



# 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

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## Abstract

**Purpose** Recent developments in life cycle impact assessment (LCIA) target at better addressing biodiversity impacts, including the extended modeling of drivers of biodiversity loss. This led to the development of multiple LCIA methods addressing the area of protection of ecosystem quality (i.e., biodiversity loss) over time. This paper aims at systematically comparing available operational LCIA methods and models for assessing the main drivers of biodiversity impacts of EU consumption and unveiling similarities and differences among current methods.

**Methods** This paper compares the biodiversity impacts of EU consumption by implementing eight LCIA methods and models: five full LCIA methods (namely, LC-IMPACT, Impact World +, Ecological Scarcity 2013, ReCiPe 2016, and Stepwise), a land-use intensity-specific LCIA model, and two approaches based on the GLOBIO model. The EU Consumption Footprint model is adopted as case study. The comparative analysis between the assessed methods aimed at identifying convergent and divergent results regarding the drivers of biodiversity impacts of EU consumption. The analysis focused on four different levels: impact category, representative product (modeled consumed products), inventory process, and elementary flow. The agreement among the methods in defining an element as relevant was evaluated. Finally, gaps among methods were assessed in terms of coverage of impact categories and elementary flows.

**Results and discussion** The analysis unveiled that there is a certain level of agreement among available LCIA methods and models regarding the most contributing impact categories and products to the overall biodiversity footprint due to EU consumption. Land use, climate change, and ecotoxicity had a major contribution to overall impacts, thereby highlighting their role as drivers of biodiversity loss. Biodiversity impacts were due to a limited number of consumed products, where food (meat), mobility, and household goods were identified as top contributors. Most contributing inventory processes and elementary flows were associated to most contributing representative products (e.g., animal feed). The relevance and presence of elementary flows in LCIA methods and models were heterogeneous for most of the impact categories.

**Conclusions** The results of this study highlight the importance of impact category coverage in the assessment of biodiversity impacts. Limited coverage of impact categories (e.g., methods limited to assess land use) might underestimate the impacts of other drivers of biodiversity loss, especially climate change and ecotoxicity. Further efforts are required to assess the effects of spatial regionalization and the inclusion of missing drivers, recently developed in LCIA.

**Keywords** Impact assessment · Biodiversity footprint · Life cycle assessment · Sustainable consumption

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## 1 Introduction

Biodiversity is “the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems” as defined by the Convention of Biological Diversity (CBD) (UN 1992). Human activities are increasingly pressuring worldwide biodiversity thereby

compromising the quality of ecosystems and their support to human well-being and socioeconomic systems (Cardinale et al. 2012; IPBES 2019; Pörtner et al. 2021). The urgency to address biodiversity loss and to measure the contribution of supply chains has been recently restated by the Kunming-Montreal Global Biodiversity Framework (Target 15), agreed at the 15th meeting of the Conference of Parties to the UN CBD (CBD 2022). Biodiversity loss occurs at multiple levels such as decreased species population size, extinct species, or reduced species habitat. The Living Planet Index developed by the World Wide Fund for Nature (WWF) quantified a decrease of 68% of the size of monitored populations between 1970 and 2016, including mammals, birds, amphibians, reptiles, and fish (WWF 2020). This decrease of biodiversity had a different intensity among world regions (with the highest value of 94% observed for the Latin America and Caribbean) and was more intense for freshwater ecosystems (decrease of 84%) due to pressures such as overexploitation and habitat degradation through pollution or flow modification (Dudgeon et al. 2006). The Red List Index of the International Union for Conservation of Nature (IUCN) shows an increased global list of critically endangered species (IUCN 2021). The Species Habitat Index registered a 2% loss of suitable habitat for wildlife between 2000 and 2018, with projected scenarios of socioeconomic development being far from optimistic and projecting habitat loss due to land use change that would put at risk hundreds of species worldwide (Powers and Jetz 2019). To face this global challenge, international organizations have defined targets to reduce current biodiversity loss, namely, the United Nations' Sustainable Development Goals (SDGs) (UN 2015), with two specific goals on life below water (SDG 14) and life on land (SDG 15), or the CBD's Aichi targets (CBD 2010), with several 2020 targets missed (e.g., target 5 on habitat loss halved or reduced) and only some of them partially achieved (e.g., target 9 on invasive alien species prevented and controlled) (CBD 2020). Also, international efforts target specific practices transversally causing biodiversity loss, such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) with the global wildlife market contributing to invasive species as well as a pathway for diseases and an international wildlife demand exceeding supply capacity (Liew et al. 2021). At the European level, the EU Biodiversity strategy for 2030 (EC 2020a) and the Farm to Fork Strategy (EC 2020b) set targets and commitments to achieve healthy and resilient ecosystems, including to minimize products coming from supply chains associated with deforestation or forest degradation on the EU market (EC 2021).

The Global Assessment of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) identifies five direct drivers of biodiversity loss: land use change, climate change, invasive species, environmental pollution, and direct exploitation of organisms (IPBES 2019).

The IPBES assessment outlined the important contribution of unsustainable patterns of production and consumption to these direct drivers. This puts into the spotlight the need to understand the role of consumption patterns on biodiversity impacts as well as of providing quantitative information on products and supply chains. With regard to biodiversity impacts, a supply chain perspective is essential to consider the indirect impacts in other world regions through imports (e.g., Scherer and Pfister 2016), which could rely on productive regions with higher concentration of vulnerable species (e.g., palm oil, rubber, and coffee) (Chaudhary and Kastner 2016). In this context, life cycle assessment (LCA) can support the assessment of biodiversity impacts resulting from the entire life cycle and supply chain of products (ISO 2006a, b).

The assessment of biodiversity loss at the endpoint level (i.e., ecosystem quality) is an environmental aspect still under refinement in the LCA community, with several life cycle impact assessment (LCIA) methods and models being developed with different levels of operationalization (Crenna et al. 2020; Curran et al. 2016; Winter et al. 2017). According to Crenna et al. (2020), there are five LCIA methods covering biodiversity loss that are operational, i.e., methods available in LCA software and those that are widely used by LCA practitioners (Crenna et al. 2020). These operational LCIA methods include Ecological Scarcity 2013 (Frischknecht and Büsler 2013), Impact World+ (Bulle et al. 2019), LC-IMPACT (Veronesi et al. 2020), ReCiPe 2016 (Huijbregts et al. 2016), and Stepwise 2006 (Weidema et al. 2008). These methods address three direct drivers of biodiversity loss: land use change, climate change and environmental pollution, and water use as other driver. Recent advancements in LCIA target the assessment of missing drivers, including invasive species (e.g., Hanafiah et al. 2013) and overexploitation (e.g., Crenna et al. 2018; Helias et al. 2018). These recent LCIA models are, however, not operational yet and not always providing an assessment at the endpoint level (Crenna et al. 2020). A recent proposal combined LCA-based quantitative indicators with semiquantitative indicators for missing direct drivers of biodiversity loss (Asselin et al. 2020). International and multi-stakeholder efforts are taking place with the aim of harmonizing the assessment of biodiversity loss in LCA. The Global Guidance on Environmental Life Cycle Impact Assessment Indicators project aims at recommending a global LCIA method for selected impact categories, including a taskforce devoted to ecosystem quality aiming at harmonizing existing impact categories, addressing new impact categories (e.g., marine plastic pollution) and better assessing extinction probabilities (UNEP 2020).

Notwithstanding the need to advance in biodiversity impact assessment in LCA, a comparison among operational LCIA methods addressing biodiversity loss is not available in the literature yet. Several studies comparing LCIA methods

for other environmental impacts are available in the LCA literature. These are mainly focusing on differences in absolute impacts and hotspot contribution (e.g., Dreyer et al. 2003; Monteiro and Freire 2012), specific impact categories and underlying impact assessment models (e.g., Pant et al. 2004; Pizzol et al. 2011), and divergences in results at the level of equivalent environmental impact categories and resulting single score (e.g., Cavalett et al. 2013). Owsianiak and colleagues (2014) summarized the reasons for disagreement and agreement among LCIA methods. On the one hand, disagreement can result from differences in the underlying impact assessment models, substance coverage, normalization references, aggregation of substances into groups, and weighting approaches. On the other hand, agreement among methods relied mainly on similar characterization models, a limited number of elementary flows contributing to specific impact categories, impacts driven by a small number of substances, and compensation of differences. Overall, in the literature, the authors identified that the selection of the LCIA method was determinant not only in ranking different options and in defining the best one in comparative exercises, but also in identifying hotspots (including life cycle stage, process, and substances). In this context, exploring similarities and differences between available LCIA methods and models to address biodiversity loss is essential towards a consensus in the community.

