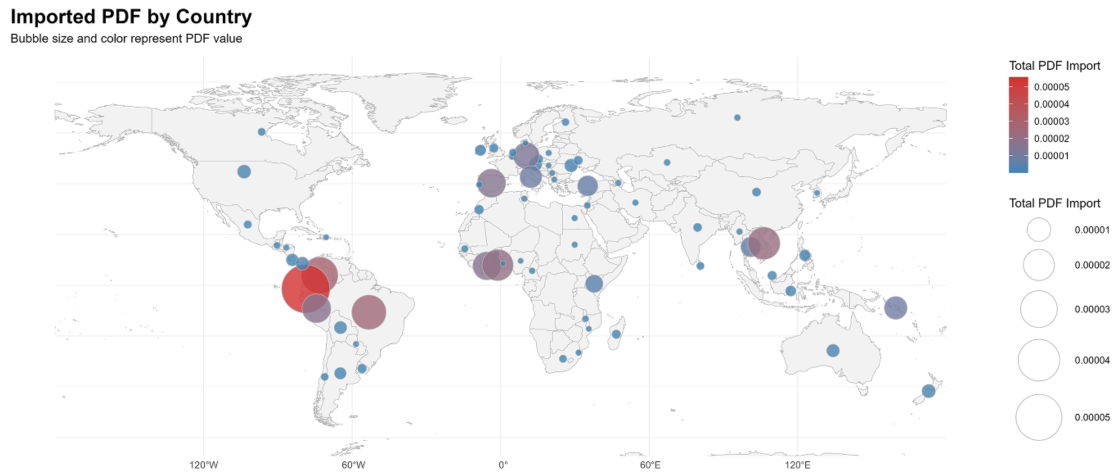

Figure 7. PDF for imported food products per country of origin of the primary products under the baseline scenario (reference year 2022). Bubble size and colour corresponds to the PDF value.

4. Discussion

The analysis demonstrates that all investigated alternative production scenarios reduced the overall biodiversity impact compared to the baseline for domestic production, while two out of three scenarios also reduced impacts, albeit only slightly, when impacts from imports are included. The grass-based and combination scenarios showed the largest reductions in domestic biodiversity impact, mainly due to decreased livestock numbers. The reduction in animal numbers, particularly ruminants, directly decreased the environmental pressures related to GHG emissions and nutrient pollution, which together drive biodiversity loss (Sanyé-Mengual *et al* 2023). These findings highlight the potential of system-level strategies that align livestock production with grassland availability and reduce feed-food competition. While global strategies like 'Half Earth' or 'Sharing the Planet' emphasize large-scale area-based conservation, our model illustrated the biophysical mechanisms of land reallocation. By shifting toward grass-based ruminants, we demonstrated how land can be specifically freed from concentrate feed production and reallocated to direct food crops (e.g. cereals and legumes), maintaining caloric supply while reducing environmental pressures. This provides a concrete example of how 'integrated sustainability measures,' including food loss and waste reduction and dietary shifts mentioned by Kok *et al* (2023), can be operationalized within a specific national context. Similarly, a recent case study in Norway found GHG emissions and impact on biodiversity to be lower for a scenario with reduced feed-food competition (Olsen *et al* 2025). We emphasize that the scenarios analysed here addressed feed-food competition only for ruminants and kept feed areas and imports for monogastric animals constant, thus focusing on the impacts of the two key strategies conversion to grass-based ruminant and/or organic production, without a full implementation of circularity in the sense of animals being fed on biomass not eatable for humans only ('feed-no-food').

