Sustainable Production and Consumption 37 (2023) 169–179

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

The EU Bioeconomy Footprint: Using life cycle assessment to monitor environmental impacts of the EU Bioeconomy

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ARTICLE INFO

Article history:
Received 6 December 2022
Received in revised form 11 February 2023
Accepted 18 February 2023
Available online 26 February 2023

Editor: Prof. Piera Centobelli

Keywords:
Life cycle assessment
Bioeconomy
Consumption footprint
Policy monitoring
SDG12
Bioeconomy strategy
Environmental footprint

ABSTRACT

From an environmental perspective, the transition from a fossil to a bio-based economy may underpin some trade-offs associated to the environmental impacts of bio-based supply chains and, there is thus a need to have an effective monitoring system. The goal of this paper is to develop a Life Cycle Assessment-based Bioeconomy Footprint to assess and monitor along time the environmental impacts of the EU bioeconomy. The composition of the Bioeconomy Footprint was defined in two steps: (a) defining the sectors to be included, and (b) selecting the representative products per sector; resulting in the inclusion of 76 representative final products covering eight bio-economy sectors. The overall impact is quantified based on the consumption intensity and the environmental impacts of the life cycle of each representative product. The EU Bioeconomy Footprint has increased by +23 % between 2010 and 2020, which can only partly be explained by the increase of population (+1–2 %). Food consumption has the highest share of the total impacts, 83–85 % across the years, followed by bioenergy (9–10 % of total impacts), while other sectors show a limited contribution to the overall impacts. However, further developments are needed to improve the current coverage of some sectors, e.g. non-food agriculture, and bio-based chemicals, pharmaceutical, plastic and rubber sector. Potential monitoring indicators based on the Bioeconomy Footprint are proposed as basis for the EU Bioeconomy Monitoring System, including approaches from time trends to an absolute assessment against the planetary boundaries.

1. Introduction

Narratives surrounding the EU Bioeconomy have often focused on a techno-economic interpretation of the term (Ramcilovic-Suominen and Pülzl, 2018; Vivien et al., 2019), centered around economic output, technological innovation, and the substitution of fossil carbon with biological molecules. The 2018 EU Bioeconomy Strategy (European Commission (EC), 2018), while remaining largely anchored to an anthropocentric and utilitarian view of nature, better acknowledges the role of the biosphere as the basis for a healthy planet (Folke et al., 2016).

Activities in the bioeconomy sectors are especially reliant on healthy ecosystems to ensure a sustained production of biomass, but at the same time activities along the bioeconomy supply chains generate environmental impacts which can damage local and global ecosystems. For instance, while from a sustainable production and consumption perspective, an expansion of the bioeconomy sectors is often considered as a positive development (Gawel et al., 2019), this may lead to significant negative effects, such as lose-lose bioenergy pathways which would not mitigate climate change and be detrimental for local forest ecosystems (Giuntoli et al., 2022). Several other trade-offs across geographical, temporal, and sectorial scales, have also been identified for bioeconomy sectors and products (Bringezu et al., 2012; Brizga et al., 2019; Brandão, 2020; Corrado and Sala, 2018; Giuntoli et al., 2015; Camia et al., 2021). For instance, Bringezu et al. (2021) revealed potential spillover effects and geographical displacement of environmental impacts associated to the German bioeconomy, Searchinger et al. (2008) underlined the indirect land use change and deforestation associated to the consumption of biofuels in Europe, and Agostini et al. (2014) highlighted the temporal trade-off in climate change impacts linked to the use of forest biomass for energy.

It is therefore necessary and essential to monitor and evaluate environmental impacts associated with bioeconomy activities and bio-based commodities to identify and minimize negative impacts as well as potential trade-offs. The EU Bioeconomy Monitoring System (henceforth 'BMS') (Giuntoli et al., 2020; Robert et al., 2020; Bogdanski et al., 2021) is being implemented to monitor the progress towards a sustainable and circular EU bioeconomy (European Commission (EC), 2021). The BMS covers a broad spectrum of aspects related to the bioeconomy, and a key component of progress towards Objective 3 "Reducing dependence on non-renewable, unsustainable resources" was identified as

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https://doi.org/10.1016/j.spc.2023.02.015

reducing the environmental impacts of the bioeconomy as a whole (see Fig. S1 in SM).

Given the need of addressing the Bioeconomy and the related sectors and products in a holistic manner, from extraction of raw materials to waste generation, Life Cycle Assessment (LCA) is considered as reference method for the environmental assessment. Moreover, LCA allows to assess a multiplicity of different environmental impacts, unveiling burdens, benefits and trade-offs not only among life cycle stages along the supply chain but also among environmental issues. Over the last thirty years, there has been a clear evolution in the use of LCA along the policy cycle (Sala et al., 2021) and a recognition of the pivotal role of LCA in support to sustainability assessment (Sanyé-Mengual and Sala, 2022). For instance, the Consumption Footprint developed by the European Commission – Joint Research Centre (EC-JRC) assesses the environmental impacts of EU consumption through a full bottom-up model based on representative products (Sala et al., 2019; Sanyé-Mengual and Sala, 2022, Sanyé Mengual and Sala, 2023). This indicator combines consumption statistics with process-based LCA to quantify the environmental impacts of around 165 representative products of five areas of consumption: food, mobility, housing, household goods, and appliances. The assessment includes the 16 impact categories of the Environmental Footprint (EF) method (EC-JRC, 2021), which can also be presented as a single weighted score. The experience of the Consumption Footprint demonstrated that LCA-based indicators can effectively support the assessment and monitoring of the impacts of consumption at the macro-scale. Several of the policy initiatives under the European Green Deal umbrella already acknowledge the importance of a supply-chain approach to identify the potential impacts that EU consumption can have on other world regions through embedded impacts in imported goods (European Commission (EC), 2020a, 2020b, 2020c, 2020d). The Consumption Footprint indicator is also being employed for monitoring purposes in the EC resilience dashboards (European Commission (EC), 2021), the revised Circular Economy Action Plan and the 8th Environmental Action Programme (European Commission (EC), 2022a).

Life cycle thinking has been already employed for assessing the bioeconomy at multiple levels and addressing different sustainability dimensions (Ferreira et al., 2022). On environmental aspects, many existing studies focus specifically on the evaluation of the biophysical land footprint of the bioeconomy or of specific sub-sectors such as calculating the agricultural and cropland footprint of the EU (Bruckner et al., 2015, 2019; De Laurentiis et al., 2022; O'Brien et al., 2015, 2017). Some studies present additional footprints, such as water and carbon footprints, but refer to the overall economy rather than to the bioeconomy specifically (Arto et al., 2012; O'Brien et al., 2017). Besides looking at overall footprints, several studies have employed LCA to evaluate the environmental impacts of bio-based production technologies as well as to compare current conventional fossil-based technologies against their bio-based alternative (e.g., Caldeira et al., 2020; Mendieta et al., 2021). Regarding the social dimension of sustainability, different approaches based on social LCA have been employed to explore the social effects of the bioeconomy, such as frameworks implemented in case studies on the German wood sector (Jarosch et al., 2020; Siebert et al., 2018).

