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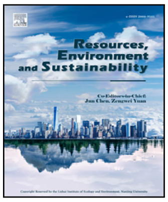

Research article

A life cycle thinking-based environmental risk framework for screening sustainable feedstocks in early-stage bioeconomy projects

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ABSTRACT

Understanding the environmental impacts of bio-based feedstock production is essential for sustainable bioeconomy development. Consequential life cycle assessment (LCA) evaluates environmental sustainability, often identifying "hidden" impacts incurred through market displacements. However, it is often impractical to screen multiple bioeconomy feedstocks and value chains using full consequential LCA early in project conceptualisation, owing to high requirements in terms of time, data, and expertise. As a result, critical environmental risks may not be discovered until too late in project development to redirect investment towards more sustainable options. This paper introduces the Bio-based feedstock Environmental Risk Assessment (Bio-ERA) Framework, designed to support early screening of potential upstream environmental risks associated with increased demand for bio-based feedstocks. The Bio-ERA Framework comprises a decision tree that systematically guides stakeholders through consequential life cycle thinking, elucidating sometimes hidden (indirect) pathways of impact among feedstock sourcing decisions. Seven important environmental aspects are addressed: Finite Resource Inputs, Greenhouse Gas (GHG) Emissions, Air Quality, Water Quality, Ecosystem Diversity, Terrestrial Carbon Storage, and Indirect Land Use Change. Criteria are proposed to structure evaluation of (i) probability and (ii) severity of environmental impact, in relation to four categories of feedstock: primary (determining product), high-value by-product, low-value by-product, and waste. Example applications demonstrate how the framework can generate an environmental risk profile for specific feedstocks sourced in specific contexts. Bio-ERA does not avoid the need for detailed LCA evaluation of full bioeconomy value chains, but promotes deeper interrogation and awareness of potential environmental risks associated with feedstock sourcing, in a manner that is accessible to all stakeholders. This could support earlier screening of strategic investment decisions necessary to develop a sustainable bioeconomy.

1. Introduction

Humanity is facing an array of unprecedented challenges as global population growth and accelerating unsustainable production and consumption patterns put Earth-system processes under increasing pressure. Among these, climate change, freshwater change, land-system change, compromised biosphere integrity, unsustainable biogeochemical flows, and the emergence of novel entities (*e.g.*, plastics and chemicals) pose significant threats, pushing us closer to a point beyond a safe operating space for humanity (Richardson et al., 2023; Rockström et al., 2009). In recent years, unforeseen events such as the Covid-19 pandemic and the war in Ukraine have also exposed weaknesses in global supply chains, and highlighted the importance of resilience, alongside sustainability. The "bioeconomy" has emerged as a promising concept to help address these challenges (European Commission, 2018a; Lasarte-López et al., 2023; Liobikienė and Miceikiene, 2023). The bioeconomy encompasses all economic sectors and systems that rely on biological resources to produce bio-based energy, goods, and services (European Commission, 2018a). Deployment of a sustainable bioeconomy offers a pathway towards sustainable development, potentially contributing significantly to achieving many United Nations' Sustainable Development Goals (Aworunse et al., 2023; Heimann, 2019; Ronzon and Sanjuán, 2020). Recognising its importance, the EU Bioeconomy Strategy emphasises the role of the bioeconomy in accomplishing its ambitious target of achieving "climate neutrality"

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in Europe by 2050 (European Commission, 2019, 2018a). Through its initiatives such as the Circular Economy and Bioeconomy Action Plans (European Commission, 2020, 2018b), the EU is working to strengthen and expand bio-based sectors, promote the rapid deployment of local bioeconomies, advance understanding of the bioeconomy, and establish sustainable products and sustainable consumption as the standard in the EU, amongst other significant objectives.

To realise the positive environmental potential of the bioeconomy and ensure its long-term viability, it is crucial to achieve environmentally sustainable production of bio-based feedstocks (European Commission, 2018a). The sourcing of feedstocks, the raw (unprocessed) materials used to produce bio-based products, can have significant environmental implications (Bishop et al., 2022). Whilst bio-based feedstocks can incur smaller environmental impacts compared to abiotic resources and decrease reliance on finite resources, their production can also give rise to significant impacts, including land use changes, environmental releases, and biodiversity loss (Pawelzik et al., 2013). A widely adopted method for assessing the environmental impacts of bio-based materials is life cycle assessment (LCA) (ISO, 2020a,b). LCA methodologies can be broadly classified into two distinct approaches: attributional LCA and consequential LCA. These approaches differ in their modelling strategies, addressing distinct questions about environmental performance. Attributional LCA assesses the physical flows of inputs and outputs within a life cycle and its subsystems, providing a snapshot of environmental impacts under defined conditions (Finnveden et al., 2009). Consequential LCA, in contrast, focuses on how flows change in response to specific decisions, including changes incurred (indirectly, via market effects) outside the system initially targeted by the decision[1] (Finnveden et al., 2009; UNEP, 2011). Attributional LCA typically uses average data and allocates impacts among co-products, while consequential LCA employs marginal data and system expansion to reflect market-driven changes (Ekvall, 2019; UNEP, 2011). In essence, attributional LCA answers "what are the impacts attributed to past behaviour under specified allocation rules?", whereas consequential LCA explores "what are the impacts that are expected to occur as a result of a (potential) decision?" (Santos et al., 2022).

The prospective[2] nature of consequential LCA makes it especially relevant for evaluating decisions at commercial scales. By considering both direct and indirect effects, consequential LCA enables a broader systems perspective. Indirect impacts, which can manifest via market signals, can be of far greater magnitude than direct effects. For example, if the production of corn-based ethanol biofuels increases, it may directly lead to the displacement of food crop production in favour of non-food crop cultivation, which may carry relatively little direct environmental impact. However, the displaced food crops may be cultivated in other regions to compensate for the production shortfall, triggering indirect land use change. Such changes can involve the conversion of natural land into agricultural land, leading to habitat loss and substantial indirect emissions (Schmidt et al., 2015). It has been argued that a consistent socially responsible decision-maker must always take responsibility for the activities in the consequential product life cycle (Weidema et al., 2018). Although consequential LCA outcomes may entail higher uncertainties, incorporating these indirect effects renders the results more accurate (Ekvall, 2019; European Commission, 2010). High accuracy is arguably the most important factor of an assessment, to avoid unintentionally misguiding decision makers. Uncertainty can (and should) be dealt with in consequential LCA studies (Igos et al., 2019).

Consequential LCA research has demonstrated that not all bio-based feedstocks are environmentally equal, as feedstocks can incur vastly different upstream impacts, both directly and indirectly (Bishop et al., 2022). Therefore, the careful selection and acquisition of appropriate feedstocks are critical for achieving optimal environmental performance of the final bioeconomy product. To this end, during the bioeconomy product development, feedstock sourcing should be a primary consideration, ideally through the use of consequential LCA. However, conducting a comprehensive consequential LCA is resource-intensive and demands substantial investments of time and specialised expertise. This challenge is compounded by the need for considerable data and information from multiple stakeholders — often specific to well-developed value chain configurations only determined at a high technology readiness level (TRL) (Holden, 2022). Given the multitude of emerging product innovations within the bioeconomy (Brandão et al., 2021), conducting a full consequential LCA for every possible production scenario of every prospective feedstock for potential bio-based products is unfeasible. Therefore, it is important to identify high risk feedstocks in particular contexts early in the scoping phase, rather than after resources have been allocated and a detailed consequential LCA has been undertaken. Projections indicate a substantial biomass availability gap of 40%–70% by 2050 between demand and supply (European Commission, 2022), highlighting the urgent need for a method to quickly screen potential feedstock scenarios to help prioritise and guide project development and subsequent full consequential LCA as projects develop. Additionally, despite considerable support for a sustainable bioeconomy in Europe (Dallendörfer et al., 2022), a notable lack of awareness persists among the general public and consumers regarding biobased materials (Gaffey et al., 2021). This knowledge gap underscores the critical need to enhance understanding of the environmental sustainability of bio-based feedstocks, especially considering citizen concern in this area (Lucas et al., 2022).

Streamlined methodologies have emerged to address this need, offering simplified approaches to environmental impact assessment. These methods aim to balance accuracy with practicality, reducing the complexity and resource demands of traditional LCA. Studies have streamlined LCA in several ways, including *inter alia*, focusing on the most critical life cycle phases (Ingrao and Wojnarowska, 2023), using premade datasets to enable comparative design exploration (Verghese et al., 2010), prioritising the most critical impacts, emissions, and inputs that affect the ranking of different scenarios (Wang et al., 2021), and by identifying hotspots to constrain parameterised process-based LCA (Pelton and Smith, 2015). However, streamlined LCAs to date have focused on attributional (footprint) approaches. Further, they are often tightly bound to specific products or processes, or still require substantial data inputs. This highlights a critical gap: the need for a streamlined methodology tailored to consequential LCA thinking — one that minimises data requirements and time while maintaining the ability to capture broader multi-system consequences.

To address this gap, we have utilised the principles of consequential LCA thinking to develop a methodology which enables rapid environmental screening of potential bio-based feedstocks, facilitating an early assessment of upstream environmental risks, henceforth called the Bio-ERA Framework (Bio-based feedstock Environmental Risk Assessment Framework). We test this framework across a range of feedstocks. The Bio-ERA Framework aims to identify possible areas of environmental concern associated with an increased demand for any bioeconomy feedstock in a given context. Above all, it promotes consequential LCA thinking among industry stakeholders seeking sustainable feedstock supplies, policymakers navigating complex environmental challenges, and members of wider society who may not be fully aware of the many pathways to environmental impact.

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[1] In consequential LCA terms, a consequential LCA assesses the potential global environmental impact arising from activities expected to change because of decisions that affect the demand for the *functional unit* (that is, the measure of the performance delivered by the product system) (UNEP, 2011).

[2] "Prospective" because consequential LCA focuses on the time following a decision – the relative future – even if the decision occurs in the absolute past, present, or future. The consequences of a decision cannot influence past events; the entire cause–effect chain along the supply chain is projected forward in time (Schaubroeck et al., 2021).

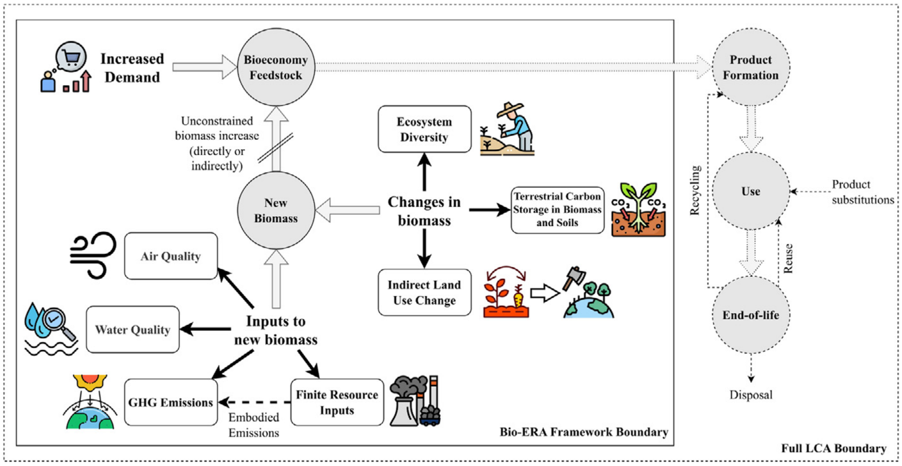


Fig. 1. Visualisation of how the scope of the Bio-ERA Framework scope fits within wider LCA boundaries. Environmental aspects (rounded boxes) included in the Bio-ERA Framework, arising from the increased demand for a specific bio-based feedstock.

2. Methods

2.1. Environmental risk assessment

2.1.1. Seven environmental aspects

The goal of this study was to create a rapid early upstream environmental risk assessment screening methodology to identify the environmental risk areas associated with increasing demand for specific bio-based feedstocks. The Bio-ERA Framework is informed by consequential life cycle thinking and is intended to inform bioeconomy stakeholders on the relative environmental risks associated with prospective feedstock supplies. Screening is based on seven pertinent environmental aspects: Finite Resource Inputs, GHG Emissions, Air Quality, Water Quality, Ecosystem Diversity, Terrestrial Carbon Storage, and Indirect Land Use Change (Fig. 1). The seven environmental aspects selected for the Bio-ERA Framework encompass key potential environmental concerns (directly or indirectly) associated with increased demand for bio-based feedstocks. The selection of these seven environmental aspects was guided by the Planetary Boundaries framework (Rockström et al., 2009; Steffen et al., 2015) and life cycle impact assessment categories used in LCA (European Commission, 2018c). These aspects are closely aligned with critical Earth-system processes, namely climate change, biosphere integrity loss, biogeochemical flows, and land-system change (Rockström et al., 2009; Steffen et al., 2015).

To briefly elaborate the environmental aspects, Finite Resource Inputs considers the dependence of new biomass production on fossil fuels, synthetic fertilisers, abiotic materials, and other non-renewable inputs. GHG Emissions represents emissions associated with new biomass production, both from biological processes and embodied emissions, encompassing carbon dioxide, methane, and nitrous oxide, which contribute to climate change. Air Quality assesses emissions of pollutants such as particulate matter and nitrogen oxides, which can have negative health impacts on humans and ecosystems (WHO, 2006). Water Quality considers direct discharge or diffuse losses of pollutants (*e.g.*, excess nutrients, pesticides) to water bodies (Giri and Qiu, 2016). Within this framework, Ecosystem Diversity assesses the potential risk of impact on the variety and heterogeneity of land use within a specific geographic area arising from increased production demands. When a certain land use or vegetation cover is required that is not already prevalent in a region, this can enhance diversity at a landscape level. Conversely, increasing demand for an already dominant land use or vegetation cover risks further reducing diversity. The importance of maintaining high Ecosystem Diversity has been demonstrated in relation to various ecological, social, and economic benefits, including enhanced resilience and adaptability, higher biodiversity, and increased delivery of wider ecosystem services (Isbell et al., 2017; Schippers et al., 2015). Terrestrial Carbon Storage represents risks of carbon stored in biomass and soils being lost as a consequence of cultivating or extracting particular feedstocks, or conversely the possibility of building additional carbon storage in biomass and soils. For example, the production of bio-based feedstocks can involve the conversion of land from forests or grasslands to cropland, which can result in the release of carbon from the soil and vegetation, and vice versa. Indirect Land Use Change considers effects that may occur in other systems or countries as a result of market perturbations arising from demand for a new feedstock. When the production of new biomass leads to a change in the occupation of some production capacity, there may be a need to compensate for this change elsewhere if the demand for this original production remains. Due to the constrained nature of land, additional demand for this product is supplied from land already in "use" via agricultural land expansion (*e.g.*, deforestation) and intensification, resulting in significant environmental impacts (Schmidt et al., 2015; Tonini et al., 2016). For further details on these seven environmental aspects, please refer to Section 2.1.4.

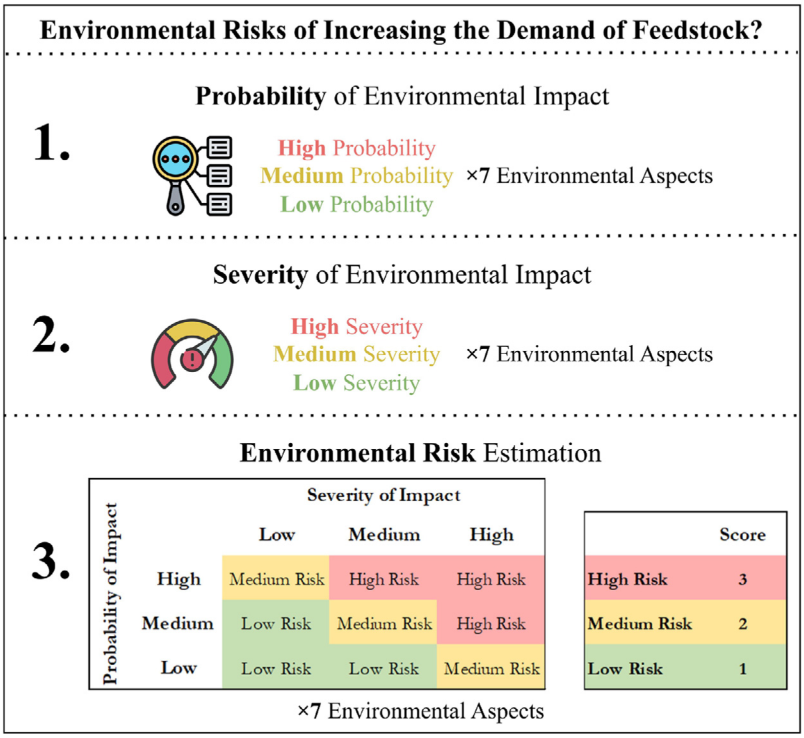
2.1.2. Environmental risk scores

In order to assess the *risk* of environmental impact from the increased demand of any bio-based feedstock (including primary feedstocks, by-products, and wastes), the Bio-ERA Framework follows a structured approach that incorporates several discrete, easy-to-implement steps that culminate in an overall environmental risk score for each of the seven environmental aspects. This scoring system is based on two key factors: the *Probability* of environmental impact and the *Severity* of environmental impact (as outlined in Sections 2.1.3 and 2.1.4, respectively).

The Probability and Severity factors are each assigned a rank of low, medium, or high, based on explicitly defined criteria. These scores are then cross-referenced in a risk table (Fig. 2), which provides a combined risk score of 1–3 for each environmental aspect, denoting low risk to high risk (Fig. 2). The total environmental risk is then calculated following Eq. (1), where *i* represents each of the seven environmental aspects.

$$Total\ Environmental\ Risk = \sum_{i=1}^{7} Probability\ of\ Impact_i \times Severity\ of\ Impact_i \quad (1)$$

Eq. (1) yields an overall numerical score (with a maximum of 21) pertaining to the potential environmental risk associated with increasing the demand for each bio-based feedstock. It is important to note that the Bio-ERA Framework is not intended to offer a precise indication of aggregate upstream environmental damage, but rather provides a quick and accessible identification of likely risk hotspots.



Probability of Impact	Severity of Impact: Low	Severity of Impact: Medium	Severity of Impact: High
High	Medium Risk	High Risk	High Risk
Medium	Low Risk	Medium Risk	High Risk
Low	Low Risk	Low Risk	Medium Risk

	Score
High Risk	3
Medium Risk	2
Low Risk	1

Fig. 2. The Bio-ERA Framework, structured into three discrete steps. In Step 1, the Probability of environmental impact is assessed across all seven environmental aspects (see Fig. 3, Section 2.1.3). Step 2 entails estimating the Severity of environmental impact for each of the seven environmental aspects (see Fig. 4, Section 2.1.4). In Step 3, the above risk table is used to estimate the environmental risk of increasing the demand for the chosen bio-based feedstock for each environmental aspect, based on the classification of the Probability and Severity of environmental impact. Additionally, scores are assigned to each level of environment risk (High, Medium, or Low) estimated for each of the seven environmental aspects, bottom right.

2.1.3. Probability of environmental impact — Step 1

As consequential LCA traces the environmental impacts of a product forward in time, unconstrained (marginal) suppliers are used to represent production systems that can respond to changes in demand for a particular product at the lowest (long-term) cost. The production capacity of many products can be constrained by various factors, including lack of raw materials, quality constraints, geography, technology, and policy and regulations (Weidema et al., 1999). Unconstrained products whose production volume can respond to changes in demand are called "determining products". "By-products" (also called "dependent co-products") are products outputted to the technosphere that are produced in conjunction with the main product (the determining product) and retain some value, but their production volume is constrained by the demand for the determining product, meaning that the production volume of the co-producing activity is *not* affected by changes in demand for the by-product itself (Ekvall and Weidema, 2004). For example, suppliers of bovine meat will not increase their production in response to an increase in demand for leather (Santos et al., 2022). Therefore, if the product of interest is constrained, an increased demand will not affect the levels of production or extraction of that resource. Instead, less of that constrained product is available for other parts of the technological system (*i.e.*, the wider economy), which in turn may increase production from other (unconstrained) suppliers who provide an equivalent functioning product. "Wastes" have many different definitions in the literature. However, in consequential LCA terms, a waste is essentially a co-product that does not carry any market value, and therefore has no direct effect on production volumes of originating feedstocks when demand for them increases. However, (preferred) waste handling activities which compete for the same waste products may be affected to satisfy the demand (Prosman and Sacchi, 2016).

Within this Bio-ERA Framework, we establish a relationship between the "product type" of bio-based feedstocks (*i.e.*, determining products, by-products, or waste products) and the Probability of environmental impact. Considering the definitions described above, we propose that bio-based feedstocks comprising determining products or high-value by-products are highly likely to have significant environmental impacts through associated additional production capacity. In contrast, low-value by-products and wastes are less likely and unlikely, respectively, to drive severe environmental impacts through additional (marginal) production. The rationale behind this idea is that an increase in demand for a determining product feedstock would likely result in increased production activities of that feedstock through expansion and/or intensification of that biomass production to meet the rising demand, which could necessitate considerable inputs and consequently result in severe environmental impacts. An increase in demand for high-value by-product feedstocks may reduce the availability of this biomass for alternative uses for which the feedstock may have originally been used (Ekvall and Weidema, 2004). If the demand for the original use of the high-value by-product feedstock remains, additional alternative production may be introduced into the market from unconstrained suppliers of equivalent functioning products to fulfil this demand, which could incur significant environmental impact. Conversely, low-value by-products may not be fully utilised or may have lower market demand and higher substitutability (by other low-value or waste feedstocks) across a range of applications or industries. This reduces the likelihood that utilisation of such by-products incurs considerable additional production activities, and thus environmental impact, compared with high-value by-products. Waste bio-based feedstocks are associated with low probability of environmental impacts as production markets are unlikely to be affected by increasing demand.

The initiation of Step 1 in the Bio-ERA Framework involves identifying whether the feedstock functions as the determining product or not (Fig. 3). This classification is important because multiple products can arise from a single production system, making it challenging to pinpoint which product drives the system's operation. To address this complexity, we follow the framework outlined by 2.-0 LCA Consultants (2015),

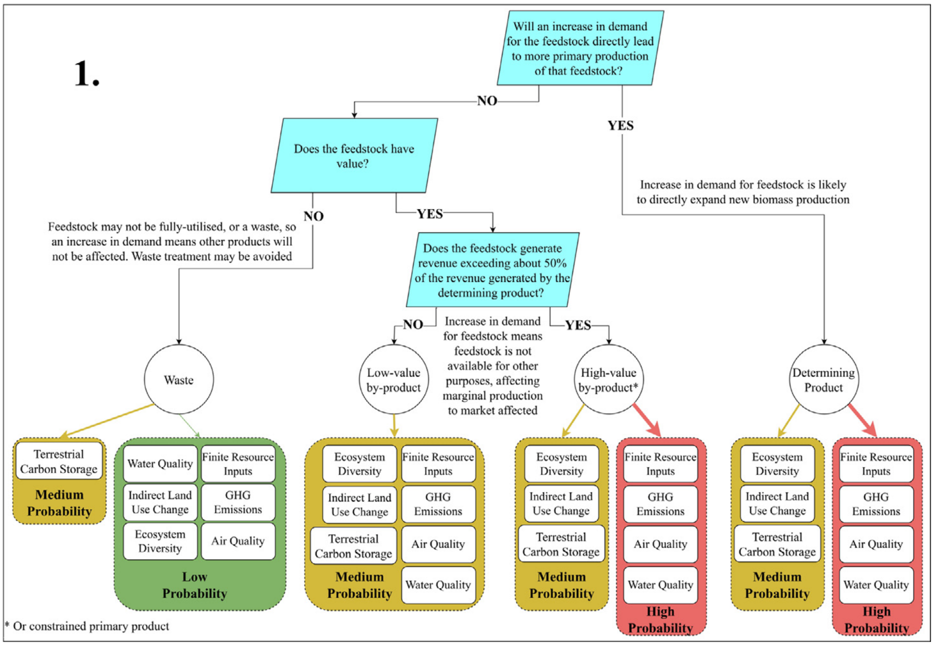


Fig. 3. Step 1 of the Bio-ERA Framework: The questions (blue rhomboids) to estimate the Probability of environmental impact across seven environmental aspects (rounded boxes) arising from increased demand for bio-based feedstocks, characterised according to product type (circles). Asterisk denotes constrained primary products.

which provides criteria for identifying the determining product in such scenarios. If the feedstock does not constitute the determining product, the subsequent stage entails assessing its relative share of revenue for the production process (Fig. 3). A zero-value output is regarded as a waste. Distinguishing between high-value and low-value by-products is less clear cut, but necessary to assess the potential environmental risks of the feedstocks via the Bio-ERA Framework. While there is no official definition, we propose a rule of thumb for classification. By-products that generate revenue exceeding 50% of the revenue generated by the determining product can be considered high-value by-products, while those generating less than 50% of main product revenue are classified as low-value (Fig. 3). Although revenue information may not always be readily available during rapid screening, and prices can fluctuate significantly, transparent documentation of assumptions and adherence to the precautionary principle are sufficient for screening purposes. In cases of uncertainty between the two categories, erring on the side of caution by assigning “high-value” is recommended.

In some instances, the perceived primary product itself may be a constrained feedstock. For example, although an increase in demand for wild-caught fish may lead to a temporary price increase and thus increase the revenue of the fishing activity, due to various constraints such as quotas and limited availability, this price surge does not translate to an increased supply of this primary feedstock. Rather, marginal consumers[3] may opt for more affordable unconstrained substitutes, such as farmed fish, resulting in an increased demand and production of that output instead (Weidema et al., 2018). Within the Bio-ERA Framework, constrained primary feedstocks can be treated with the same probability and consequential thinking as a high-value by-product (Fig. 3).

The exception to the above Probability level assumptions arises for the following aspects: Ecosystem Diversity, Indirect Land Use Change, and Terrestrial Carbon Storage (Fig. 3). