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How to quantify biodiversity footprints of consumption? A review of multi-regional input–output analysis and life cycle assessment

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Reducing direct pressures on biodiversity will only be possible once the consumption drivers behind them are identified. Target 4 of the Convention on Biological Diversity highlights the importance of moving towards sustainable patterns of production and consumption. However, linking consumption patterns to impacts on biodiversity is a complex task, especially in today's globalized world. Here, we review how environmentally extended multi-regional input–output analysis and life cycle assessment have been used to analyze the impacts of consumption on biodiversity, as well as the main challenges in doing so. Finally we discuss how these methods can provide new indicators to measure the progress towards policy goals.

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Introduction

In the latest assessment of the progress towards the global biodiversity targets (Aichi targets) it was shown that the use of natural resources is still increasing [1••,2]. This appropriation of natural resources occurs to satisfy the needs of humans. When it leads to the loss or degradation of habitats, pollution, climate change, biotic change or overexploitation, the consequences for biodiversity are mostly negative. Identifying activities that pose direct threats to biodiversity is essential to prevent biodiversity loss, but ultimately, reducing these pressures will only be possible once consumption drivers behind them are identified. In the Strategic Plan for Biodiversity 2011–2020 of the Convention on Biological Diversity (CBD), Aichi target 4[1] highlights the importance of moving towards sustainable patterns of production and consumption. The importance of this target in the achievement of the Strategic Plan as a whole has been demonstrated by its high level of upstream and downstream interactions with other targets [3]. This means that actions taken to achieve Aichi target 4 are likely to contribute to the progress of several other targets (downstream interactions), and that actions taken to achieve other targets are also likely to contribute to the progress of Aichi target 4 (upstream interactions).

From the indicators suggested to measure progress towards Aichi target 4 [4], the trends in ecological footprint and related concepts (for example, water footprint and human appropriation of net primary productivity) are the ones that are related to the impacts of consumption on biodiversity. However, they do so only indirectly, as there is no direct causal relationship between the ecological footprint, or related indicators, and impacts on biodiversity [5–7]. Moreover, the metrics behind these indicators (global ha, km^2, m^3 or Pg Carbon) fail to reflect the consequences derived from the spatial differences in biodiversity (for example, the appropriation of 1 km^2 of forest land in the Brazilian Amazon will have a different impact on biodiversity than an appropriation of 1 km^2 of semi-natural grassland in the highlands of the United Kingdom). So there is a need for considering specific

[1] *"By 2020, at the latest, Governments, business and stakeholders at all levels have taken steps to achieve or have implemented plans for sustainable production and consumption and have kept the impacts of use of natural resources well within safe ecological limits."*

indicators that can identify which consumption activities have larger impacts on biodiversity.

Directly linking consumption patterns to impacts on biodiversity is a complex task, especially in today's globalized world. Supply chains are increasingly global, thus spatially disconnecting production processes and consumption, as well as associated impacts. Environmentally extended multi-regional input–output (EMRIO) analysis and Life Cycle Assessment (LCA), methods from the Industrial Ecology field, have been widely used to trace the environmental pressures arising from consumption activities. Historically, the term 'footprint' has been more closely related to EMRIO than to LCA, probably due to the earlier maturity of the LCA terminology and community [8]. There are several definitions for the term 'footprint' [9]. In this paper we use the term 'footprint' to refer to metrics that capture the direct effects of an activity as well as the indirect effects that are transferred along a supply chain; and that can be quantified both through EMRIO and LCA methods [8]. Here, we compare and review both methods and how they have been used so far to analyze the impacts of consumption on biodiversity. Next, we present the challenges ahead. Finally, we discuss how developments in these fields can improve progress towards the achievement of the Strategic Plan and its Aichi targets.

Table 1

Overview of the global multi-regional input–output databases available for environmental analysis (A) and life cycle assessment methodologies for quantification of environmental impacts (B). A life cycle assessment methodology concerns an ensemble of different models used to compute different characterization factors. LCA methodologies [1] and [2] are still under development; in this case the information was retrieved from the projects websites (www.lc-impact.eu and www.impactworldplus.org, respectively). The numbers between brackets represent the total number of sub-categories within each impact category for each methodology.