Most studies calculate footprints using either I/O approaches, fully based on monetary values, or hybrid approaches integrating some biophysical properties (Ferreira et al., 2022). However, only a few sectoral studies actually employ a bottom-up LCA approach to assess the bioeconomy (e.g. Mehr et al., 2018; Schweinle et al., 2020; Suter et al., 2017). Castellani et al. (2019a) compared these two approaches revealing that while a top-down approach might cover the full economy (e.g., services), process-based LCA offers a higher level of granularity and a broader coverage of elementary flows, thereby enhancing the assessment of multiple impact categories. The experience with the Consumption Footprint indicator has shown that the granularity of this approach allows to assess environmental hotspots in terms of the areas of consumption, representative products, life cycle stages, processes, and specific elementary flows (i.e., resource use or emissions to the environment).

This paper explores the potential implementation of the Consumption Footprint rationale to define a footprint indicator for the EU Bioeconomy, henceforth 'Bioeconomy Footprint'. This indicator can be a powerful tool for a comprehensive and effective monitoring of the bioeconomy sectors: to capture environmental impacts over time, identifying environmental hotspots, highlighting geographic and sectorial trade-offs, and identifying burden shifts among impact categories and along the supply chain.

2. Materials and methods

The Bioeconomy Footprint (BF) follows the rationale of the Consumption Footprint indicator (Sala et al., 2019; Sala and Sanyé-Mengual, 2022), recently updated in (Sanyé Mengual and Sala, 2023), which is based on a full bottom-up approach. The Bioeconomy Footprint aims to quantify the environmental impacts of the EU bioeconomy, which refers to bio-based products consumed in the EU including both those produced in the EU and those imported. The Bioeconomy Footprint is based on the quantification of the consumption intensity and the environmental impact intensity of a set of representative products (RP), as detailed in Eq. (1).

$$\begin{aligned}&\textit{Bioeconomy Footprint}\\&\quad=\textstyle\sum_{RP=1}^{n}\textit{Consumption intensity}_{RP}*\textit{Unitary environmental impact}_{RP}\end{aligned} \tag{1}$$

This section details the process to define the composition of the Bioeconomy Footprint, the quantification of the consumption intensity and the modelling of environmental impacts by RP. Further information and details are provided in the Supplementary Material (SM).

2.1. Composition of the Bioeconomy Footprint

To define the composition of the Bioeconomy Footprint, i.e., the list of RPs to be covered as a Basket of representative Products (BoP), two steps were followed: (a) defining the sectors to be included, and (b) selecting the RPs for each sector. The EU bioeconomy strategy (European Commission (EC), 2018) defines the bioeconomy to cover all sectors and systems that rely on biological resources, their functions and principles. Some authors (Ronzon et al., 2020; Ronzon and M'Barek, 2018) have defined the sectorial boundaries of the EU bioeconomy including the sectors for biomass production (Agriculture, Forestry, Fishing and Aquaculture) and the sectors manufacturing bio-based products (see Table S2). Table 1 shows the sectors included in this Bioeconomy Footprint. A complete overlap is not possible given the different scope of the two exercises. However, as shown in Table S2, a large majority of bioeconomy sectors is covered in the BF.

The bio-based products already included in the Consumption Footprint (i.e., food, textiles, wood-based furniture and paper products) are the backbone of the analysis, which was then complemented with additional products representing other bio-based sectors (Table 1). While all food products from the Consumption Footprint were included, a selection was performed for household goods, which can be partly bio- and partly fossil-based: only products with more than 70 % of bio-based materials in the bills of materials (BoMs) were selected to be included in the Bioeconomy Footprint. This threshold led to the inclusion of two textile products (T-shirts and jeans), four types of furniture items (wardrobe, sofa, wooden seat and wooden table), and four types of paper products (newspaper, book, toilet paper and breast bad), which are upscaled to represent all similar products in those sectors. The choice of the bio-based share threshold was based on expert judgement and the composition of the available RPs in the Consumption

Table 1
Composition of the Bioeconomy Footprint: bioeconomy sector, representative product, origin of representative products (RPs), and number of RPs (further details in SM, Section 3).

Bioeconomy sector	Specification	Origin of RPs		Number of RPs
		Consumption Footprint (Sanyé Mengual and Sala, 2023)	Additional products	
Agriculture (food/non-food)	Primary production of food products	x		40
	Primary production of cotton for textiles		x	1
	Primary production of biofuel crops		x	6
Forestry	Primary production of soft and hard wood for all products		x	8
Fishing and aquaculture	Primary production of fish products	x		4
Manufacture of food	Manufacturing of all food products	x		45
Manufacture of wood products and furniture	Manufacturing of wooden furniture	x		4
Manufacture of bio-based textiles	Manufacturing of bio-based textiles	x		2
Manufacture of paper products	Manufacturing of paper products	x		4
Manufacture of bio-based chemicals, pharmaceutical, plastic and rubber	Manufacturing of bio-plastic bag		x	1
Manufacture of biofuels	Manufacturing of biodiesel and bioethanol		x	8
	Biomethane production for transport		x	1
Production of bioelectricity	Production and use of electricity from biomass		x	4
Production of bioheat	Production and use of heat from biomass		x	7

Footprint. Agricultural commodities are separated between food and non-food products to individually assess their importance. Non-food products include cotton cultivation for the production of the textiles included, and crops cultivated for biofuels production. The forestry sector covers all soft and hard wood used in the EU (domestic production and imported) for paper products and other wood products. The manufacturing of bio-based chemicals, pharmaceutical, plastic and rubber sector includes only bio-based plastic due to limited data availability regarding both consumption intensity and life cycle inventory. Bioplastic bag was selected as representative product, without upscaling it to cover the whole sector. In the case of bioenergy, representative products were selected combining available statistics and life cycle inventory (LCI) data and they cover the whole production and consumption of bioenergy in the EU27 (see SM, Section 3.6 for details).

This two-step process yielded a composition of 76 representative final products representing eight bio-economy sectors. In addition, 59 primary products used in the manufacturing of final products were included in the assessment.