Our results confirm that domestic biodiversity impacts are dominated by the ruminant sector, while impacts from domestic production and imported commodities are largely driven by the import of stimulants like coffee and cocoa. This aligns with global findings identifying cattle, coffee, and cocoa as top-ranking commodities threatening species in biodiversity-rich regions like Brazil, Colombia and Indonesia (Lenzen *et al* 2012, Hoang *et al* 2023). Because biodiversity impacts are inherently local, tailored action is required at both scales. Domestically, this mainly concerns animal products, and their reduction has large domestic biodiversity impact reduction potential. For imports, however, stimulants show by far the biggest potential for impact reduction, as previously shown in other studies (e.g. (Lenzen *et al* 2012, Scherer and Pfister 2016, Hoang *et al* 2023, Fan *et al* 2024) and should be targeted much more explicitly in biodiversity conservation strategies. It can also be noted that for these key imported commodities, the yield gap between organic and conventional production is not relevant for the overall biodiversity impacts as the higher land use is balanced by lower per hectare biodiversity impacts for organic production.

Notably, all alternative scenarios could not reach the level of fat supply of the baseline. This highlights the importance to also focus on plant-based fat sources from oil crops when identifying pathways towards diets with higher plant-based shares, next to a focus on protein supply. From a nutritional perspective, the reduced fat supply observed in this study may not be problematic, given that the fat intake of the Swiss population is above recommended levels (Eggenschwiler *et al* 2025). When impacts are expressed per calorie, the advantages of organic production become less apparent. Due to lower yields, the organic scenario was unable to produce the same amount of calories domestically and would therefore require an increase in imports to reach the same food supply as the status-quo. This would further increase the already higher land use per unit of food produced in import countries, leading to higher biodiversity impact via land occupation. This higher impact due to land use could not be offset with the domestically slightly lower pressures from emissions and nutrient input. This underlines a key trade-off: while less intensive systems reduce input-driven pressures, they also tend to expand land requirements (e.g. Mwambo *et al* 2021, Leon 2024). Achieving biodiversity benefits at the system level thus requires further changes than a transformation to organic production as shown here by the combination scenario, which combines organic production with decreased livestock numbers due to a grass-based feeding regime and decrease of food loss and waste. However, these systems then also produce less animal sourced foods and therefore demand a change in the consumption pattern of the population.

4.1. Methodological considerations and limitations

The study applies LCIA-based biodiversity CFs from the GLAM framework to a national food system model, providing a comprehensive approach for evaluating biodiversity impacts from multiple environmental pressures on a food systems level and with a globally applicable framework. This is illustrated with the analysis for Switzerland as case study country, but the approach in principle allows for comparative studies between different countries. This method enables the analysis of major drivers—land use, eutrophication, acidification, and climate change—and their relative contribution to biodiversity loss. It is important to note that characterization factors are derived from specific ecological relationships and therefore represent only a subset of taxa and environmental contexts. For example, eutrophication effects are modelled through freshwater fish species responses only (Zhou *et al* 2024). Furthermore, it has to be emphasized that the biodiversity metric PDF describes potential species loss linked to environmental pressures and therefore describes a risk what could happen, but not a direct prediction of the impact of a scenario.

Biodiversity assessments in general, and in particularly those applied here on a food system level with the GLAM framework are limited by a relatively broad scale, approximations, simplifications and omissions. Regional or national scale assessments may obscure local or farm-level biodiversity changes, making it difficult to capture fine-scale variations and landscape-level processes (Westaway *et al* 2024, Bromwich *et al* 2025). Most indicators and methods quantify only a few impacts related to specific species groups and regions and without temporal considerations, failing to provide a holistic view of biodiversity loss across food systems (Ran *et al* 2024). Thus, for example, impacts on soil microbiota and its diversity are hardly ever assessed, albeit this is a central basis for long term agricultural productivity. Further, in the present study the ecotoxicological impact of pesticides is missing due to a lack of data. Biodiversity impact due to freshwater and terrestrial ecotoxicity have been assessed on an exploratory basis (cf supplementary section 3). The assessment suffered from incomplete information and missing CFs for key substances, especially those allowed in organic agriculture (e.g. copper). Including ecotoxicity under these conditions would therefore risk introducing substantial uncertainty. Pesticides related to intensive agriculture can have major negative impacts on natural ecosystems (Ankit *et al* 2020), however, also substances allowed in organic agriculture can pose a risk to biodiversity (e.g. Mebane (2023)). This begs the question how to deal with incomplete quantitative results in sustainability assessments and whether such incomplete numbers are more insightful than no numbers. Refraining from any quantification would be the alternative to incomplete numbers in contexts where data for relevant aspects is missing. Overall, challenges to represent the real-life complexity of biodiversity arise from the mismatch between the scales and levels of biodiversity and food systems and insufficient data quality and availability (Crenna *et al* 2019).