A) Global multi-regional input–output databases

Database	Regional detail	Sector detail	Period covered	Environmental extensions				Availability
				Land use-related	Carbon emissions-related	Water use-related	Pollution emissions-related	
EORA [42]	187 countries	Variable (26 to 511 sectors)	1990-2012	Yes	Yes	Yes	Yes	Free for use at degree-granting academic institutions
EXIOBASE 3 [43]	44 countries 5 regions	163 sectors 200 products	1995-2011	Yes	Yes	Yes	Yes	Free under license
GRAM [44]	54 countries 1 region	48 sectors	1995, 2000 and 2005		Yes			Not available
GTAP 9 [45]	122 countries 18 regions	57 sectors	2004, 2007 and 2011	Yes	Yes			Proprietary
WIOD [46]	40 countries 1 region	35 sectors	1995-2011	Yes	Yes	Yes	Yes	Free

B) Life cycle assessment methodologies

Method	Spatial differentiation of impacts	Number of impact categories	Ecosystem-related impact categories						Availability
			Climate change	Acidification	Eutrophication	Toxicity	Land use	Water use	
CML2002 [47]	Europe, global	8(11)	Yes	Yes	Yes	Yes			Free
Eco-Indicator 99 [48]	Europe, global	3(12)		Yes	Yes	Yes	Yes		Free
EDIP 2003 [49]	Europe, global	7(13)	Yes	Yes	Yes	Yes			Free
EPS 2000 [50,51]	Europe, global	4(13)			Yes	Yes	Yes		Free
ILCD [52]	Europe, global	11(29)	Yes	Yes	Yes	Yes	Yes		Free
Impact 2002+ [53]	Europe, global	4(14)	Yes	Yes	Yes	Yes	Yes		Free
LIME2 [54]	Japan, global	15(15)	Yes	Yes	Yes	Yes	Yes		Free
LUCAS [55]	Global	8(10)	Yes	Yes	Yes	Yes	Yes		Free
ReCiPe [56]	Europe, global	11(16)	Yes	Yes	Yes	Yes	Yes		Free
Swiss Ecoscarcity [57]	Global	1(8)	Yes	Yes			Yes	Yes	Free
TRACI [58]	US, Global	8(10)	Yes	Yes	Yes	Yes	Yes	Yes	Free
LC-Impact[1]	Country, continent, global	3(15)	Yes	Yes	Yes	Yes	Yes	Yes	Free
ImpactWorld+[2]	Country, continent, global	3(17)	Yes	Yes	Yes	Yes	Yes	Yes	Free

Measuring the biodiversity impacts of consumption

Environmentally extended multi-regional input–output analysis (EMRIO)

Input–output (IO) models consist of a system of linear equations describing the economic flows between all sectors of a country in a certain year. Several multi-regional input–output databases with environmental extensions are available (Table 1) [10]. An environmental extension measures the direct environmental impact/ pressure arising from the activity of a production sector in a certain country [11••]. The main feature of these databases is the description of international trade relations. This allows calculating indirect environmental impacts by tracing the distant consumption drivers. Lenzen *et al.* [12••] published the first EMRIO with a biodiversity extension, consisting of a description of the threats that each sector from each country exerts on different species. Other biodiversity metrics applied so far in EMRIO include mean species abundance [13•], potentially disappeared fraction of species (PDF) [14], occupied bird ranges and missing individual birds [15].

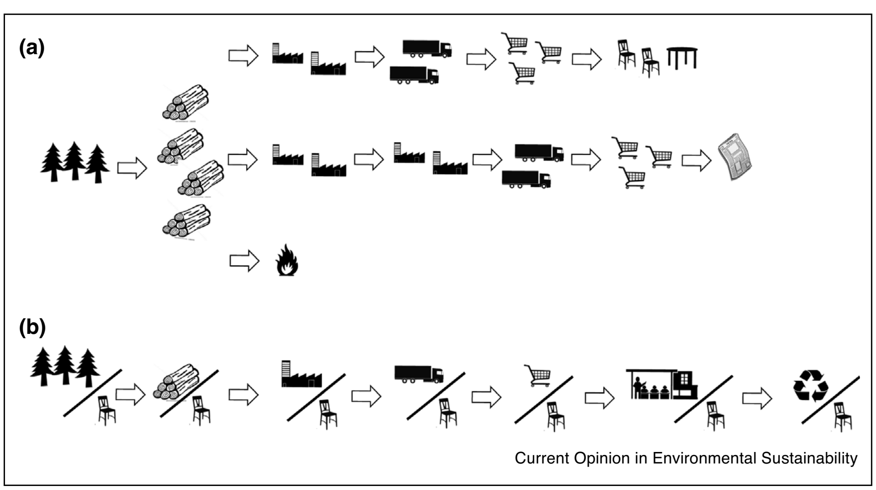
Life cycle assessment (LCA)

Contrary to IO models, the focus of LCA is product or process specific (Figure 1). The aim is to collect all emissions and resource uses throughout the whole life cycle; from extraction of raw materials to production, use and disposal [16,17]. After collecting the amounts consumed or emitted (e.g. kg of CO_2, m^3 of water) their impacts are determined. In LCA, the indicators of impact are called characterization factors; they provide information on the amount of impact per amount of resources consumed or pollutants emitted in one year (e.g. number of species lost per year per km^2 of land used). Traditionally, in LCA impacts to biodiversity are covered in several impact categories: climate change, photochemical ozone formation, terrestrial acidification, freshwater and marine eutrophication, ecotoxicity, as well as land and water stress. Some of those categories target one type of ecosystem (e.g. aquatic ecosystems for freshwater eutrophication), or they take multiple types into account (e.g. terrestrial and aquatic ecosystems for climate change). Most categories have recently become spatially refined [18,19], meaning that the determination of the impact to biodiversity is not homogenous across all areas, and new and more complex impact pathways have been added [20•,21]. In most impact categories 'biodiversity' impacts refer to 'potentially disappeared fractions of species' (PDF), comparing the original species richness to the fraction left after a human intervention. More recently, there have been first attempts to also include the aspect of vulnerability of species into the assessments [22,23], acknowledging that not all species show the same level of resilience. In this context, the UNEP/SETAC Life Cycle initiative is working to reach consensus on the indicators and models to be used for the assessment of land use impacts on biodiversity, as well as in developing guidelines for a standardization of the methods applied [23–25]. An extensive review of the biodiversity indicators used in LCA can be found in [26].

Challenges ahead

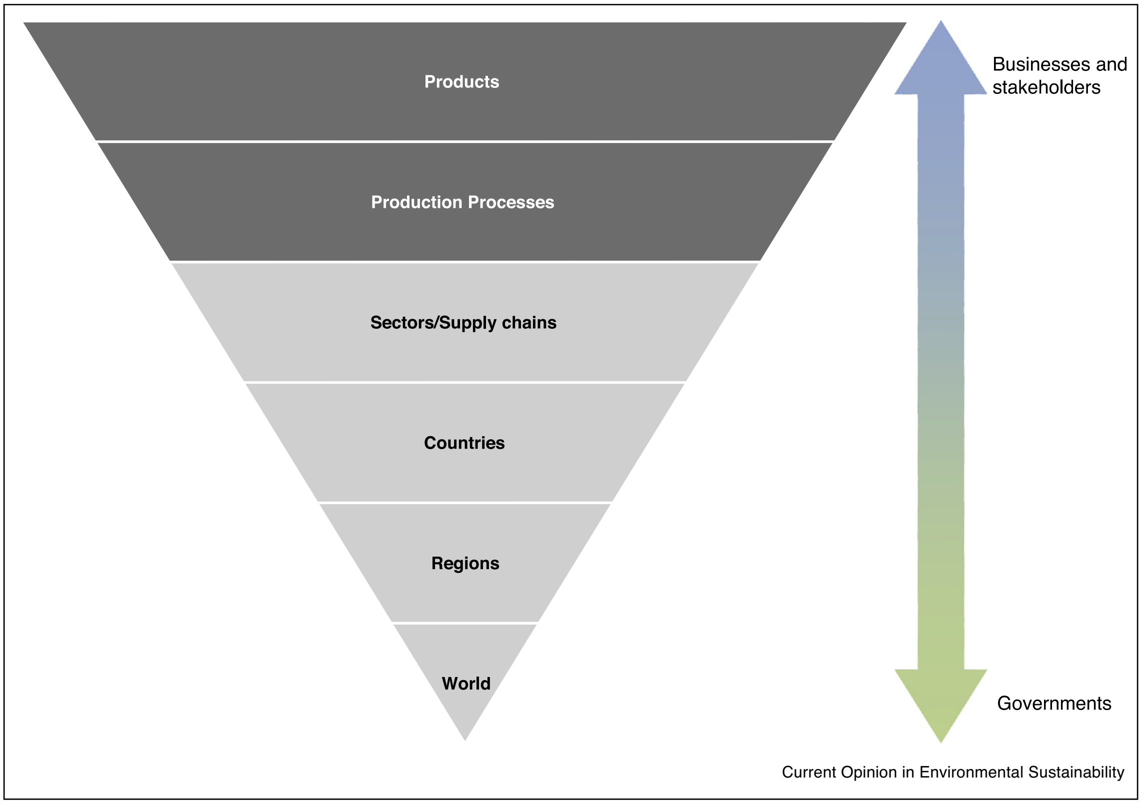
EMRIO and LCA are suitable methods to study the impacts of consumption of goods and services and progress has been made in how to integrate biodiversity in them. In depth discussions on how to integrate biodiversity in LCA have been addressed elsewhere [26,27•,28,29], and to a minor extent the suitability of