2.2. Quantification of consumption intensities per representative product

Consumption intensity per RP was calculated based on the 'apparent consumption approach', i.e., taking into account production in the EU as well as imports and exports, as detailed in Eq. (2). This approach leads to account for the environmental impacts generated by the representative products consumed in the EU.

$$Consumption\ intensity_{RP} = Production_{RP} + Imports_{RP} - Exports_{RP} \qquad (2)$$

Data sources employed to quantify the consumption intensities per RP depends on the bio-economy sector. The consumption intensity of food (food agriculture, fishing and aquaculture, manufacturing of food) and household goods (manufacturing of paper, wood products and textiles) were retrieved from the same statistical data sources used for the Consumption Footprint (Eurostat, 2021a, 2021b; FAOSTAT, 2021; EFSA, 2021), and described in Sanyé Mengual and Sala (2023). In addition, the consumption intensity of plastic bags was retrieved from Eurostat (2021a, 2021b), with the assumption that 1 % of all plastic bags are bio-based (EEA, 2021). The consumption intensity for the forestry sector combined JRC data with Eurostat (2021c, 2021d) data. Specifically, the total amount of roundwood consumed in Europe for all products was derived from Eurostat (2021c). The overall wood consumption was then divided between hardwood (33 %) and softwood (67 %) according to EU average in 2010–2019 (Eurostat, 2021d), as well as between pulp wood (81 %) and logs (19 %) (Cazzaniga et al., 2019). The consumption of crops used in non-food commodities are those crops needed to produce biofuels and textiles, and their quantity was calculated based on the amount of biofuels consumed as reported in energy statistics (Eurostat, 2021e), the efficiencies reported in the ecoinvent dataset (biofuels) (Wernet et al., 2016) or as modelled in the Consumption Footprint (textiles) (Castellani et al., 2019b). Biofuel consumption intensity is based on the total final energy consumption of biodiesel and biogasoline (Eurostat, 2021d), which is then allocated to different feedstocks based on the USDA annual reporting of biofuels production and consumption in the EU (USDA, 2021). Bio-based heat and electricity consumption intensities are based on Eurostat (2021e, 2021f). Additional details are reported in SM. Consumption intensity data was retrieved from all years from 2010 to 2020 for EU-27 from the sources described above. Data gap filling was employed in the case of missing data in following cases: a) data was given year(s) before, i.e. data was available e.g. until 2018, so it was assumed that also 2019 and 2020 should have data, and b) data was available year(s) before and after, i.e. data was available e.g. until 2013 and then again after 2016, so it was assumed that also 2014 and 2015 should have values. Linear regression (case a) and interpolation (case b) were used as data gap filling method.

2.3. Modelling of the environmental impacts

The environmental impacts of the EU bioeconomy were calculated by multiplying consumption intensity with the environmental impact intensity of each RP. The environmental impact intensity per RP was calculated following an LCI model, without taking into account the year, i.e. the impact of each RP was maintained constant for all years. Modelling was done using SimaPro LCA software v.9.2 (Pré Sustainability, 2021). The assessment includes the life cycle stages of primary production and manufacturing for most of the products (cradle-to-gate approach) including transports of inputs used in primary production and manufacturing, as well as transport from primary production to the manufacturing site. For bio-based heating and electricity, also the use phase is included (cradle-to-use approach), because of the nature of those products, i.e. they are produced and used at the same time. Note that with a monitoring purpose in mind, the Bioeconomy Footprint is an attributional LCA model that aims at providing a picture of the current impact of the EU bioeconomy. Therefore, the model does not include potential credits due to market substitution as the current macroeconomic context of continuous growth does not ensure that the potentially substituted material is not used in another economic sector.

The LCI models of those products present in the Consumption Footprint were adapted from the same model. Data sources, modelling assumptions and employed background datasets are detailed in Castellani et al. (2017), Crenna et al. (2019a), Sinkko et al. (2019), Castellani et al. (2019b), and in Sala and Sanyé-Mengual (2022). Production of food was assumed to be mostly European, taking into account only transport impacts of imported food products, with the exception of e.g. coffee and tea, which are mainly imported, and thus also their production was assumed to be outside of the EU. For the production stage of textiles, paper products and furniture, the import market has been considered to model the manufacturing stage by using specific factors of energy efficiency and the specific electricity mix of importing countries. Environmental impacts of other sectors, i.e., agriculture (non-food), forestry, bioenergy and bio-based plastics were modelled using the most appropriate ecoinvent 3.6 processes (Wernet et al., 2016) taking into account import shares when applicable. For example, forestry is divided according to European and imported shares using ecoinvent datasets for Europe (domestic production) or Rest of World (RoW, for imported amount), and biofuels are modelled according to the most appropriate dataset found in ecoinvent 3.6 database based on the origin of the majority of fuel. The production of bio-plastic bags was roughly modelled by combining starch biopolymer production and plastic film extrusion processes assuming 97.6 % efficiency. Allocation between products from the same system (e.g. biofuel and oil cake) was already included in the datasets employed in the modelling. The mapping between RPs and LCI datasets is detailed in SM, Section 3.

The Life Cycle Impact Assessment (LCIA) employs the EF 3.0 method (EC-JRC, 2018; Fazio et al., 2018), which includes 16 impact categories, namely Climate Change, Ozone Depletion, Particulate Matter, Ionising Radiation, Photochemical Ozone Formation, Acidification, Eutrophication (terrestrial, freshwater and marine), Water Use, Land Use, Resource Use (fossils and minerals and metals), Human Toxicity (cancer and non-cancer), and Ecotoxicity. Emissions to the environment and resources use (as environmental pressures) contributing to each impact category are converted to a common unit using characterization factors based on an impact assessment model taking into account the cause-effect chain of impact potential of each environmental pressure. For example, the impact category Land Use considers both land occupation and transformation depending on different land use types (e.g. cropland, grassland, forest), for which a different characterization factor is assigned. Characterized impacts were then normalized and weighted using EF 3.0 sets for normalization and weighting to present results as the single weighted score (Crenna et al., 2019b; Sala et al., 2018).

3. Results

The Bioeconomy Footprint of the EU-27 per impact category and as single score impact for the years 2010 and 2020 are presented in Fig. 1; the contribution of food, bioenergy and other sectors is disaggregated. Food consumption has the highest share of the total impacts, 83–85 % across the years, followed by bioenergy (9–10 % of total impacts), while other sectors show a limited share of the total impacts. Most of the impacts in the food sector in almost all impact categories are due to primary production, being as high as 97 % of food sector impacts in Eutrophication, terrestrial impact category. In product level, meat consumption is the most contributing product group, followed by dairy products (Sanyé Mengual and Sala, 2023). Agriculture and manufacturing of food and beverages are the two biggest sectors in the bioeconomy both in terms of employment and value-added, contributing together for 77.2 % of all jobs in the bioeconomy and for 64.5 % of the overall value-added of the EU bioeconomy in 2019 (see Table S2 and Ronzon et al., 2020; European Commission (EC), 2021). It is thus not surprising that the food sector is the main contributor also to the bioeconomy footprint. More detailed information about the food sector impacts can be retrieved from the Consumption Footprint Platform (EC-JRC, 2022).

However, differences in the role of the different sectors are observed among impact categories, e.g. bioenergy has a relevant contribution to

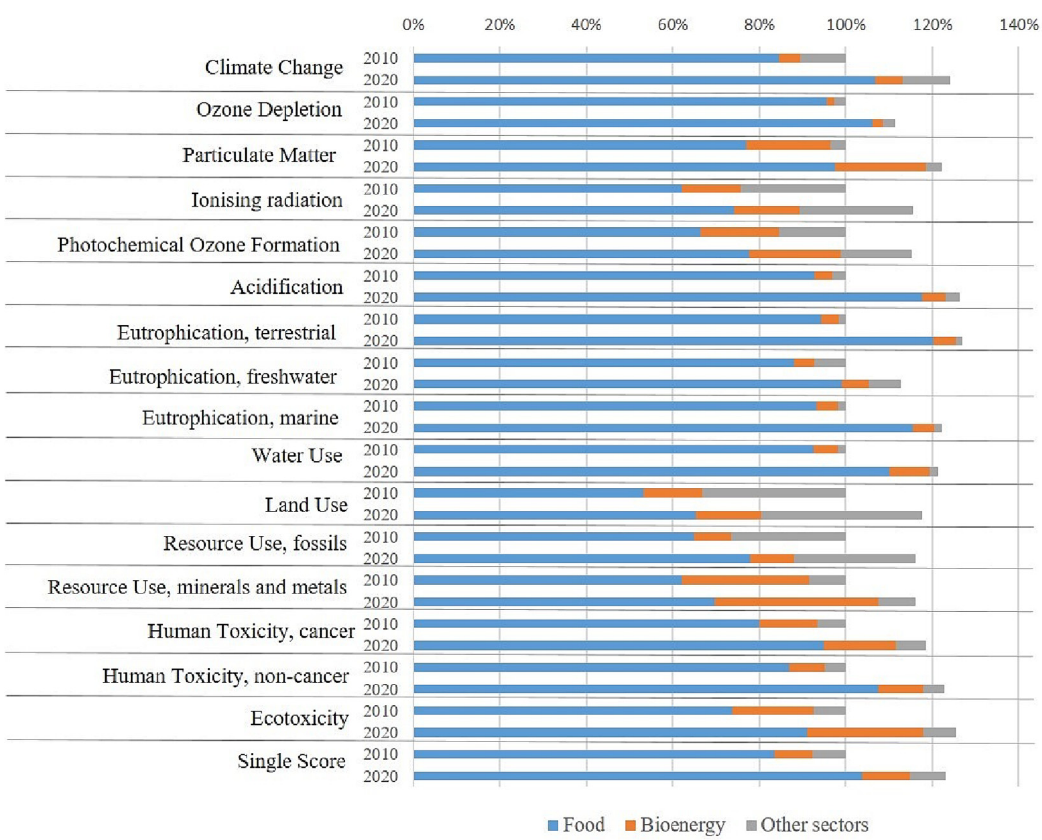

Fig. 1. Comparison of the EU Bioeconomy Footprint impacts in 2010 and 2020 per impact category and as single score impact, showing contributions of food, bioenergy and other sectors.

Resource Use, minerals and metals (30 %) and Particulate Matter (almost 20 %). In addition, the 'Other sectors' share is relevant for Land Use (more than 30 %) and in Ionising Radiation (around 24 %). More information on results per impact category can be found in the SM, Section 4.

The total environmental impact of the EU Bioeconomy has increased over time, with a total increase of +23 % between 2010 and 2020 (Fig. 1), with the highest increase in Eutrophication, terrestrial (+27 %), and lowest in Ozone Depletion (+11 %). This can only partly be explained by the increase in European population (+1–2 %). In the same time period, the consumption intensity of the RPs considered in the analysis have also increased in most of the sectors (Fig. 2). Only in the case of paper and plastic (and consequently bio-plastics), overall consumption has decreased since 2011. Most product categories have seen a decrease or stagnation in consumption in 2020 which can be likely linked to the global COVID-19 pandemic. The biggest increase in consumption is observed for the bioenergy sector (+19 %), with the biogas sector doubling between 2010 and 2020 (Fig. 3a). However, the share of biogas is still low, while the share of wood-based energy is dominating the bioenergy sector. Although wood-based energy represented 65 % of the total consumption in the bioenergy sector in 2020, this type of energy usually contributed to less than 65 % to the different impact categories – highlighting its lower environmental impact intensity compared to other bioenergy pathways (Fig. 3b). Wood-based energy has the highest contribution in Particulate Matter, Photochemical Ozone Depletion, Ionising Radiation and Land Use impact categories; while biodiesel has the biggest contribution in Eutrophication, freshwater and Eutrophication, marine impact categories; and biogas in Water Use impact.

4. Discussion

This section explores the methodological challenges, limitations of the Bioeconomy Footprint, potential future refinements of the model, and strategies for developing a useful indicator for the EU BMS.

4.1. Methodological challenges

Defining a comprehensive set of environmental indicators to integrate in the EU BMS underpinned complex assumptions and methodological choices. As highlighted in previous sections, the choice of a life cycle approach was motivated by its relevance in the EU Green Deal and related policies. Additionally, LCA approaches allow the possibility to encompass different environmental indicators and product's life cycle stages, allowing to identify hotspots and possible trade-offs. However, the construction of the Bioeconomy Footprint highlighted some challenges related to the selection of products, LCA-related methodological choices and assumptions, and harmonization with the approach adopted for the socio-economic indicators of the EU BMS.

Despite a conceptual life cycle approach of the Bioeconomy Footprint, the full life cycle of the products is not included in this assessment. For most of the products, only primary production and manufacturing phases are included, because sectors selected for the study were either related to primary production (e.g., agriculture, aquaculture, forestry) or manufacturing (e.g., food manufacturing). Regarding the use phase, the model considers the use phase of bio-energy (heat and electricity) due to its relevance in their life cycle, while it is excluded from the remaining products for which is mainly negligible (e.g., food products and textiles) or not relevant (e.g., paper) (Table 2). Other major life cycle stages that were excluded from the study are packaging and End of Life. Related to food, packaging is a crucial part of the life cycle, as many food products cannot be sold without packaging, but for some products, e.g. bioenergy, it is not relevant. Packaging can be bio-based (e.g., cardboard, bio-plastic), fossil (e.g., fossil plastic, aluminium), or a combination (e.g., cardboard box with fossil plastic window). However, bio-based packaging is partly covered by the forestry sector (i.e., wood used for cardboard boxes) and bio-plastic manufacturing.

Some overlaps and double-counting are possible. For example, a potential double-counting can take place in the generation of process heat by biomass within certain industries: certain LCA processes (e.g. for paper production) might already include the consumption of bio-heat, thus if the bioenergy sector accounted for the total production (and consumption) of process heat this would be double-counted. To minimize this effect the model excludes the final energy consumption of biomass in certain sectors, meaning these impacts will not be classified as 'bioenergy' but will be reported under 'food' or 'other sectors' categories. Specifically, following the sectorial definition used by Eurostat (2019), the final energy consumption of biomass in the following sectors is excluded from the bioheat sector: Pulp, paper, and print; wood and wood products; Food and Tobacco; Non-specified (which includes furniture industries); Textile and leather. Furthermore, while the impacts of bio-based electricity generation are fully accounted as a self-standing

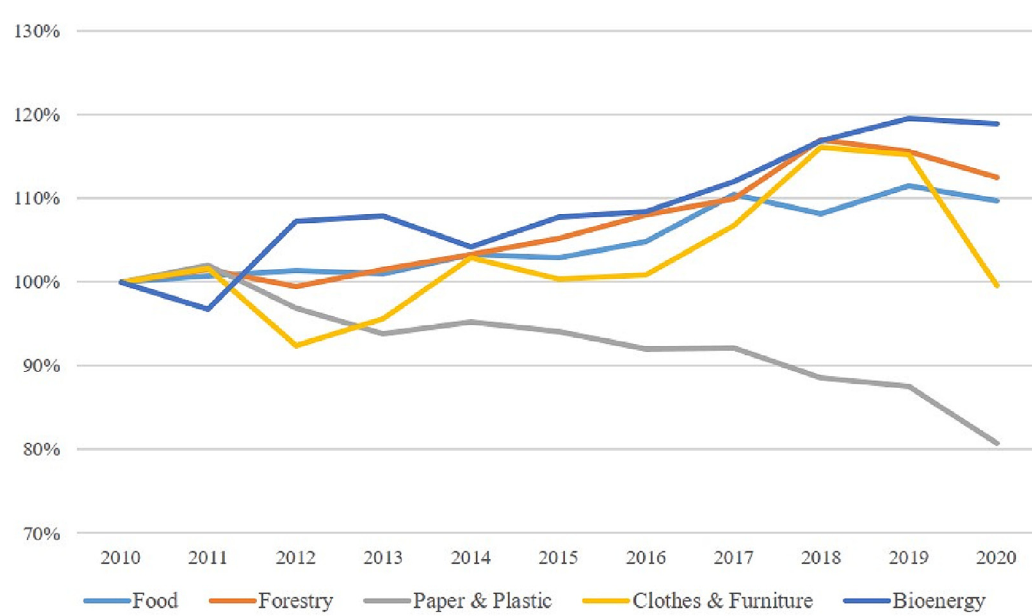

Fig. 2. Development of consumption intensities in different sectors between 2010 and 2020 in EU-27.

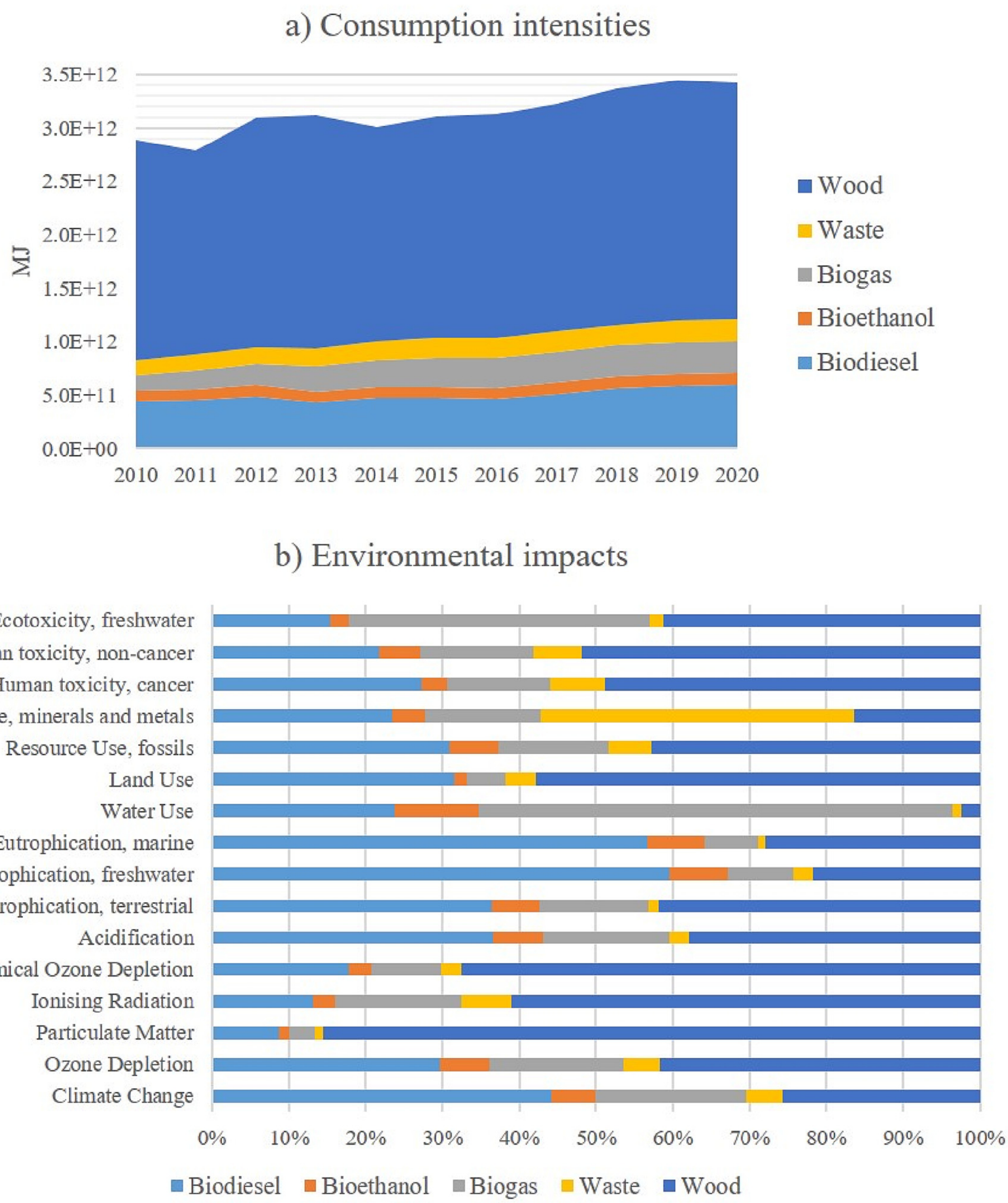

Fig. 3. Consumption intensity aggregated by bioenergy feedstock between 2010 and 2020 in the EU-27 (a), and shares of environmental impacts of final energy consumption divided for different bioenergy sources in 2020 (b). Note that while the aggregation is useful for visualization purposes, each category aggregates very different energy supply chains, e.g. "biodiesel" category contains biodiesel produced from different feedstocks and is used both in traffic use and for heating; the "wood" category contains both pathways in which wood is used for electricity and heat production in utilities and pathways in which wood is used for process heating in industrial applications or in domestic applications. The disaggregated consumption intensities are presented in the Fig. S4 in SM.

sector, these impacts are also included in the EU average consumption mix used in manufacturing processes of bio-based commodities. This instance of double-counting is accepted in this study due to its assumed lower relevance.

The environmental impacts in this work are calculated through the EF 3.0 method. This method considers the contribution of emissions of biogenic-CO_2 to climate change to be zero. This choice is subject to an ongoing scientific and normative debate (Agostini et al., 2020), because excluding the impact of biogenic-C emissions on the climate might mischaracterize the overall climate change mitigation potential of bio-based materials and bioenergy, especially ignoring the temporal dynamics associated with the biomass growth cycle and temporal storage of carbon in harvested wood products (Tonini et al., 2021; Giuntoli et al., 2015). Alternative metrics and methods to account for the impact of biogenic-CO_2 have been proposed (e.g. Cherubini et al., 2011; Tiruta-Barna, 2021) and research has also pointed out the potential role of emissions of Near-Term Climate Forcers and biogeophysical climate forcers in determining the actual climate change impact of bio-based products (Cherubini et al., 2016; Agostini et al., 2020). International efforts to develop and agree on a common methodology to account for biogenic carbon in LCA are ongoing (European Commission (EC), 2022b; Life Cycle Initiative, 2022); further developments of the Bioeconomy Footprint could include testing the effects of different carbon accounting approaches.

Table 2
Coverage of life cycles stages in the study: x = life cycle stage included; NA = life cycle stage not included; NR = life cycle stage is not relevant for the product.

	Primary production	Manufacturing	Packaging	Distribution & Retail[a]	Use	End of Life
Food	x	x	NA	NA	NA	NA
Textiles	x	x	NA	NA	NA	NA
Paper	x	x	NA	NA	NR	NA
Furniture	x	x	NA	NA	NA	NA
Bio-plastic	x	x	NR	NA	NR	NA
Biofuels	x	x	NR	NR	NA	NR
Electricity	x	x	NR	NR	x	NR
Heat	x	x	NR	NR	x	NR

[a] Distribution refers to transportation of ready product from manufacturing to retail and/or end user. Transportation of raw materials is part of the manufacturing stage.

4.2. Limitations of the Bioeconomy Footprint

Defining a bio-based product is all but straightforward, considering that very often products are partly made by biomass and partly by fossil materials. Isolating the bioeconomy within the total economy requires inevitable assumptions to define an arbitrary boundary. In the Bioeconomy Footprint, the selection of RPs was based on the products available in the Consumption Footprint and the application of a threshold of 70 % of bio-based components in the BoM. The definition of this threshold should be further investigated to identify the sensitivity of the composition of the Bioeconomy Footprint to this parameter and define potential adjustments to optimize the coverage of bioeconomy. However, in the current version of the Bioeconomy Footprint, only six out of 135 RPs are subject to that threshold, thus the selection of the threshold is not significantly affecting the results. Ronzon and M'Barek (2018) defined bio-based shares for hybrid sectors of the economy based on the relative monetary value of bio-based products manufactured by each sector, however this method still required expert judgement to define the bio-based content of each product. To the knowledge of the authors, this is the first attempt to define a threshold of products combining bio- and fossil-based materials.

Some sectors are better covered than others in the Bioeconomy Footprint. For example, the food sector (both primary production and manufacturing) covers all products included in the Consumption Footprint, i.e., 85 % of consumed food. In the case of forestry, the model covers the whole sector, i.e., the total amount of wood used in the EU for all purposes (sawlogs, veneer logs and pulpwood), while manufacturing of wood-based products includes only wooden furniture and paper products, excluding further processing of wood to be used in construction sector. The sectors regarding bio-based chemicals, pharmaceutical, plastic and rubber are currently represented only by one product, i.e., bio-plastic bag, and one polymer, i.e., starch-based polymer, which act as a proxy for all biodegradable plastic bags consumed in the EU. This narrow coverage is associated to the limited availability of both annual consumption statistics of the sector and LCI data of this type of products. This sector has been growing steadily (European Commission (EC), 2019) and a steady growth is expected in the future as fossil-based materials continue to be substituted with alternative, bio-based ones. For instance, bioplastics currently represent about 1 % of the around 370 million tonnes of plastic produced annually, but according to the latest market data, global bioplastics production capacities are set to increase 36 % between 2020 and 2025 up to 2.87 million tonnes (European Bioplastics, 2021). Bio-based cosmetics and personal care products is also an important sector in the EU, with a bio-based share of production equal to 44 % (Spekreijse et al., 2019), but products are usually only partly bio-based challenging the proper modelling in the Bioeconomy Footprint.

The exclusion of bio-based cosmetics also affects the representativeness of non-food agriculture, where crops cultivated for bio-oils used in cosmetics are not included in this iteration of the Bioeconomy Footprint. Non-food agriculture is underrepresented also regarding cotton. The current model covers only T-shirt and jeans as representative products which are upscaled to cover all similar clothes, while cotton is used also in other types of household textiles, e.g., sheets or curtains, which are currently excluded. Further refinements might therefore strive to cover the whole agricultural output (as currently modelled for forestry), which would then include all crops for all uses.

Although statistical and modelling data were available to assess the consumption intensity of the entire bioeconomy, the limited availability of LCI data constraints the modelling of the environmental impact intensity. In the case of bioenergy, consumption statistics had more granularity on feedstock and technology mixes used compared to the available level of detail in LCI databases. For example, bioethanol production from rye was used as proxy representing also bioethanol from wheat, barley and triticale. Similarly, only bio-based electricity production in combined heat and power (CHP) plants was available in LCI data although part of the electricity is produced also in plants producing only electricity, which have lower efficiency compared to CHP plants. Future iterations of the Bioeconomy Footprint might improve the details and representation of bioenergy pathways, for instance by leveraging results from recent and on-going dedicated exercises (Bouman, 2020). The availability of LCI datasets also limits the capability to refine the temporal granularity of the indicators: since commercial LCA databases do not update their data often, the current iteration of the BF maintains the unitary environmental impact constant. Finally, concerning the geographical scope of the datasets, the model aims at representing the EU market. For this purpose, most datasets are taken to represent the EU-mix or the main producer area for specific tropical products (e.g., Peru for quinoa).

Comparing the results of the current study to the other approaches available in the literature is challenging if not outright impossible. As shown in Table S17 in Section 5 of the SM, it is evident that the scope of environmental impacts and representative products captured in this study is broader than most of the existing literature. Indeed, many studies focus on a limited set of indicators which do not capture the whole range of impact categories reported in the Bioeconomy Footprint. Also, land footprint assessed in many studies provides a narrower perspective compared to the current study, which takes into account the land use impact from occupation and transformation, while land footprint indicators typically refer only to the biophysical property of area of used land, without distinction of the impact of different type of land uses (e.g. cropland, forest). Additionally, the majority of studies focus either on partial sectorial coverage of the bioeconomy or on calculating footprints for the whole economy without disaggregating bio-based sectors.

4.3. Development of an informative indicator

The overall goal of this exercise is to develop one, or more, meaningful and informative indicators to be included within the EU BMS to provide useful information to decision-makers and other stakeholders on the evolution of the environmental impacts associated to the EU bioeconomy. There are several options to translate the Bioeconomy Footprint into an informative indicator. Table 3 presents five possible options with associated pros and cons. The final decision should be however taken in a participatory process involving the interested stakeholders, e.g., through the European Bioeconomy Policy Forum.[2]

The simplest indicator to produce would be the time-trend of the Bioeconomy Footprint (option 1), which can be expressed both as a single weighted score (as in Fig. 1) or considering the 16 EF impact categories (as in SM, Fig. S3). However, presenting a single absolute value and the relative evaluation along time, the interpretation of the indicator could be partial: for instance, the increasing trend shown in Fig. 1 could simply be linked to an increased consumption of bio-based

[2] https://ec.europa.eu/info/events/high-level-launch-european-bioeconomy-policy-forum-2020-nov-12_en.

Table 3
Overview of the potential indicators based on the Bioeconomy Footprint, including definition, pros and cons.

Option nr.	Indicator	Definition	Impact categories	Desired trend	Pros	Cons
1	Bioeconomy footprint trend for defined time period	$Indicator\ (-) = Bioeconomy\ footprint_{Score}(t_0) - Bioeconomy\ footprint_{Score}(t_n)$	Both single weighted score and 16 impact categories.	↑↓[a]	Basic indicator	Ambiguous interpretation.
2	Impact share of the bioeconomy within the whole economy	$Indicator(\%) = \frac{Bioeconomy\ footprint_{Score}(u)}{Consumption\ footprint_{Score}(u)}$	Both single weighted score and 16 impact categories.	↑	Contextualization of the bioeconomy sector in relation to whole economy	Ambiguous interpretation. The trend of the indicator may be determined by too many variables (See SM).
3	Decoupling	$Indicator\ (-) = \frac{(Bioeconomy\ footprint_{t-END} - Bioeconomy\ footprint_{t-BEGIN})/Bioeconomy\ footprint_{t-BEGIN}}{(Gross\ Value\ Added\ Bioeconomy_{t-END} - Gross\ Value\ Added\ Bioeconomy_{t-BEGIN})/Gross\ Value\ Added\ Bioeconomy_{t-BEGIN}}$, where t-END represents the last year of the period under investigation and t-BEGIN represents the first year.	Both single weighted score and 16 impact categories.	↓	Similar to other 'decoupling' indicators. Clear desired directionality (downwards)	More suitable to assess long-term trends rather than annual data trends. Need to be complemented with absolute indicators (e.g. Indicator 1)
4	Efficiency of production and consumption processes in the Bioeconomy	$I(u/t) = \frac{Bioeconomy\ footprint_{Score}(u)}{Total\ biomass\ consumed\ in\ EU(t)}$	Both single weighted score and 16 impact categories.	↓	Clear desired directionality (downwards)	Efficiency, relative, metrics may indicate a relative decoupling but may hide the fact that total impact might still be increasing.
5	Planetary Boundaries	$I(-) = \frac{Bioeconomy\ footprint_{Score}(u)}{Downscaled\ PB(u)}$	To evaluate the 16 impact categories individually.	↓	Relates the Bioeconomy footprint to absolute biophysical thresholds. Provides an assessment not only of positive trends but of absolute sustainability.	Defining a downscaling of each PBs would be required, e.g., along geographical scale (EU) and sectorial scale (Bioeconomy)

[a] It is desired that the bioeconomy enlarge the market share substituting current fossil-based options, but at the same time to decrease the overall impacts through more sustainable solutions.

commodities, thus not conveying any useful information on the specific environmental impacts of the EU bioeconomy sectors. An assessment of the share of the Bioeconomy Footprint compared to the environmental impacts of total EU consumption (option 2) could be an alternative to show the contribution of the bioeconomy to the overall environmental impact of the EU consumption. However, as shown in Section 6 in SM, this indicator cannot be assigned a clear interpretation and a clear desired directionality: for instance, with the expected increase of the magnitude of the bioeconomy this indicator would increase because of an increase in the overall consumption intensities of bio-based RPs, but this trend would provide no information on the actual contribution of the bioeconomy to the environmental impacts of the EU consumption. As well, the output of this indicator would also depend on trends in consumption of non-bio-based products, which could alter the direction over time.

This ambiguity could be overcome by defining efficiency indicators that relate the environmental impacts with other metrics of the bioeconomy sector. Assessing the decoupling (option 3) would allow comparing the evolution of environmental impacts against the evolution of the economic output of the bioeconomy identifying whether the bioeconomy sector is becoming more environmentally friendly. This may generate an indicator with a clear desired directionality. Such perspective would mirror the environmental decoupling assessment performed for the Consumption Footprint indicator (Sanyé-Mengual et al., 2019). Compared to other indicator options, such assessment should be rather performed for an entire timeframe rather than annually. The Bioeconomy Footprint could be also evaluated against the total mass of biomass consumed in Europe (i.e., footprint per kg) (option 4) to provide information on the efficiency of production processes and consumption patterns of the EU bioeconomy.

However, relative measures do not capture the actual sustainability of trends, particularly efficiency indicators can overlook the trends in consumption intensity (Hauschild, 2015). The development of the Planetary Boundaries (PBs) framework (Rockström et al., 2009; Steffen et al., 2015) and its operationalization for the EF method (Sala et al., 2020) enable the assessment of the Bioeconomy Footprint from an absolute sustainability perspective. Such perspective has already been proposed for the bioeconomy regarding the land footprint (Liobikiene et al., 2020), and was also suggested for bioeconomy monitoring in the stakeholder survey conducted by Zeug et al. (2021). The Bioeconomy Footprint can be compared with the PBs for each individual EF impact category (option 5). Fig. 4 shows the illustration of that comparison for the year 2020. At this stage, the assessment against the PBs is performed at the per capita level, i.e., comparing the Bioeconomy Footprint per capita against the PB per capita of each impact category. Similarly to what is done for the Consumption Footprint (Sala et al., 2020) an egalitarian principle is applied to allocate the same share of PB to the entire global population. Even without any further downscaling, Fig. 4 can provide clear messages on the areas that need intervention. Indeed, if the bioeconomy alone is responsible for overtaking high-risk thresholds, then these areas require immediate attention. However, the assessment could be refined through further downscaling of the PB: from the safe operating space for the overall consumption to the space for the bio-economy. Such downscaling could be approached based on economic value, as done in other studies for specific products (Ryberg et al., 2018).

Compared to available indicators in the literature, the Bioeconomy Footprint provides certain advantage to specific discussion points. On the one hand, Egenolf and Bringezu (2019) argued that resource footprints can be employed as proxies of environmental damage indicators while also reducing the number of metrics included in a monitoring system. By employing the EF method, the Bioeconomy Footprint can summarize the comprehensive analysis of 16 impact categories into a single weighted score (i.e., integrating into a unique value the resulting impact of thousands of environmental pressures considered in the LCI of representative products). On the other hand, existing footprinting approaches might be limited to environmental pressures (e.g., material footprint) or combining pressure and impact indicators under unclear criteria (e.g., Egenolf and Bringezu, 2019). The Bioeconomy Footprint instead provides a clear metric of environmental impact, based on the 16 LCIA models translating environmental pressures (i.e., resource use, emissions to the environment) into environmental impacts. As well, the use of impact categories allows for integrating data on thousands of environmental pressures into a reduced set of indicators, which allows for better monitoring and decision-making.

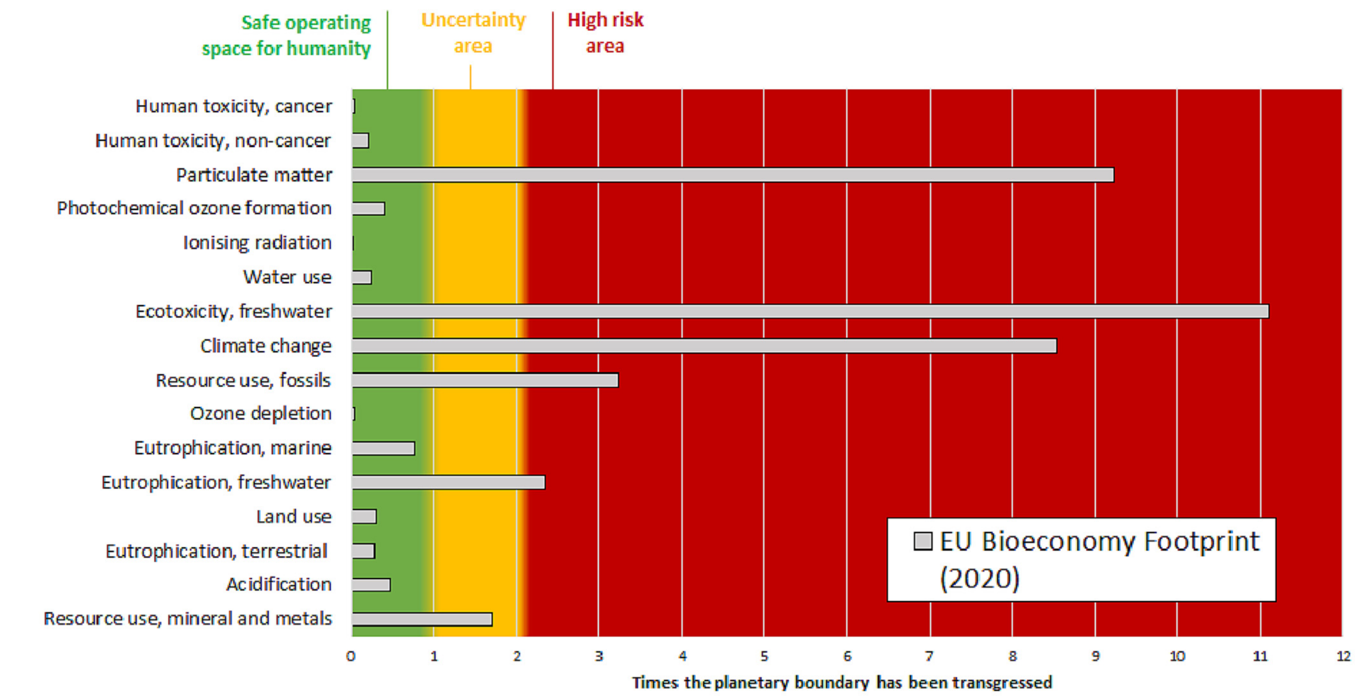

Fig. 4. Bioeconomy Footprint compared to Planetary Boundaries. Note that Bioeconomy Footprint is compared here to global Planetary Boundaries (per capita), without taking into account the share that could be allocated to the EU bioeconomy.

5. Conclusions

This study presents the Bioeconomy Footprint, a process-based LCA approach to measure the environmental impacts of the EU bioeconomy with the aim of enabling the assessment and monitoring of the progress of the EU Bioeconomy Strategy. The indicator contributes to the literature through a macro-scale approach at the impact level (16 EF environmental impact categories and single weighted score), with a high level of granularity to support decision- and policymakers. The assessment of the trend of the EU Bioeconomy Footprint highlights the major role of the food sector, which is on one hand fully bio-based and on the other hand associated to basic consumer needs. Beyond the agricultural production of food, the manufacturing of food, textile, bioheat and bioelectricity showed a relevant role in the overall impact. With the increasing penetration of bio-based products, the relative contribution of food products is expected to decrease over time, while in absolute terms the impacts might remain high.

The development of the Bioeconomy Footprint outlined different methodological challenges associated to: (a) the modelling of the life cycle of products and the alignment with other metrics of the EU BMS, (b) the selection of RPs and the definition of bio-based products, (c) the potential double-counting between the life cycle of different products, and (d) the current coverage of the Bioeconomy Footprint and the representativeness of possible indicators.

The Bioeconomy Footprint can support the goals of potential users of the EU BMS to prioritize actions through its granularity and to inform stakeholders. Furthermore, this metric is based on the Consumption Footprint which is considered in the monitoring framework of other EU policies, being one of the headline indicators of the EU 8th Environmental Action Programme. Towards a meaningful and informative use of the Bioeconomy Footprint within the EU BMS, the development of a specific indicator is required. Different options are proposed and discussed in this paper outlining the need to take decisions in multi-stakeholder contexts. The proposed alternatives vary from basic indicators relying on the assessment of trends to more elaborated metrics reflecting evaluations of resource decoupling and resource efficiency, to an assessment against the PBs framework to provide an absolute sustainability perspective.

Further steps will pursue a definition of indicators which can be agreed among multiple stakeholders, the development of Member State level data, as well as the identification of further improvements of the Bioeconomy Footprint, such as improved coverage of products and life cycle stages. Furthermore, towards embracing the multidimensionality of the EU BMS, the implementation of social LCA indicators to the Bioeconomy Footprint can be explored, as currently available for the Consumption Footprint (Mancini et al., 2023), as well as the assessment of biodiversity impacts (e.g., Crenna et al., 2019a).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.02.015.

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