Biodiversity assessment outcomes are highly sensitive to the scope of included indicators, as trade-offs and synergies between impact categories can significantly alter overall conclusions. For instance, studies focusing solely on land use efficiency often suggest that organic agriculture exerts higher environmental pressure than intensive systems due to yield gaps and the resulting increase in land requirements (e.g. Crosnier *et al* (2025) where biodiversity impact is assessed in such a way that it basically captures land use only). However, when a broader range of impact categories and management intensities are considered, as done in this study, the ecological benefits of extensive agriculture coupled with site conformed measures become evident. For Switzerland, these advantages are particularly distinct when organic farming is coupled with adapted production systems, such as grass-based feeding regimes. The positive performance of such systems would likely be further emphasized if data on pesticide ecotoxicology were available, as intensive agriculture is known to have major negative impacts on natural ecosystems via this pathway (Ankit *et al* 2020), or if impacts on the soil microbiome would be covered, which is known to be negatively affected by intensive agriculture (Peltoniemi *et al* 2021, Walder *et al* 2022, Tripathi *et al* 2025).

To comprehensively assess the nutritional adequacy of the Swiss food supply, further analysis regarding macro- and micronutrients and their bioavailability is required. The integration of other key nutrients, such as iron or zinc, might reveal new trade-offs. Additionally, the increase of cereals, as seen in the grass-based and combination scenario, could lead to a reduction in some micronutrients and also lead to a risk of overconsumption of carbohydrates, if cereals would be increased drastically (Khan *et al* 2025). Furthermore, a holistic evaluation of dietary sustainability should incorporate the processing stage, as energy-intensive processing can significantly affect the overall environmental footprint of consumer products (Heusala *et al* 2020, Bortolini *et al* 2023).

4.2. Broader environmental and food supply implications

From the perspective of food supply, the grass-based and combination scenarios indicate that it is possible to maintain the national supply of calories and protein while decreasing biodiversity impacts. These systems achieve such efficiency by reallocating land from concentrate feed production toward direct food crops, thereby compensating for reduced animal output. In contrast, the organic scenario produces fewer calories and proteins overall, reflecting the yield gap between organic and conventional systems. Importantly, the scenarios addressed in this paper are rather moderate regarding concentrate feed and livestock reduction, as they focus on such for ruminants only, keeping monogastric livestock rather constant. Reducing concentrate feed supply to those would mobilize substantial additional potential for impact reduction, however also coupled to more drastic changes of production and consumption patterns towards plant-based diets.

GHG and nutrient-related impacts follow a similar pattern: reductions in livestock intensity result in lower GHG emissions, freshwater eutrophication, and acidification. The combination scenario, which integrates grass-based feeding, organic production shares, and food loss and waste reduction, achieves the most balanced outcome, lowering biodiversity impacts without major compromises in food supply. However, this scenario requires shifts in dietary patterns, particularly reduced consumption of animal products due to the lower availability of products derived from ruminants, such as beef and dairy. Without such adjustments, the benefits for biodiversity might be offset by higher imports, effectively externalizing impacts.

To meet nutrient requirements and current fat supply under less intensive systems, crop rotations might need to integrate more oilseed species, though this could pose agronomic challenges (Ma *et al* 2023, Tariq Ahmad *et al* 2025). Likewise, targeted measures to reduce high-impact imports (mainly coffee and cocoa products) or source them from biodiversity-friendly production systems can further reduce the external biodiversity footprint.

To sum up, although focused on Switzerland, our findings offer international relevance for other high-income countries with significant grassland resources. The SOLm-GLAM approach provides a globally applicable framework for including biodiversity assessments on food system level for analysing the trade-offs between production intensity, food security, and biodiversity. Our findings suggest that for nations with high meat consumption and significant trade dependencies, the transition to less intensive, resource-adapted systems is a viable pathway to meet global biodiversity targets without compromising long-term food supply.