The analysis focused on the contribution of consumption patterns to the final potential biodiversity loss depending on the LCIA methods and models at different levels, from the area of consumption to the environmental pressure. For this purpose, this paper analyzes the biodiversity impacts of EU consumption by employing the Consumption Footprint model developed by the European Commission–Joint Research Centre (EC-JRC) (Sanyé Mengual and Sala 2023; Sala and Castellani 2019). This indicator has been employed to evaluate the environmental impacts of EU consumption from both relative (e.g., decoupling assessment (Sanyé-Mengual et al. 2019)) and absolute (e.g., against Planetary Boundaries (Sala et al. 2020)) sustainability perspectives. However, the analysis of biodiversity impacts has been limited to EU food consumption and a specific LCIA method (ReCiPe version 2008 and 2016) (Crenna et al. 2019). This analysis will cover all consumption areas (i.e., food, housing, mobility, appliances, and household goods) included in the Consumption Footprint model. Compared to available studies employing a multi-regional input–output approaches (e.g., Lenzen et al. 2012), an analysis of the biodiversity impacts due to consumption based on a full bottom-up approach (i.e., process-based LCA) allows for a higher level of detail to assess drivers of impacts beyond the economic sector (e.g., products, life cycle stages, and inventory processes).

This paper aims at assessing the main drivers of biodiversity impacts due to EU consumption by comparing available

LCIA methods and models. For this purpose, specific objectives are (a) identifying convergent and divergent messages among LCIA methods and models in terms of ranking and hotspot contributors at the level of impact category, representative product, elementary flow, and inventory process and (b) evaluating gaps in current method and models.

## 2 Methods

This section presents the case study, the selected LCIA methods and models, and describes the performed comparative analysis to unveil convergent and divergent results from the different methods applied.

### 2.1 Case study: EU consumption footprint

The case study is the biodiversity impacts of EU consumption in 2015 through the implementation of the Consumption Footprint model, which was developed by the EC-JRC to monitor SDG12 (Sanyé Mengual and Sala 2023; Sala and Sanyé Mengual 2022; Sala and Castellani 2019). The functional unit of the analysis is the consumption patterns of the overall EU in the year 2015, which was selected as a representative year at the time this analysis started. The Consumption Footprint is a full bottom-up LCA-based indicator that includes the EU consumption of 164 representative products of five areas of consumption, namely, food (45 food products), housing (30 archetypes), mobility (34 vehicles), appliances (18 household appliances), and household goods (37 consumer goods). A representative product is a consumed product selected for the Consumption Footprint model based on consumption statistics to represent the most consumed products within an area of consumption and product group (e.g., almonds and cashew are the two representative products for the product group “nuts” within the “food” area of consumption). For each representative product, consumption intensity data are gathered and a Life Cycle Inventory (LCI) is modelled. The indicator combines statistical data on consumption intensity at the EU level (e.g., Eurostat 2020, as detailed in Sanyé Mengual and Sala 2023) and process-based LCI data covering the entire life cycle of products (cradle-to-grave approach). Regarding consumption statistics, the Consumption Footprint considers the apparent consumption for a given year as production plus imports minus exports. LCI data are in line with the International Life Cycle Data system guidelines (EC-JRC 2010) and primary data are collected from background reports of EU policies and literature (e.g., EU Ecolabel preparatory reports). Trade statistics were employed to define the average EU market and the respective share of exporting countries to the EU to model international trade, which considered associated environmental pressures due to raw material extraction, production processes, and

logistics (e.g. the share of imported clothes produced in South-East Asia to consider specific energy consumption mix in manufacturing stages). The case study relies on LCI databases for background processes, including ecoinvent v3.6 (Wernet et al. 2016) and agrifootprint 2.0 (Durlinger et al. 2014), and was evaluated with Simapro 9.1 (Pré Consultants 2020). Note that for the ecoinvent background process, the datasets representing the allocation at the point of substitution system model were selected, which can lead to negative technosphere flows as expansion of product systems is used to avoid allocation within treatment systems.

This case study was selected due to two main reasons. Firstly, the model covers the different areas of consumption thereby including a large range of different products, which might be associated to different environmental pressures and associated impacts. Secondly, the granularity of the model as a process-based LCA approach that allows for different levels of detail in the contribution analysis (i.e. area of consumption, product group, representative product, life cycle stage, inventory processes, and elementary flow). Such detail supports an identification of the most contributing elements in the consumption patterns of EU citizens to biodiversity impacts.

## 2.2 LCIA methods and models for biodiversity endpoint assessment

The selected LCIA methods and models addressing biodiversity loss are based on a recent review of approaches to assess biodiversity impacts (Crenna et al. 2020). Operational LCIA methods and models as well as a business-applied approach have been included. The selection of LCIA methods and models has followed four criteria, targeting the inclusion of (a) midpoint and/or endpoint impact assessment methods, (b) methods addressing either single or multiple impact categories, (c) methods with different level of operationalization (from approaches that require self-derivation of characterization factors (CFs) to methods available in commercial software), and (d) methods with diverse levels of regionalization (from only global factors by default to highly regionalized methods). Note that LCIA assesses potential impacts rather than actual impacts based on impact assessment models.

Overall, eight different LCIA methods and models have been evaluated (Table 1), including five full LCIA methods, a land use-specific model, and two approaches based on the GLOBIO model (Schipper et al. 2016).

The eight LCIA methods and models are the following:

- Land use intensity-specific global CFs (LUIS) (Chaudhary and Brooks 2018), using “potentially disappeared fraction of species over time” (PDF-y) as unit of damage on global biodiversity.
- Ecological Scarcity 2013 (ES) (Frischknecht and Büsser 2013), whose impacts on biodiversity are assessed as Umweltbelastungspunkte (UBP), which means “environmental burden points”.
- GLOBIO, approach to derive CFs based on the biodiversity footprint (GLO-BF) (Wilting et al. 2017; Wilting and van Oorschoot 2017; Hanafiah et al. 2012), assessing biodiversity loss as Mean Species Abundance (MSA) loss on a square meter and year (MSA loss-m<sup>2</sup>·y).
- GLOBIO, approach to derive CFs based the Global Biodiversity Score (GLO-GBS) (CDC Biodiversité, 2019), using the units MSA loss-m<sup>2</sup> to quantify biodiversity impacts.
- Stepwise 2006 (SW) (Weidema et al. 2008), with impacts on biodiversity expressed as Biodiversity Adjusted Hectare Year (BAHY).
- LC-IMPACT (LC) (Verones et al. 2020), using PDF·y as the unit of damage on global biodiversity. In the case of ecotoxicity categories, impacts are assessed in PDF·m<sup>3</sup>·d and a conversion procedure was implemented following the recommendations of method developers (personal communication Francesca Verones and Peter Fantke) (detailed in Supplementary Material in Methods SM17).
- ReCiPe 2016 (RCP) (Huijbregts et al. 2017), whose impacts on biodiversity are assessed as species years (species·y). The hierarchical perspective was considered as recommended by the method authors.
- Impact World+ (IW) (Bulle et al. 2019), quantifying impacts on biodiversity as PDF of species on a square meter and year (PDF·m<sup>2</sup>·y).

The inclusion of impact categories contributing to endpoint impacts on biodiversity loss (area of protection ecosystem quality) varies among the LCIA methods and models (Table 1). The evaluated methods include approaches with both midpoints and endpoints or endpoints only. A detailed description of these methods is provided in Supplementary Materials (Table SM1). The two approaches to derive CFs for the GLOBIO model are described in Sanyé-Mengual et al. (2022). LC and LUIS consider vulnerability factors in the derivation of CFs in order to convert species loss from local or regional (PDF·y·m<sup>2</sup>) to global (PDF·y) in a consistent manner by considering the variance of vulnerability among taxonomic groups to environmental pressures (Verones et al. 2020). The temporal perspective is included in most of the LCIA methods and models (apart from GLO-GBS and SW), thereby providing impacts integrated for one year allocating the overall impact along the temporal horizon. The temporal perspective can be integrated through the LCI flow (e.g. land occupation as m<sup>2</sup>·y) or in the CF (e.g. for climate change as PDF·y/kg of CH<sub>4</sub>). Regarding ES, the temporal horizon is determined by the political targets considered in the weighting procedure establishing the critical flows (Frischknecht and Büsser 2013).

**Table 1** Coverage of biodiversity loss drivers (as in IPBES) and the associated LCIA impact categories, by LCIA method and model

Biodiversity loss direct driver (IPBES classification)	LCIA impact category (endpoint)	LUIS (EP)	ES <sup>(a)</sup> (EP)	GLOBIO-BF (EP)	GLOBIO-GBS (EP)	SW <sup>(a)</sup> (MP, EP)	LC <sup>(b)</sup> (EP)	RCP <sup>(b)</sup> (MP, EP)	IW <sup>(a)</sup> (MP, EP)
Land use and land use change (habitat transformation)	Land use: land occupation	X	X	X		X	X	X	X
	Land use change: land transformation	X		X	X		X	X	X
Climate change	Climate change		(c)	X	X	X	X	X	X
Environmental pollution	Ecotoxicity		(c)						
	Terrestrial		(c)			X	X	X	
	Freshwater		(c)			X	X	X	X
	Marine						X	X	
	Acidification								
	Terrestrial					X	X	X	X
	Freshwater								X
	Photochemical ozone formation					X	X	X	X
	Eutrophication								
	Terrestrial					X		X	
	Freshwater					X	X	X	X
	Marine						X	X	X
	Thermal pollution								X
	Ionizing radiation								X
Other	Water use						X	X	X

Methods can include midpoint impact categories (MP) and endpoint impact categories (EP), as indicated in the table header

LUIS land use intensity-specific, ES ecological scarcity, GLOBIO-BF GLOBIO-biodiversity footprint, GLOBIO-GBS GLOBIO-Global Biodiversity Score, SW Stepwise, LC LC-IMPACT, RCP ReCiPe, IW Impact World +

<sup>a</sup>These methods were available in LCA software when this exercise started (spring 2020)

<sup>b</sup>These methods were not available in LCA software when this exercise started (spring 2020), while they are now available (autumn 2022)

<sup>c</sup>Impact categories covered by the method but not linked to biodiversity loss, but to other areas of protection or targets

### 2.3 Comparative analysis among LCIA methods and models

The comparative analysis between the assessed methods aimed at identifying common and divergent messages regarding the drivers of biodiversity impacts of EU consumption. The analysis focused on four different levels, which were individually evaluated: impact category, representative product, process, and elementary flow.

To systematically compare LCIA methods and models at each level, a multiple step analysis was followed (Fig. 1).

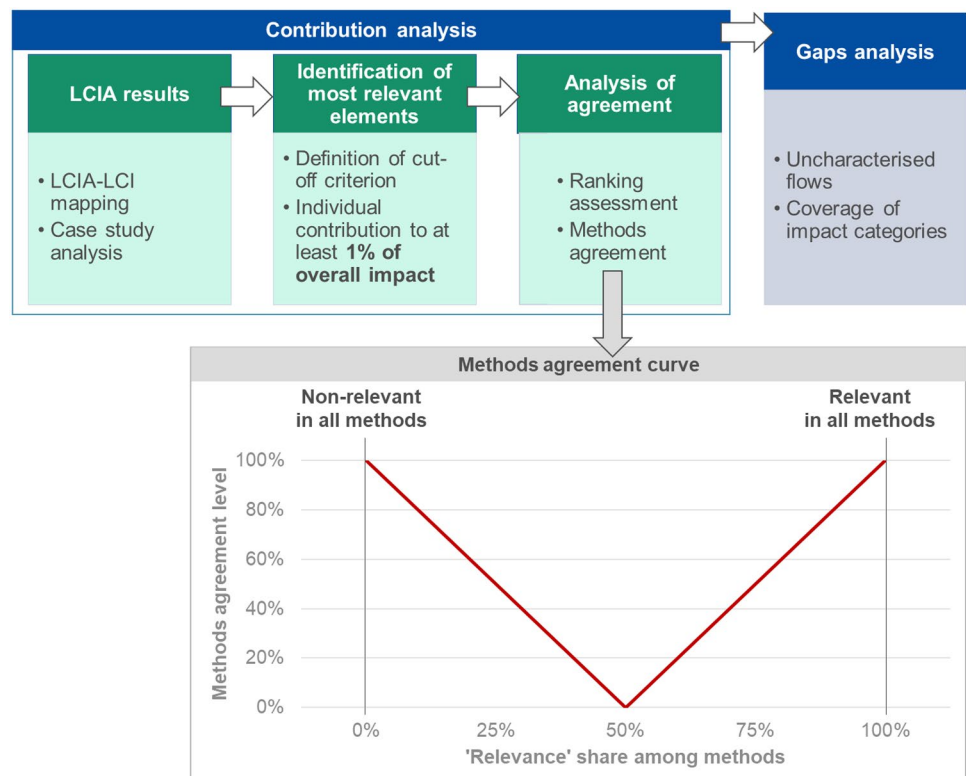
#### (a) Contribution analysis:

- a. LCIA results: the impact assessment analysis of the case study was performed. Since most of the methods were not implemented in the LCA software, a mapping between the LCI and LCIA nomenclatures was required. The followed mapping process and

an analysis of the resulting mapped methods and uncharacterized elementary flows are detailed in Sanyé-Mengual et al. (2022).

- b. Identification of most relevant elements: relevant elements are those with a substantial contribution to the overall biodiversity impact. The distinction between relevant and irrelevant contributors to the impacts was performed based on a contribution threshold of 1%. A relevant element (i.e., impact category, representative product, and inventory process) was defined as an element with an individual contribution of at least 1% to the overall impact. Note that in the case of elementary flows, relevance was defined as an individual contribution to at least 1% of the LCIA results of the associated impact category (e.g., carbon dioxide to climate change). This threshold is a value choice, and the effect of the contribution threshold on the results is later discussed. The analysis of most relevant elements was

**Fig. 1** Methodological steps followed in this analysis and definition of the method agreement curve



performed for those present in at least two of the LCIA methods and models evaluated, as in other studies comparing LCIA methods (e.g., Owsianiak et al. 2014).

- c. **Analysis of agreement among methods:** the core of the comparative analysis included the analysis of the agreement among methods, which was performed in two main steps. First, a ranking assessment was performed to evaluate the main drivers of biodiversity impacts (i.e., top contributors at impact, product, process, and elementary flow levels). Second, the agreement among the methods in defining an element as relevant (i.e., threshold of 1% contribution to overall impact) was evaluated through a method agreement curve (Fig. 1). The agreement among methods ranges between 0 and 100%, representing to what extent the contributing element is identified as relevant among the methods. For example, if two methods consider climate change, an agreement of 100% would indicate that both methods consider this impact category either relevant or non-relevant, while a lack of agreement (0%) would result from one method signaling the impact category as relevant and the other as non-relevant. A detailed explanation on the calculation principles of the method agreement curve is provided in the Supplementary Material Methods SM18.

- (b) **Gap analysis:** the coverage of impact categories and elementary flows in the methods was considered to discuss current gaps in the assessed methods towards fully addressing impacts on biodiversity.

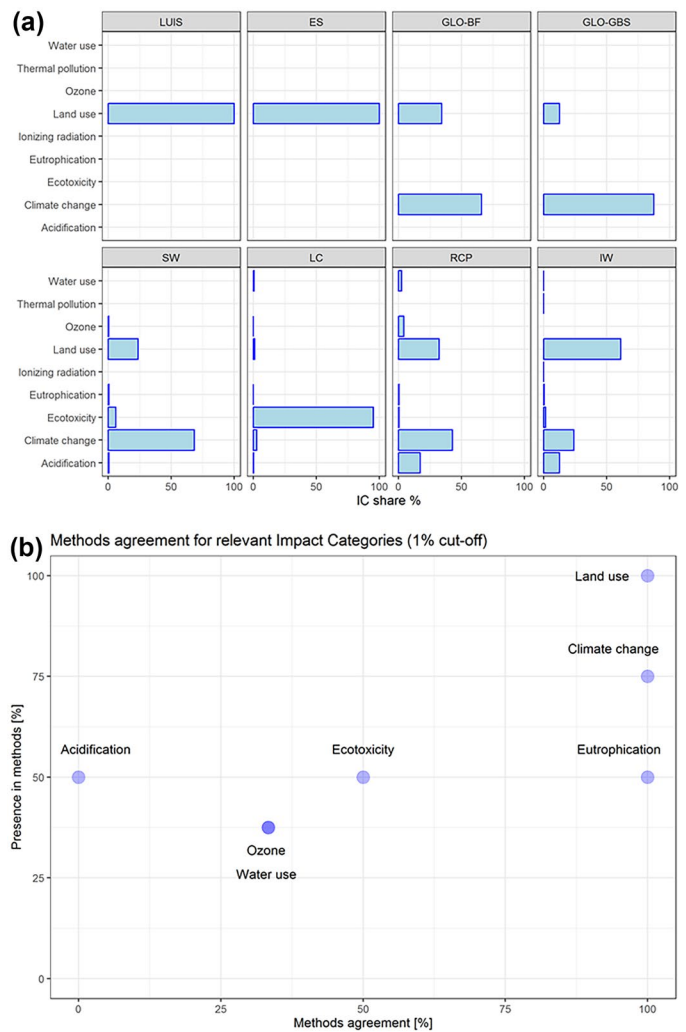
### 3 Results

This section presents the results of the comparative analysis of biodiversity impacts of EU consumption among LCIA methods and models at four different levels: impact category, representative product, process, and elementary flow.

#### 3.1 Contribution of impact categories

The contribution of the different impact categories to the overall endpoint impact to biodiversity loss (area of protection ecosystem quality) varies among the different assessed LCIA methods and models (Table SM2). Impact indicators for subcompartments or pathways are merged together for the analysis into impact category groups (e.g. land use includes both land occupation and land transformation, or acidification includes both terrestrial and freshwater) (Fig. 2a). Land use, climate change, and ecotoxicity were the impact category groups with the largest contribution to the overall impact among the different methods. Differences among methods and models in terms of ranking of impact

**Fig. 2** Comparative analysis at impact category level: **a** contribution of impact category groups to overall biodiversity impact, by LCIA method or model, and **b** relation between presence in the methods and level of agreement among methods



categories depend on the inclusion of impact categories and the characteristics of the underlying impact assessment model, namely the scope of the model (e.g. distance to target or monetization-based approaches), the coverage of aspects (e.g. land occupation and transformation for land use impacts), the coverage of elementary flows (as further detailed in Sect. 3.4), and the consideration of ecosystem compartments (e.g. emissions to the environment for toxicity impacts).

Firstly, land use contributed between 1% (LC) and 100% (LUIS, ES), being the major contributor in three LCIA methods and models (LUIS—100%, ES—100%, and IW—61%) (Table 1). Among these three approaches, LUIS and IW considered impacts due to land occupation and transformation, while ES does not address land transformation (Table SM2). For the remaining methods, land use was the second most contributing impact category group: 32% (RCP), 34% (GLO-BF), 13% (GLO-GBS), and 24% (SW). The two GLOBIO-based approaches cover only two impacts: land use and climate change (Table 1). The main difference

between GLOBIO approaches regarding the contribution of land use impacts to the overall impact was the coverage of land occupation, which was only considered in GLO-BF. The low contribution of land use for SW was associated to a different underlying impact assessment model, compared to the other methods, as well as to the exclusion of land transformation impacts (Table SM1). Among the different methods, only GLO-GBS assessed exclusively impacts due to land transformation, while ES and SW only considered impacts due to land occupation (Fig. SM1).

Secondly, climate change was the most contributing impact category for four methods: the two GLOBIO approaches (GLO-BF, GLO-GBS), RCP, and SW. Among these methods, the relative contribution of climate change ranged from 43% (RCP) to 87% (GLO-GBS), mainly due to the different role of land use in these approaches, as abovementioned. For SW, climate change contributed to 68% of the impacts, highlighting the outstanding role of climate change on biodiversity impacts. This confirms the indications of SW authors (Weidema et al. 2008), who estimated the damage CFs for climate

change based on available scientific studies on lost species area, that climate change would dominate the assessment of most product systems with this method despite the provided low CF estimate. For RCP, instead, the role of climate change was less dominant (43%), with other categories contributing to 32% (land use) and 17% (acidification) of the impacts. Climate change was the second highest contribution for IW (24%) and LC (2.7%). Note that the nomenclature and disaggregation of climate change damage differ among the different methods (Fig. SM1). All methods consider a time horizon of 100 years for the Global Warming Potential CFs (Table SM1).

Thirdly, ecotoxicity was the most contributing impact category group for LC (95.2%), including terrestrial, freshwater, and marine ecotoxicity (Fig. 2a). Note that ecotoxicity categories in LC were converted to PDF-y to be evaluated with the rest of the impact categories and the conversion process might add uncertainty to this comparison (details provided in Supplementary Material). Excluding ecotoxicity from the comparison, climate change would be the most contributing impact category group (57% of the overall impact) followed by land use (22%) and water use (15%) for LC. Ecotoxicity had a different role in the other methods covering this category: third contributor for SW (6%), fourth contributor for IW (2%), and lowest contributor for RCP (0.5%). The four full LCIA methods showed two different messages regarding which environmental compartments lead ecotoxicity impacts. On the one hand, IW and LC highlighted the role of ecotoxicity impacts on the freshwater environment (>90% of the overall ecotoxicity impacts). On the other hand, terrestrial ecotoxicity was the most contributing category in RCP and SW (>65% of the overall ecotoxicity impacts) (Table SM2 and Fig. SM1.b). This divergence resulted mainly from different underlying impact assessment models which affect the number of substances with CFs and the environmental compartments considered: while the former two employ USEtox<sup>®</sup> (around 2500 and 3100 substances, respectively), RCP is based on USES-LCA 2.0 (around 13,000 elementary flows) and SW on the IMPACT 2002 model (around 2100 substances). Details of the impact assessment models by impact category and method are provided in Table SM1.

Lastly, the remaining categories differently contributed to the overall impact among the LCIA methods and models (Fig. 2a). Acidification was identified as a relevant impact category for RCP and IW (17% and 13%, respectively), while marginal for LC and SW (<0.6%). Water use, which was not considered in SW, was the fourth most contributing category for LC (0.7%) and RCP (3%), while marginal for IW (<0.1%). Photochemical ozone formation was only identified as relevant for RCP (4%) and eutrophication had a minor role in all the methods (<1%). Although only evaluated in IW, the contribution of thermal pollution and ionizing radiation was negligible (<0.1%).

The analysis of the level of agreement among the methods revealed similar outputs (Fig. 2b), with an average agreement level around 60% (Table SM3). The relevance of land use, climate change, and eutrophication was confirmed by all methods (100% agreement). However, the presence in the different methods differed: 100%, 75%, and 50%, respectively. The level of agreement decreased for the remaining categories in the following order: ecotoxicity (50% agreement, 50% presence), photochemical ozone formation and water use (33% agreement, 37.5% presence), and acidification (0% agreement, 50% presence). This highlights a lower coverage and agreement regarding environmental pollution as direct driver of biodiversity loss. Furthermore, other environmental impacts that can act as indirect drivers, such as water use, are covered by LCIA methods.

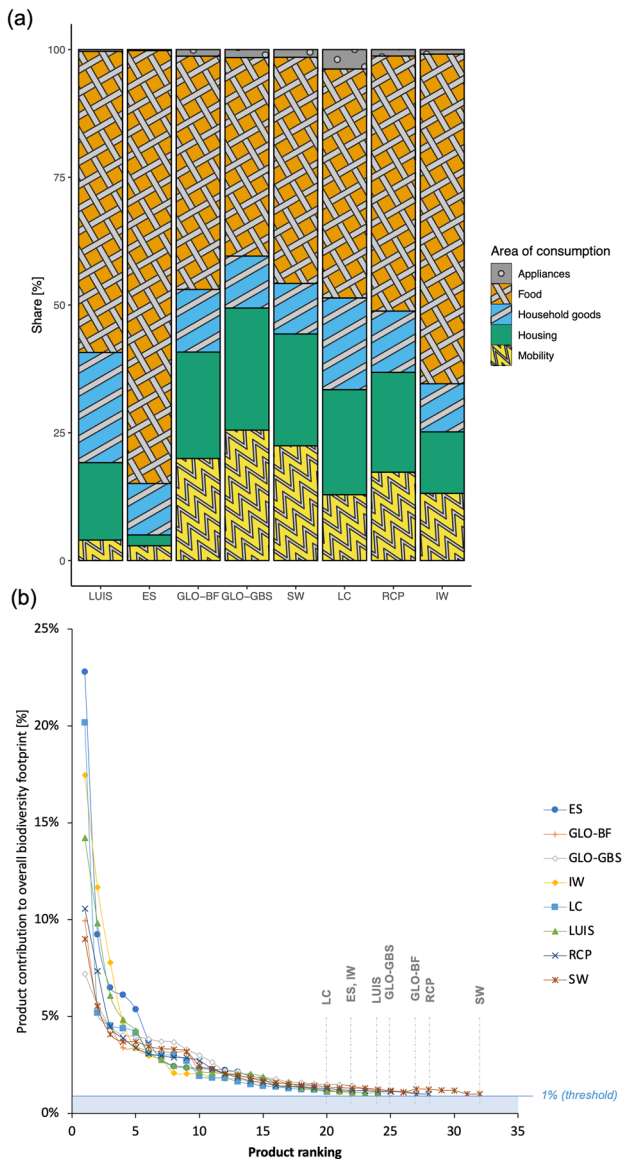
As a general note, it is important in the interpretation of the results to consider the overall coverage of the impact categories by models, e.g. when a method accounting only for land use as a driver, has got 100% of the biodiversity endpoint impact driven by only land use.

### 3.2 Contribution of representative products

The analysis of the contribution of the different areas of consumption and representative products to the overall biodiversity impacts of EU consumption emphasized the role of food consumption (Fig. 3a). Mobility and housing had a significant role in most of the methods, apart from ES due to the impact assessment model employed (i.e. distance-to-target approach) which only links land use impacts to biodiversity loss. The contribution of these consumption areas is more significant for those methods where climate change was the most contributing impact category to the overall biodiversity loss (i.e. GLOBIO approaches, SW, and RCP (Fig. 2a)). Household goods had a secondary role, except for LC due to ecotoxicity impacts of specific consumer goods (e.g. newspaper, wardrobe, and toilet paper) and for LUIS mainly due to paper and furniture products (Fig. 2a). These results highlighted the relationship between areas of consumption and impact categories in their contribution to biodiversity impacts. Finally, appliances showed a negligible role for all the methods. However, this is also associated to a modeling choice since the energy use in the use phase of these products (i.e. one of the most contributing life cycle stages to their overall impact) is accounted for in the housing area of consumption to prevent double counting. Without considering the use phase, appliances are mainly associated to impacts due to mineral resources use (Sala and Sanyé Mengual 2022), which contribute to a different area of protection not covered here.

At the product level, the contribution to biodiversity impacts was mainly originating from a number of representative products. Among the 164 representative products





**Fig. 3** Comparative analysis at representative product level: **a** contribution of the five areas of consumption to the overall biodiversity impact, by LCIA method and model, and **b** distribution of product share for top 35 contributors, by LCIA method and model

included in the Consumption Footprint model, the number of products identified as relevant ones (i.e., contributing to more than 1% of the overall impact on biodiversity) was limited to a range from 20 (LC—e.g., chocolate and T-shirt) to 28 (RCP—e.g., palm oil products and detergents) (Fig. 3b). Relevant products were responsible for a large contribution to the overall impact: between 67% (SW) and 83% (ES) (Table SM4). The distribution of relevant representative products among areas of consumption emphasizes the dominant contribution of food consumption, which shows the largest contribution to the overall impact from a single product and the largest number of identified relevant products

for all the methods and models (Fig. SM2). The methods showed an average level of agreement of 87% in the identification of relevant representative products (Table SM5).

Regarding the individual representative products, the top 3 contributing products to the overall biodiversity impacts of EU consumption were evaluated by LCIA method and model (Table 2). Broadly, food products led the ranking in all LCIA methods and models, being underlined as major contributors, in alignment with the assessment at the consumption area level (Fig. 3a). Meat (beef and pork) and chocolate were the most contributing representative products in the different methods. While all types of meat were present in the top 3 among the methods evaluated (including also poultry), chocolate was only present for those methods that consider the vulnerability of the species in the derivation of damage CFs, i.e., LC and LUIS. In particular, chocolate was the top contributor to LC (20.2% of overall impact). The high contribution of meat to the overall impact was associated to the role of livestock production in top impact categories, such as land use and climate change. In the case of GLO-GBS, consumption associated to mobility appeared in the top 3 ranking (i.e., extra-EU flights) as a result from the high contribution of climate change to the overall impact in this method. Finally, household good products (i.e., newspapers) were among the list of top-3 contributing products for LC, mainly associated to strong ecotoxicity impacts of metals soil-borne emissions due to sludge spreading in agricultural fields.

A more detailed analysis of the most contributing representative product by area of consumption unveiled convergent messages among the assessed methods (Table SM6). In general, the different methods agreed on main contributing products by area of consumption, apart from food with a more heterogeneous list of top contributing products. Differences among methods rely on the abovementioned various contribution of impact categories to the overall biodiversity impact and underlying impact assessment methods. An assessment of the most contributing representative product by area of consumption unveiled convergent messages among the assessed methods (Table SM6). In general, the different methods agreed on main contributing products by area of consumption, apart from food with a more heterogeneous list of top contributing products. Differences among methods rely on the abovementioned various contribution of impact categories to the overall biodiversity impact and underlying impact assessment methods. An assessment of the most contributing representative product by area of consumption unveiled convergent messages among the assessed methods (Table SM6). In general, the different methods agreed on main contributing products by area of consumption, apart from food with a more heterogeneous list of top contributing products. Differences among methods rely on the abovementioned various contribution of impact categories to the overall biodiversity impact and underlying impact assessment methods.

**Table 2** Area of consumption and product share of the overall biodiversity impact of the top 3 representative product contributors, by LCIA method and model

Method	Product	Area of consumption	Product share
LUIS	Meat—pork	Food	14.2%
	Chocolate	Food	9.8%
	Meat poultry	Food	6.1%
ES	Meat—pork	Food	22.8%
	Meat—poultry	Food	9.2%
	Meat—beef	Food	6.5%
GLO-BF	Meat—pork	Food	9.9%
	Meat—beef	Food	5.4%
	Meat—poultry	Food	4.5%
GLO-GBS	Meat—pork	Food	7.2%
	Meat—beef	Food	5.6%
	Air transport (extra-EU flights)	Mobility	4.5%
SW	Meat—pork	Food	9.0%
	Meat—beef	Food	5.6%
	Meat—poultry	Food	4.1%
LC	Chocolate	Food	20.2%
	Meat—beef	Food	5.2%
	Newspaper	Household goods	4.5%
RCP	Meat—pork	Food	10.6%
	Meat—beef	Food	7.3%
	Meat—poultry	Food	4.5%
IW	Meat—pork	Food	17.5%
	Meat—poultry	Food	11.7%
	Meat—beef	Food	7.8%

### 3.3 Contribution of LCI processes

The inventory processes contributing to the biodiversity impacts of EU consumption were evaluated from a ranking perspective. The top 3 most contributing processes for each LCIA method and model were underlying processes in the life cycle of the most contributing representative products (Table 3). Among the analyzed LCIA methods and models, the processes that contributed the most to biodiversity loss were those associated to meat production (e.g, grass, soybean, and beef cattle), crop production (e.g, cocoa bean and sunflower seed), mobility activities (e.g, air mobility), household energy consumption (e.g, heat), and the production of specific consumer goods (e.g, sulfate pulp used in paper products like books or newspapers). Analyzing the presence of the processes among the LCIA methods and models (Fig. 4) highlighted a broad coverage of processes identified as relevant in the impact categories of acidification, climate change, and photochemical ozone formation (100% of presence). In terms of level of agreement in the relevance among the

methods, ecotoxicity showed the lowest degree of agreement, while eutrophication and land use showed the largest variation among processes. In general, the average level of agreement among the methods regarding the relevance of processes was of 52% (Table SM8). A detailed contribution analysis of LCI processes with positive contribution (impact) (Table SM9) and negative contribution (credits) (Table SM10) is provided in the Supplementary Material.

### 3.4 Contribution of elementary flows

The elementary flows contributing to the overall biodiversity impacts of EU consumption were analyzed in terms of presence and agreement in the relevance among the methods (Fig. 5). Strong agreement and coverage were found for acidification and climate change. While the remaining impact categories showed a large variation in terms of level of agreement, photochemical ozone depletion showed a full coverage of elementary flows (100% of presence). Focusing on those elementary flows identified as relevant with a 100% agreement among the LCIA methods and models, some of these flows are not be covered in all the methods (i.e, presence < 100%). The flows showing a low presence are usually associated to impact categories that have a lower contribution to the overall biodiversity footprint (e.g, ozone depletion and eutrophication) and that are not considered in all assessed LCIA methods and model. The exclusion of such impact categories leads in any case to overlooking relevant individual elementary flows and potentially underestimate biodiversity impacts.

Analyzing the contribution of individual elementary flows to each specific category (Table SM11), the methods agreed on the relevance of around 70% of the elementary flows. The level of agreement ranged from 100% (climate change, acidification, and eutrophication) to 40% (ecotoxicity). This analysis outlined the role of the underlying impact assessment models and the coverage of elementary flows of the different methods in defining top 3 contributing flows by impact category (Tables SM12), such as for land transformation, land occupation, and ecotoxicity. Land transformation in ReCiPe was not aligned to the rest of the methods with a more limited scope: only land transformation to and from natural land (i.e, non-use situation) compared to a larger coverage of land impacts in other methods. As a result, relevant flows in other methods were not characterized in ReCiPe, such as “annual crop” and “mineral extraction site”. The consideration of the intensity of use in LUIS was observed for land occupation (i.e, where “occupation, forest, intensive” showed a larger relevance compared to other methods). The relevance of elementary flows contributing to ecotoxicity categories was determined by the underpinning impact assessment model (e.g, USEtox<sup>®</sup>, USES-LCA, and Impact 2002) and the compartments considered (i.e, freshwater, marine, and terrestrial).

**Table 3** Top 3 inventory processes contributing to the overall biodiversity impacts of EU consumption and corresponding process share, by LCIA method and model. Processes are associated to food production (FP), mobility (MB), household goods (HG), and underlying processes of energy and materials production (EMP)

Method	Process	Process group	Process share
LUIS	Wood chips, wet, measured as dry mass {CH}  hardwood forestry, mixed species, sustainable forest management	HG	6.1%
	Land tenure, arable land, measured as carbon net primary productivity, perennial crop {CI}  clear-cutting, secondary forest to arable land, perennial crop	FP	4.8%
	Rapeseed, at farm/AU	FP	4.6%
ES	Soybean, at farm/BR	FP	7.5%
	Cocoa bean {CI}  cocoa bean production, sun-dried	FP	6.0%
	Sunflower seed, at farm/DE	FP	5.3%
GLO-BF	Heat, central or small-scale, natural gas {Europe without Switzerland}  heat production, natural gas, at boiler atmospheric low-NOx non-modulating < 100 kW	EMP	4.4%
	Soybean, at farm/BR	FP	3.4%
	8 TTW–AIR–extra EU–transport, passenger, aircraft {RER}  intercontinental	MB	2.8%
GLO-GBS	8 TTW–AIR–extra EU–transport, passenger, aircraft {RER}  intercontinental	MB	4.8%
	Land tenure, arable land, measured as carbon net primary productivity, perennial crop {CI}  clear-cutting, secondary forest to arable land, perennial crop	FP	4.5%
	Soybean, at farm/BR	FP	4.0%
SW	Heat, central or small-scale, natural gas {Europe without Switzerland}  heat production, natural gas, at boiler atmospheric low-NOx non-modulating < 100 kW	EMP	4.8%
	Heat, central or small-scale, other than natural gas {CH}  heat production, softwood chips from forest, at furnace 50 kW	EMP	4.5%
	8 TTW–AIR–extra EU–transport, passenger, aircraft {RER}  intercontinental	MB	3.1%
LC	Cocoa bean {CI}  cocoa bean production, sun-dried	FP	19.3%
	Blasting {RoW}  processing	EMP	9.7%
	Sludge from pulp and paper production {RoW}  treatment, landfarming	HG	7.7%
RCP	Heat, central or small-scale, natural gas {Europe without Switzerland}  heat production, natural gas, at boiler atmospheric low-NOx non-modulating < 100 kW	EMP	2.9%
	Soybean, at farm/BR	FP	2.9%
	Milk raw, at farm/NL	FP	2.8%
IW	Soybean, at farm/BR	FP	12.1%
	Soybean, at farm/AR	FP	8.8%
	Rapeseed, at farm/AU	FP	4.5%

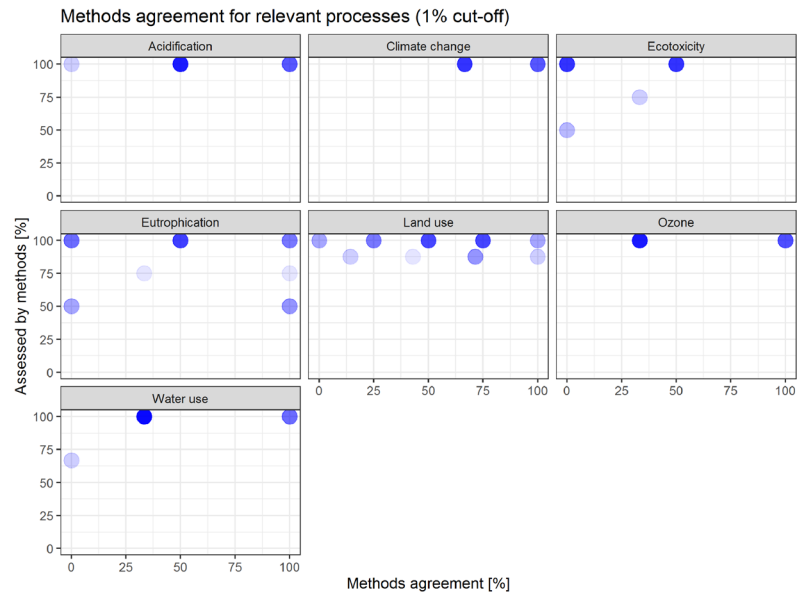
### 3.5 Gap analysis

The coverage of impact categories was not homogeneous among the assessed methods (Table 1). Land use and climate change were the categories with the largest coverage among methods: all methods included impacts due to land use, while climate change impacts were addressed by 6 out of 8 methods. However, an exclusive focus on land use limits the assessment to a specific direct driver of biodiversity loss thereby underestimating the overall impacts on biodiversity. Notwithstanding the inclusion of climate change expands the coverage of biodiversity impacts to another direct driver, this leads to missing the contribution from other impact categories—which ranged between 9% (SW) and 95% (LC). Among these other categories, ecotoxicity (up to 95%), acidification (up to 17%), photochemical ozone formation (up to 4%), and water use (up to 3%) were identified as relevant

impact categories. These categories mainly addressed environmental pollution as a direct driver of biodiversity loss. On the contrary, eutrophication, thermal pollution, and ionizing radiation showed negligible contributions (< 1%).

Most of the relevant elementary flows (listed in Table SM11) were already covered by all methods for all impact categories, but ecotoxicity (where aluminum emissions elementary flows were characterized only in IW and LC). During the analysis of the uncharacterized elementary flows conducted in the mapping process (Sanyé-Mengual et al. 2022), SW and ES were the methods with the largest absolute number of uncharacterized elementary flows among the five full LCIA methods (Table SM13). This is associated to the coverage of certain impact categories and the associated flows, such as water use. Most of uncharacterized elementary flows were associated to biodiversity-related impact categories (between 92 and 96% of all uncharacterized flows,

**Fig. 4** Comparative analysis at inventory process level: presence and agreement in methods on the definition of relevant processes



depending on the method) (Table SM13). When assessing the number of uncharacterized flows by typology, further efforts were identified to be required to cover flows regarding chemicals (organic, inorganic, and radioactive—being these the largest chemical groups uncharacterized).

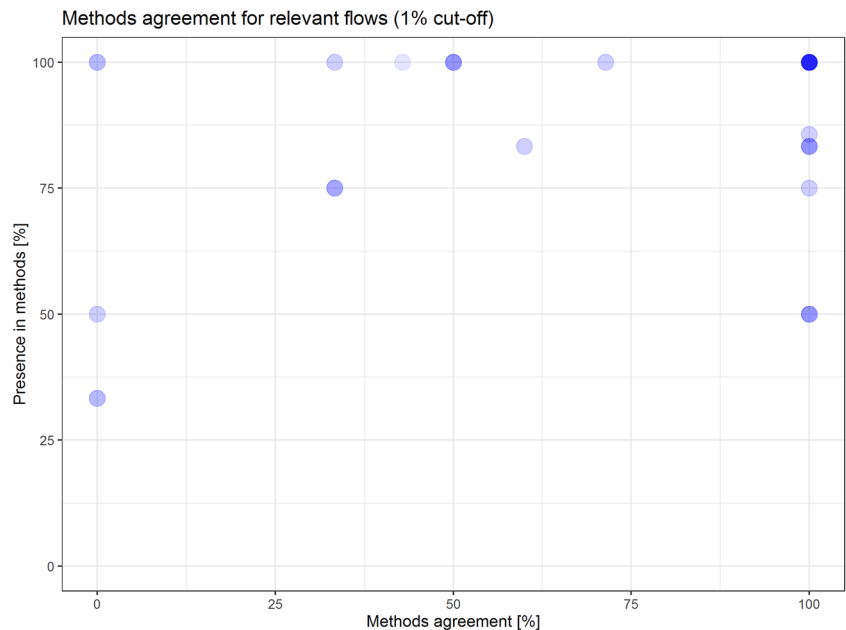
### 4 Discussion

This section further discusses the biodiversity impacts of EU consumption, the current coverage of biodiversity impacts by LCIA methods and models, and the limitations of this study.

#### 4.1 Biodiversity impacts of EU consumption: relevant products and impact categories

The biodiversity footprint of EU consumption is driven by a limited number of products, with only up to 17% (in number, depending on the method) products being identified as relevant (> 1% of overall impact) and contributing to more than 67% of the footprint. A dominant role of food consumption on biodiversity impacts due to consumption is aligned with literature findings (IPBES 2019; Wilting et al.; 2017). Ensuring food security (SDG 2) and biodiversity

**Fig. 5** Comparative analysis at elementary flow level: presence and agreement in methods on the definition of relevant elementary flows



conservation (SDGs 14 and 15) are global challenges with a high level of interconnection (Frison et al. 2011; Fischer et al. 2017), with biodiversity loss putting at risk food production (Crist et al. 2017). For example, 75% of global food crop types require animal pollination with populations being affected by biodiversity loss (IPBES 2019). The largest contribution to biodiversity loss might depend on the food product, such as large land occupation (e.g. rice and wheat) or production in rich biodiversity world regions (e.g. palm oil and cocoa) (Chaudhary and Kastner 2016). In the case of EU food consumption, animal-based products were the main contributors to biodiversity loss, in agreement with previous analyses. The large contribution of this product group is associated not only to the consumption intensity (amount) but also to the environmental impact of the product (Crenna et al. 2019; Notarnicola et al. 2017).

Together with climate change, land use had a major role in contributing to the overall biodiversity impact, in line with Crenna et al. (2019). At the EU level, a proposal for a deforestation regulation aims at limiting the expansion of agricultural land for a set of products (i.e. cattle, wood, palm oil, soya, cocoa, or coffee) (EC 2021). However, this might exclude some relevant product groups responsible for land use impacts that contribute to biodiversity loss (e.g. other oils, cereal-based products, and chemicals) (Table SM15). For LC-IMPACT, ecotoxicity was the most contributing impact category. This highlighted the role of these three direct drivers of biodiversity loss due to EU consumption among the assessed LCIA methods and models. Nonetheless, the role of these three categories in absolute terms was determined by the coverage of impacts by the different methods. Some methods were limited to land use or climate change drivers leading to a limited coverage of impact categories that underestimates biodiversity impacts, particularly due to environmental pollution. The methods covering multiple impact categories allow for observing the contribution of different impact categories, which can support prioritizing modeling and refinement efforts in further LCIA developments regarding biodiversity impacts (e.g. better coverage of environmental pollution). However, it has to be noted that the models are conceptually different for separate impact categories within a method. For instance, toxicity, climate change, and land use-related biodiversity loss in LC-IMPACT are differing a lot. Firstly, toxicity impacts are based on lab-scale toxicity tests coupled with continental fate models, and impacts are integrated over the residence time in the environment capped at 100 years (residence times can be thousands of years). Secondly, the climate change impact model for species loss is based on climate change models, using average temperature increase and resulting species loss over a time horizon of 100 (core CFs) or 1000 (extended CFs) years. Thirdly, land use-related species loss is based on enhanced species-area relationships based on empirical

studies and endemic species richness data to account for global species loss. The impacts therefore differ in terms of time horizon covered and timing of the impacts (short term for land use and longer term for climate and toxicity). This should be considered in the interpretation and is an issue that cannot be solved by changed methods, since the effect is different and requires normative choices to make them as comparable as possible. It is important that users of aggregating methods are aware of these facts and individual weighting or modeling choices of impact pathways and scopes might give higher importance to specific impacts (e.g. land use vs. climate change or vice versa). Furthermore, the models translating from local to global species loss and level of regionalization differ as well, which makes the final aggregated impacts highly affected by value choices. This is especially visible for ecotoxicity. USEtox<sup>®</sup> is the basis for toxicity impacts in both the IW and LC methods, while climate change and acidification methods are also sharing the same underlying concepts. However, the impact contribution of toxicity is much higher in LC, because of the different midpoint to endpoint conversion. Further research is suggested to dig into the details of endpoint toxicity assessment.

A direct link was observed between the relevance of representative products and of impact categories. The coverage of different impact categories also influenced the resulting ranking of products. Mobility arose in the top 3 contributing products for those methods in which climate change largely dominates the overall biodiversity impact (i.e. GLO-GBS and SW). Household goods (particularly paper products) were identified as top contributing products only in LC-IMPACT, where ecotoxicity had the largest contribution as impact category. On the other hand, the impact assessment approach was also reflected in the ranking of products. For example, chocolate was top contributor in LC-IMPACT and LUIS (1<sup>st</sup> and 2<sup>nd</sup>, respectively), which derive the CFs considering also the vulnerability of the species based on the IUCN list (Verones et al. 2020; Chaudhary and Brooks 2018).

#### 4.2 Current coverage of biodiversity drivers in LCIA methods and models

The analysis of biodiversity impacts of EU consumption revealed that the available operational LCIA approaches lack a complete assessment of the drivers of biodiversity loss. First, the assessed LCIA methods and models covered only 3 out of 5 direct drivers of biodiversity loss: climate change, land use, and environmental pollution (although only partially as specific types of pollution are still not addressed in LCA such as noise or light, Winter et al. 2017). While advancements in LCIA to cover missing drivers (e.g. invasive species (Hanafiah et al. 2013) and overexploitation (Helias et al. 2018)) have taken place, these are still not operational or fully developed at the endpoint level (Crenna

et al. 2020). Therefore, direct important drivers along the supply chain of products are missing (e.g, overexploitation of fisheries, invasive species, and pollination decline affecting agricultural production). Furthermore, LCIA developments encompass also emerging environmental pressures on biodiversity loss, such as the entanglement of marine species due to macroplastic waste (Woods et al. 2019). While the LCA community has started to develop LCIA models towards a full coverage of these issues and a harmonized framework, further operationalization and integration in existing methods are still needed especially for supporting biodiversity footprinting of supply chains and disclosure of information to stakeholders. To fulfill the need of practitioners for a comprehensive picture of the overall impacts on biodiversity in an agreed and harmonized approach, LCIA methods still need to develop consistent models for assessing not only all direct drivers of biodiversity loss but also emerging environmental issues. However, from a research perspective, variability of methods is helpful to analyze different aspects of biodiversity that underlie specific methods.

Second, most of the analyzed LCIA methods and models addressed community composition (species richness), which is only one of the six Essential Biodiversity Variables (EBVs) defined by Pereira et al. (2013) to monitor worldwide biodiversity change. Only the two approaches based on GLOBIO evaluate species population through the MSA metric. Among the recent developments in LCIA, the coverage of EBVs has been widened in the non-operational midpoint models (Crenna et al. 2020). For example, ecosystem function is addressed in models on biotic resource use (Crenna et al. 2018; Langlois et al. 2014), ecosystem structure in a land use model employing the hemeroby-based biodiversity footprint potential (Geyer et al. 2010), and species traits in a land use model based on the functional biodiversity index metric (de Souza et al. 2013). However, none of the available methods and models is currently addressing the EBV on genetic composition (Crenna et al. 2020). In this sense, comprehensive impact assessment models and metrics considering the different dimensions of biodiversity might be further explored and developed for a better coverage of EBV. For this purpose, LCA might benefit from specific scientific fields, such as biology conservation (Marques et al. 2021) or forest management (Gaudreault et al. 2020). In fact, although biodiversity can be associated with three levels (i.e, ecosystems, species, and genetic biodiversity), current LCIA approaches are mainly limited to assess species biodiversity and partly ecosystem diversity (Winter et al. 2017).

Comparative exercises such as this study are key to be able to identify the discriminating power of different current approaches, namely, to which extent, despite differences, they are pointing to the same ranking of products or to the same hotspots.

### 4.3 Limitations of this study

One of the limitations of this study was associated to the definition of “relevant” element, based on a defined contribution threshold. In the literature, a threshold of 1% contribution has been already employed. Owsianiak and colleagues (2014) employed a 1% threshold to discard less relevant elementary flows into an “others” category, which represented up to 3% of the impact. In this analysis, a 1% contribution threshold excluded between 4 and 1% of the impact depending on the impact category, with the largest exclusion in ecotoxicity where the largest number of elementary flows is considered (Table SM14). The sensitivity of the method agreement to the contribution threshold was evaluated for a range from 1 to 10%, highlighting a larger sensitivity of the relevance of impact categories than for inventory processes and elementary flows (Tables SM14), due to a more limited number of impact categories. The variation of the contribution threshold to define relevant elements affected largely some impact categories (e.g, acidification, ozone depletion, and water use) than others (e.g, climate change).

The WWF’s Living Planet Index showed a range between –24% (Europe) and –94% (Central and South America) (WWF 2020), highlighting the different intensity of biodiversity loss among world regions and the relevance of regionalized assessments. Accordingly, regionalization in LCIA methods and models has been enhanced in recent developments, including in methods addressed in this paper (e.g, LC-Impact and Impact World+). However, regionalization was limited in this study to the impact category of water use (i.e, with country-level CFs) although CFs with higher spatial resolution were available for several categories (e.g, ecoregions for land use). This resulted from the spatial resolution of the LCI of the case study, which was based on commercial LCI databases including only regionalized flows at country level for water use. This aspect was already identified during the mapping phase (Sanye-Mengual et al. 2022), outlining that LCIA developments towards higher spatial resolution mismatched data available in LCI databases leading to a partial implementation of the methods. Being this a common issue, the LCA community already highlighted the need for regionalized LCI data to overcome such barrier (Mutel et al. 2019). Regionalization aspects will be further elaborated towards integrating the role of spatial resolution in comparing biodiversity impacts of EU consumption among different LCIA methods and models.

Towards addressing biodiversity loss impacts of EU consumption, LCI data quality is also crucial. During this exercise, the commercial databases were updated towards a more robust analysis. In particular, LCI data need to be time representative to properly encompass technology development

(e.g. agricultural yields). In particular, due to the high relevance of food consumption to the overall impacts of EU consumers, attention should be paid to quality data regarding crop yield, which can affect the associated land impacts.

Lastly, a sensitivity analysis was performed to understand how results might vary due to changing consumption patterns along time. A comparison of biodiversity impacts due to EU food consumption in 2010, 2015, and 2020 was run to identify potential variability regarding temporal evolution of impacts and contribution by impact category and by representative product (Supplementary Material SM16). The sensitivity analysis focused on food consumption, as an area of consumption associated with increasing impacts on biodiversity. Results showed that impacts increased in the time range 2010–2020 with similar contribution by impact category in the three analyzed years (with agreement among all assessed LCIA methods and models). Lastly, the most contributing products per impact category barely changed during the analyzed period, apart from with few exceptions such as the identification of “cheese” as main contributor to acidification in 2020 instead of “beef meat” (as in 2010 and 2015).

## 5 Conclusions

Assessing biodiversity impacts at the endpoint is an open challenge for the LCA community. Towards identifying convergent and divergent messages stemming from the results of the available methods, this paper compared the biodiversity impacts of EU consumption using five LCIA methods (namely, Ecological Scarcity 2013, IMPACT World+, LC-IMPACT, ReCiPe2016, and Stepwise) and three LCIA models, i.e. a land use-specific model (land use intensity-specific CFs) and two approaches derived from the Global Biodiversity (GLOBIO) model. The analysis unveiled that there is a certain level of agreement among available LCIA methods and models regarding the most contributing impact categories and products to the overall biodiversity footprint due to EU consumption. Biodiversity impacts due to EU consumption were due to a limited number of consumed products, with food (animal-based products and chocolate), mobility, and household goods as top contributors. Land use and climate change impacts had a major role in contributing to the overall biodiversity footprint, representing more than 75% of the overall impact, apart from LC-IMPACT with ecotoxicity as main contributor (95%). Disagreements among methods and models were based on the inclusion of impact categories and the characteristics of the underlying impact assessment model (e.g. consideration of species vulnerability and scope in terms of environmental compartments). As a result, differences on top representative products driving biodiversity impacts were mainly associated to the contribution of impact categories to the overall biodiversity impacts by method (e.g. substantial

contribution of mobility in methods with a large contribution of climate change, household goods as top contributors due to high contribution of ecotoxicity in LC-IMPACT).

The results of this study highlighted the relevance of impact category coverage in the assessment of biodiversity impacts. A limited coverage of impact categories (e.g. methods limited to assess land use) might underestimate the impacts of other drivers of biodiversity loss. Furthermore, differences in the scope of the methods in terms of elementary flows characterized (e.g. land use transformation was partially covered in ReCiPe) influenced the role of the different impact categories and representative products in their contribution to the overall biodiversity impacts.

Current available LCIA methods and models are focusing on three direct drivers of biodiversity loss: land use change, global warming, and environmental pollution. While LCIA advancements are addressing other drivers (i.e. invasive species and overexploitation), these are yet to be addressed in models which could be considered fully operational. Moreover, further efforts are needed to better assess the effects of regionalization in a comparative analysis of LCIA methods and models, due to the large relevance of local conditions in biodiversity impacts and the recent developments in the LCA community, leading to models addressing impacts at increasing spatial resolution.

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**Data availability** All data used in the study are available in the referenced studies and in the Supplementary Materials.

## Declarations

**Conflict of interest** The authors declare no competing interests.

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