Figure 1



Difference between input–output analysis approach **(a)** and life cycle assessment approach **(b)**. Input–output analysis enables the analysis of the impacts from production to consumption of different sectors, and supply chains. Life cycle analysis enables the analysis of the impacts from production to consumption and disposal (cradle to grave) of specific products or processes.

Figure 2



Levels of application of LCA (dark grey areas of the pyramid) and EMRIO (light grey areas of the pyramid) and main interest of actors. The arrow represents the level of interest spanning from governments (green) to businesses and other stakeholders (blue). The position in the pyramid of the different levels of application represents the number of actors associated with each.

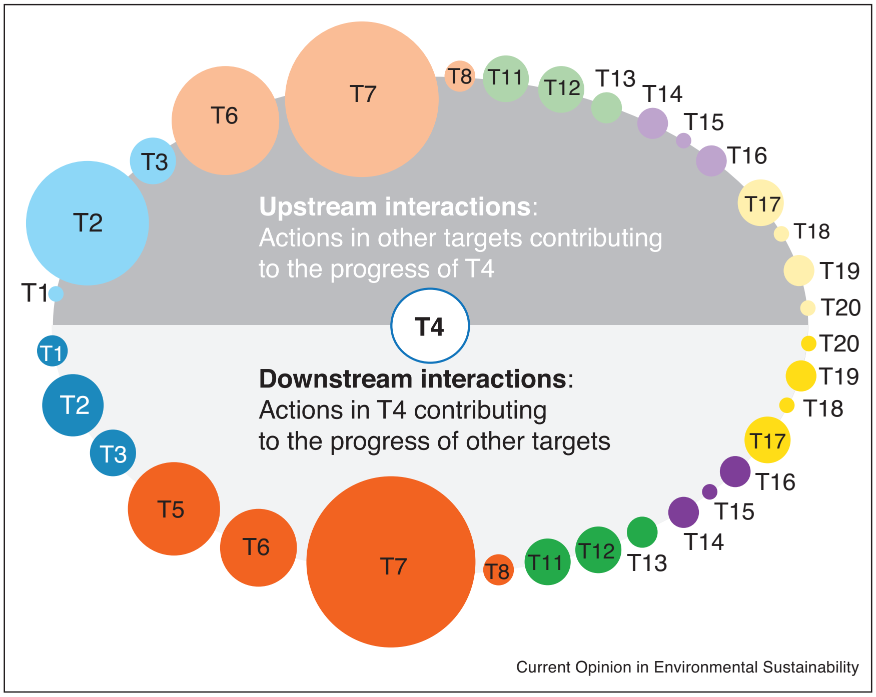
EMRIO to study biodiversity impacts [30•]. Here, we highlight what we consider are the most important aspects to be addressed in future research.