5. Conclusion

Overall, this study highlights the interlinkages between biodiversity outcomes, production systems, production regions and consumption habits. By linking biodiversity impact assessment with food system modelling, it becomes possible to identify leverage points for national strategies that jointly address food security and ecological sustainability. While organic agriculture reduces input-driven pressures, the associated yield gap increases land requirements, risking the externalization of impacts through imports if diets remain unchanged. To mitigate this trade-off, production strategies must be coupled with demand-side shifts; specifically, the combination scenario demonstrates that aligning livestock production with grassland availability and reducing feed-food competition paired with more extensive production and reductions in food loss and waste can lower biodiversity impacts without compromising food security. However, the relevance of this trade-off between the benefits of organic production and its generally increased land use is not central for all indicators and crops, e.g. where impacts per hectare are correspondingly lower. Notably, for the total biodiversity impact of the scenarios, that is dominated by the imports of stimulants and spices (mainly coffee and cocoa), the differences between the scenarios are small and also the organic scenario shows only slightly higher values.

The combined SOLm-GLAM approach provides a method for biodiversity assessments on food system level, applicable to any country. It provides valuable relative comparison of scenarios and insights into the direction and magnitude of their biodiversity impacts due to different drivers, compared to other studies where biodiversity is underrepresented or limited to individual drivers such as land use or climate change. However, it still simplifies the reality of the vast complexity of biodiversity. A significant limitation remains the exclusion of ecotoxicological impacts from pesticides or aspects related to the soil microbiome due to data scarcity, which likely underestimates the benefits of extensive systems. The main challenge regarding this incomplete coverage is that such missing results implicitly count equivalent to a zero impact. It is thus of central importance to highlight these gaps and how they may bias results when communicating such biodiversity assessments. In addition, given the high uncertainty of available data, results should be interpreted as directional rather than absolute. Future development of spatially explicit and multi-taxa indicators is essential to capture the full complexity of biodiversity in food system assessments.

Acknowledgments

The authors thank the two reviewers and the editors for their thorough and very helpful feedback that greatly contributed to the quality of this paper.

This research was conducted as part of the project 'Deliberative Diets: Connecting Producers and consumers to value the sustainability of Swiss food systems scenarios' funded by the Swiss National Science Foundation, Sinergia Funding Programme, grant no. CRSII5_202300.

Data availability statement

The data that supports the findings of this study are openly available in the supplementary files of this article.

Supplementary Text available at https://doi.org/10.1088/2976-601X/ae7c02/data1.

Supplementary Data 1 available at https://doi.org/10.1088/2976-601X/ae7c02/data2.

Author contributions

Eva Augustiny 0009-0005-0674-4005
Conceptualization (lead), Data curation (lead), Formal analysis (lead), Investigation (equal), Methodology (equal), Software (equal), Validation (equal), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Adrian Muller 0000-0001-7232-9399
Conceptualization (equal), Data curation (equal), Formal analysis (equal), Investigation (equal), Methodology (equal), Software (equal), Supervision (equal), Validation (equal), Writing – original draft (equal), Writing – review & editing (equal)

Ashley Green
Conceptualization (supporting), Supervision (supporting), Writing – review & editing (supporting)

Alexander Mathys 0000-0003-1633-848X
Conceptualization (supporting), Supervision (equal), Writing – review & editing (supporting)

Stephan Pfister 0000-0001-8984-2041
Conceptualization (supporting), Methodology (supporting), Writing – review & editing (supporting)

Michael Curran 0000-0002-1858-5612
Conceptualization (supporting), Funding acquisition (equal), Project administration (equal), Writing – review & editing (supporting)

Anita Frehner 0000-0002-0039-8421
Conceptualization (equal), Investigation (equal), Methodology (equal), Project administration (equal), Supervision (equal), Validation (equal), Writing – original draft (equal), Writing – review & editing (equal)

References

Agridea and FiBL 2022 *Deckungsbeiträge* Ausgabe 2022

Agristat and Schweizer Bauernverband (SBV) 2022 *Statistische Erhebungen und Schätzungen über Landwirtschaft und Ernährung* SES 2022 Schweizer Bauernverband (SBV)

Alvarez R 2022 Comparing productivity of organic and conventional farming systems: a quantitative review *Arch. Agron. Soil Sci.* **68** 1947–58

Ankit, Saha L, Kishor V and Bauddh K 2020 Impacts of synthetic pesticides on soil health and non-targeted Flora and Fauna *Ecological and Practical Applications for Sustainable Agriculture* ed K Bauddh, S Kumar, R P Singh and J Korstad (Hrsg.) (Springer) pp 65–88

Beretta C, Stoessel F, Baier U and Hellweg S 2013 Quantifying food losses and the potential for reduction in Switzerland *Waste Manage.* **33** 764–73

Bio Suisse 2022 Bio in Zahlen 2022 (available at: https://fokus.sbv-usp.ch/biodiversitaet/images/Literatur/Deutsch/Bio_Suisse_2023_Bio_in_Zahlen_2022.pdf)

Bortolini M, Cafarella C, Ferrari E, Galizia F G, Gamberi M and Ventura V 2023 Assessing energy requirements in the European (EU-28) food sector *Sustainable Development and Pathways for Food Ecosystems* pp 259–72

Bromwich T *et al* 2025 Navigating uncertainty in life cycle assessment-based approaches to biodiversity footprinting *Methods Ecol. Evol.* **17** 1387–404

Chain-Guadarrama A, Martínez-salinas A, Aristizábal N and Ricketts T H 2019 Ecosystem services by birds and bees to coffee in a changing climate: a review of coffee berry borer control and pollination *Agric. Ecosyst. Environ.* **280** 53–67

Chen C, Chaudhary A and Mathys A 2020 Nutritional and environmental losses embedded in global food waste *Resour. Conserv. Recycl.* **160** 104912

Clark M, Springmann M, Rayner M, Scarborough P, Hill J, Tilman D, Macdiarmid J I, Fanzo J, Bandy L and Harrington R A 2022 Estimating the environmental impacts of 57,000 food products *Proc. Natl Acad. Sci. USA* **119** e2120584119

Crenna E, Sinkko T and Sala S 2019 Biodiversity impacts due to food consumption in Europe *J. Clean. Prod.* **227** 378–91

Crosnier A, Baudry G, Jeangros L, Meier E S, Cisco G, Spring L and Barjolle D 2025 True cost accounting for food application: environmental, social and health impacts of bread *J. Clean. Prod.* **524** 146224

de la Cruz V Y V, Tantriani T, Cheng W and Tawaraya K 2023 Yield gap between organic and conventional farming systems across climate types and sub-types: a meta-analysis *Agric. Syst.* **211** 103732