First, both EMRIO and LCA have mainly used species diversity as a proxy for biodiversity [12••,27•,29]. Despite its importance, species diversity is only one of the dimensions of biodiversity [31], covering other dimensions for example its functional and structural aspects should also be considered [26], for a more integrated understanding of the impacts on biodiversity. Second, an important issue to consider when applying EMRIO and LCA is the choice of a reference situation to which the impacts are being determined against (e.g. natural or current) [27•] and the scale of the impacts (local impacts on biodiversity versus regional/global impacts on biodiversity) [26,27•]. Consistently treating the reference situation and scale of impact across drivers is considered particularly relevant to keep consistency in the analysis. Third, the majority of studies are based on the determination of a metric of impact to biodiversity per unit of resource used; thus assuming a linear relationship between the amount of resources used and the effects on biodiversity [28,29]. However, biodiversity responses are known to be dependent on scale, they can be non-linear and unforeseen (for example, when critical thresholds are reached) [32]. Fourth, the lack of spatial detail is identified as a challenge for the application to biodiversity for both LCA and EMRIO [30•]. Particularly in LCA, the implementation of spatially explicit life cycle inventory data would provide a major step forward in the biodiversity impact assessment of the consumption of specific goods and services. With increasing analytical capabilities, there is interest in exploring methodological synergies between EMRIO and LCA and developing hybrid approaches [8]. This has the potential to increase the detail in the level of analysis, which would be beneficial for biodiversity footprinting [30•]. Finally, two drivers of biodiversity loss, overexploitation and the presence of invasive and alien species, have not yet been included in EMRIO and have been seldom addressed in LCA [26,33,34]. From a modelling perspective these are the least understood drivers of change, were major gaps and uncertainties still exist [35–37].

Policy relevance

In the policy arena, EMRIO and LCA have already been used to derive indicators to measure progress towards

Figure 3



Downstream and upstream interactions of Aichi target 4. Countries design national biodiversity targets, which are then associated to the Aichi targets by the CBD (www.cbd.int/nbsap/targets). Here, we selected national targets related to Aichi target 4. Only national targets that relate to more than one Aichi target were selected. We then identified the main Aichi target related to each of those national targets, and the remaining Aichi targets were considered as influenced by it. The size of the circles is proportional to the number of national targets where such interactions were found. The colors of the circles represent each Strategic Goal: A 'Mainstreaming biodiversity' — blue, B 'Reduce direct pressure' — orange, C 'Improve status' — green, D 'Enhance benefits' — purple, E 'Enhance implementation' — yellow.

sustainable development [38–41], which may facilitate the acceptance of these type indicators for biodiversity policies. For example, the EIPRO (Environmental Impacts of Products) study used both EMRIO and LCA to analyze the impacts of products consumed in Europe and has been important in shaping European Union product policy [38]. Another study used EMRIO and LCA to analyze the environmental impacts of production and consumption and assess priority products and materials [39]. The increase in number of global MRIO databases and the vast number of LCA methodologies providing different characterization factors (Table 1) can also facilitate the uptake and acceptance of indicators based on these methods by allowing comparisons across the different results provided and enabling sensitivity and uncertainty analysis [41].

Additionally, biodiversity indicators developed through EMRIO and LCA can greatly contribute in achieving progress towards Aichi target 4 at levels that match the actors identified (*governments, business and stakeholders at all levels)* (Figure 2). The linkages of this target with the other targets of the Strategic Plan (Figure 3) [3] can potentially enhance the reach of EMRIO and LCA in conservation related policies. Input–output analysis is consistent with the System of National Accounts,[2] and therefore biodiversity and ecosystem services extensions developed under this framework will greatly contribute to the integration of biodiversity into national accounting (Aichi target 2). The development of a biodiversity extension for an input–output framework requires knowledge on the impacts associated with economic sectors, which can contribute to integrate biodiversity priorities in sectoral policy frameworks and management plans (Aichi target 5, 6 and 7). LCA requires detailed information on the impacts associated with production process; therefore it can contribute to Aichi target 5, 6 and 7, especially focusing on particular products or production processes known to have a great impact on biodiversity.

Conclusions

EMRIO and LCA are two established methods from the field of Industrial Ecology that can be used to understand the impacts from consumption on biodiversity. In a

[2] The System of National Accounts is the internationally agreed standard set of recommendations on how to compile measures of economic activity (http://unstats.un.org/unsd/nationalaccount/sna.asp).

deeply teleconnected world consumption and production are often spatially disconnected and consumers may not be aware of the impact they drive elsewhere.

Although further developments in how to best integrate biodiversity in EMRIO and LCA are still required; these methodologies can already provide different types of biodiversity footprint indicators to measure progress towards sustainable patterns of production and consumption.

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