de Lima R F, Viegas L, Solé N, Soares E, Dallimer M, Atkinson P W and Barlow J 2014 Can management improve the value of shade plantations for the endemic species of São Tomé Island? *Biotropica* **46** 238–47
de Visser S, Scherer L, Huijbregts M and Barbarossa V 2023 Characterization factors for the impact of climate change on freshwater fish species *Ecol. Indic.* **150** 110238
Eggenschwiler M, Linzmajer M and Bally L 2025 *Der Schweizer Ernährungsatlas 2024—Eine Schätzmethodik des Ernährungsverhaltens der Schweizer Bevölkerung basierend auf Einkaufsdaten* (Institut für Handelsmanagement, Universität St.Gallen)
Fan S, Newbold T, Tscharntke T, Tang W, Yu Z and Liu Y 2024 Impact of crop type on biodiversity globally *Glob. Change Biol.* **30** e70005
FAO 2022 FAOSTAT (available at: www.fao.org/faostat/en/#data)
FOAG 2022 *Agrarbericht 2022* (Federal Office for Agriculture (FOAG)) (available at: https://2022.agrarbericht.ch/de)
FOEN 2024 *Switzerland's Greenhouse Gas Inventory 1990–2022: National Inventory Document and reporting tables* (Federal Office for the Environment (FOEN)) (available at: www.climatereporting.ch)
Frehner A, De Boer I, Muller A, Van Zanten H and Schader C 2022 Consumer strategies towards a more sustainable food system: insights from Switzerland *Am. J. Clin. Nutr.* **115** 1039–47
FSO 2022 Landwirtschaftliche Betriebe und Landwirtschaftliche Nutzfläche (LN) auf Klassifizierungsebene 3 nach Kanton (available at: www.pxweb.bfs.admin.ch)
Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM)—Life Cycle Initiative 2023 (available at: www.lifecycleinitiative.org/activities/life-cycle-assessment-data-and-methods/global-guidance-for-life-cycle-impact-assessment-indicators-and-methods-glam/) (Accessed 15 February 2023)
Hashemi F, Mogensen L, van der Werf H M G, Cederberg C and Knudsen M T 2024 Organic food has lower environmental impacts per area unit and similar climate impacts per mass unit compared to conventional *Commun. Earth Environ.* **5** 250
Hawes C, Iannetta P P M and Squire G R 2021 Agroecological practices for whole-system sustainability *CAB Rev.: Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* **16** 005
Heusala H, Sinkko T, Sözer N, Hytönen E, Mogensen L and Knudsen M T 2020 Carbon footprint and land use of oat and faba bean protein concentrates using a life cycle assessment approach *J. Clean. Prod.* **242** 118376
Hoang N T, Taherzadeh O, Ohashi H, Yonekura Y, Nishijima S, Yamabe M, Matsui T, Matsuda H, Moran D and Kanemoto K 2023 Mapping potential conflicts between global agriculture and terrestrial conservation *Proc. Natl Acad. Sci. USA* **120** e2208376120
Iordan C-M, Kuipers K J J, Huang B, Hu X, Verones F and Cherubini F 2023 Spatially and taxonomically explicit characterisation factors for greenhouse gas emission impacts on biodiversity *Resour. Conserv. Recycl.* **198** 107159
IPBES 2019 *Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* Zenodo (https://doi.org/10.5281/zenodo.6417333)
Isbell F, Reich P B, Tilman D, Hobbie S E, Polasky S and Binder S 2013 Nutrient enrichment, biodiversity loss, and consequent declines in ecosystem productivity *Proc. Natl Acad. Sci. USA* **110** 11911–6
Jaisli I and Grüter R 2024 Potentials of grassland-based livestock farming in Switzerland—a scenario comparison *Sustainability* **16** 10362
Karlsson J O, Parodi A, van Zanten H H E, Hansson P-A and Röös E 2021 Halting European union soybean feed imports favours ruminants over pigs and poultry *Nat. Food* **2** 38–46
Khan B S, Shukat R, Butt M S and Riaz A 2025 Multi-dimensional analysis of cereal-based diets in Pakistan: consumption trends, socio-economic determinants, and policy implications *Pak. J. Agric. Sci.* **62** 329–39
Knorr S, Weisener C G and Phillips L A 2023 Agricultural land management alters the biogeochemical cycling capacity of aquatic and sediment environments *Agric. Ecosyst. Environ.* **357** 108661
Kohli K, Prajapati R, Shah R, Das M and Sharma B K 2024 Food waste: environmental impact and possible solutions *Sustain. Food Technol.* **2** 70–80
Kok M T J *et al* 2023 Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world *Biol. Conserv.* **284** 110068
Lampkin N H, Smith J and Smith L G 2016 *Agroecology and Organic Farming as Approaches to Reducing the Environmental Impacts of Agricultural Chemicals* (The Royal Society of Chemistry) (https://doi.org/10.1039/9781782626916-00094)
Lanz B, Dietz S and Swanson T 2018 The expansion of modern agriculture and global biodiversity decline: an integrated assessment *Ecol. Econ.* **144** 260–77
Lebrun M N, Dorber M, Verones F and Henderson A D 2025 Novel endpoint characterization factors for life cycle impact assessment of terrestrial acidification *Ecol. Indic.* **171** 113241
Lenzen M, Moran D, Kanemoto K, Foran B, Lobefaro L and Geschke A 2012 International trade drives biodiversity threats in developing nations *Nature* **486** 109–12
Leon A 2024 A synthesis of the evidence regarding the efficacy of alternative field management practices in rice cultivation using life cycle assessment *Sci. Total Environ.* **926** 171693
Liu L *et al* 2020 Challenges for global sustainable nitrogen management in agricultural systems *J. Agric. Food Chem.* **68** 3354–61
Ma B-L, Liang C, Herath A, Caldwell C D and Smith D L 2023 Canola productivity and carbon footprint under different cropping systems in eastern Canada *Nutr. Cycl. Agroecosyst.* **127** 191–207
Mebane C A 2023 Bioavailability and toxicity models of copper to freshwater life: the state of regulatory science *Environ. Toxicol. Chem.* **42** 2529–63
Muller A *et al* 2017 Strategies for feeding the world more sustainably with organic agriculture *Nat. Commun.* **8** 1–13
Mwambo F M, Fürst C, Martius C, Jimenez-martinez M, Nyarko B K and Borgemeister C 2021 Combined application of the EM-DEA and EX-ACT approaches for integrated assessment of resource use efficiency, sustainability and carbon footprint of smallholder maize production practices in sub-Saharan Africa *J. Clean. Prod.* **302** 126132
Notz C 2021 *Für Wiederkäuer neue Bio-Fütterungsrichtlinien [Allgemeine Presse and Fachartikel (nicht peer-reviewt)]* (Schweizer Bauer) (available at: https://orgprints.org/id/eprint/42995/)
Olsen H F, Samsonstuen S, Mogensen L, Röös E, Knudsen M T and Møller H 2025 When arable land is the limit: paths for future livestock production—an example from Norway *Agric. Syst.* **229** 104446
Peltoniemi K, Velmala S, Fritze H, Lemola R and Pennanen T 2021 Long-term impacts of organic and conventional farming on the soil microbiome in boreal arable soil *Eur. J. Soil Biol.* **104** 103314
Pereira H M *et al* 2024 Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050 *Science* **384** 458–65
Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers *Science* **360** 987–92
R Core Team 2025 *R: a language and environment for statistical computing* [software]

Ran Y *et al* 2024 Environmental assessment of diets: overview and guidance on indicator choice *Lancet Planet. Health* **8** e172–e87
Richner W and Sinaj S 2017 *Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017)* (Spezialpublikation Agoscope) S.276 (available at: www.grud.ch)
Ritzel C, Möhring A and von Ow A 2024 Vulnerability assessment of food imports—conceptual framework and empirical application to the case of Switzerland *Heliyon* **10** e27058
Rochat C, Eap C B, Bochud M and Chatelan A 2020 Caffeine consumption in Switzerland: results from the first national nutrition survey menuCH *Nutrients* **12** 28
Rockström J, Edenhofer O, Gaertner J and DeClerck F 2020 Planet-proofing the global food system *Nat. Food* **1** 3–5
Samanta S, Sarkar T, Chakraborty R, Rebezov M, Shariati M A, Thiruvengadam M and Rengasamy K R R 2022 Dark chocolate: an overview of its biological activity, processing, and fortification approaches *Curr. Res. Food Sci.* **5** 1916–43
Sanyé-Mengual E, Biganzoli F, Valente A, Pfister S and Sala S 2023 What are the main environmental impacts and products contributing to the biodiversity footprint of EU consumption? A comparison of life cycle impact assessment methods and models *Int. J. Life Cycle Assess.* **28** 1194–210
Scherer L and Pfister S 2016 Global biodiversity loss by freshwater consumption and eutrophication from Swiss food consumption *Environ. Sci. Technol.* **50** 7019–28
Scherer L, Rosa F, Sun Z, Michelsen O, De Laurentiis V, Marques A, Pfister S, Verones F and Kuipers K J J 2023 Biodiversity impact assessment considering land use intensities and fragmentation *Environ. Sci. Technol.* **57** 19612–23
Schneider C and Helbing M 2024 *Fütterungsrichtlinien 2024 nach Bio Suisse* (Forschungsinstitut für biologischen Landbau FiBL) (https://doi.org/10.5281/zenodo.10521676)
Schwarzmueller F and Kastner T 2022 Agricultural trade and its impacts on cropland use and the global loss of species habitat *Sustain. Sci.* **17** 2363–77
Schweizer Obstverband 2022 Beeren-Anbauflächen
Schweizerischer Bundesrat 2022 Aktionsplan gegen die Lebensmittelverschwendung (available at: https://www.bafu.admin.ch/dam/en/sd-web/2vVtDYhy5B9N/aktionsplan_gegen_die_lebensmittelverschwendung.pdf)
Smith L G, Kirk G J D, Jones P J and Williams A G 2019 The greenhouse gas impacts of converting food production in England and wales to organic methods *Nat. Commun.* **10** 4641
Song J, Chaudhary A, Tang R, Bai X and Yang Y 2025 Life-cycle biodiversity assessment of global crop production: advances, framework, and outlooks *J. Environ. Manage.* **393** 126934
Souza D M, Teixeira R F M and Ostermann O P 2015 Assessing biodiversity loss due to land use with life cycle assessment: are we there yet? *Glob. Change Biol.* **21** 32–47
Tang F H M, Wyckhuys K A G, Li Z, Maggi F and Silva V 2025 Transboundary impacts of pesticide use in food production *Nat. Rev. Earth Environ.* **6** 383–400
Tariq Ahmad L, Quseen Mushtaq R and Jan N 2025 Bacterial Pathogens of the Oilseed Crops *Oilseed Crops* (Wiley) pp 91–111
Tasca A L, Nessi S and Rigamonti L 2017 Environmental sustainability of agri-food supply chains: an LCA comparison between two alternative forms of production and distribution of endive in northern Italy *J. Clean. Prod.* **140** 725–41
Toledo V M and Moguel P 2012 Coffee and sustainability: the multiple values of traditional shaded coffee *J. Sustain. Agric.* **36** 353–77
Tripathi S, Dabral S, Kundu S, Saini D K, Jamal H, Meena R K, Somayanda I, Varma A, Bahuguna R N and Jagadish S V K 2025 Harnessing the plant-associated microbiome: a sustainable solution for enhancing crop resilience to abiotic stresses and problematic soils *Plant Stress* **18** 101033
van Zanten H H E, Simon W, van Selm B, Wacker J, Maindl T I, Frehner A, Hijbeek R, van Ittersum M K and Herrero M 2023 Circularity in Europe strengthens the sustainability of the global food system *Nat. Food* **4** 320–30
Verones F *et al* 2022 Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in life cycle assessment *Ecol. Indic.* **142** 109204
Walder F, Schmid M W, Riedo J, Valzano-held A Y, Banerjee S, Büchi L, Bucheli T D and van der Heijden M G A 2022 Soil microbiome signatures are associated with pesticide residues in arable landscapes *Soil Biol. Biochem.* **174** 108830
Wan N-F *et al* 2025 Pesticides have negative effects on non-target organisms *Nat. Commun.* **16** 1360
Westaway S, Żyłowski T, Hardiman S and Smith L G 2024 Integrating sustainability assessment tools with life cycle analysis for agroecological systems: a UK case study *Agric. Syst.* **219** 104045
Willer H, Trávníček J and Schlatter B 2024 *The world of organic agriculture. Statistics and emerging trends 2024* Research Institute of Organic Agriculture FiBL, Frick, and IFOAM – Organics International
Zhou J, Mogollón J M, van Bodegom P M, Beusen A H W and Scherer L 2024 Global regionalized characterization factors for phosphorus and nitrogen impacts on freshwater fish biodiversity *Sci. Total Environ.* **912** 169108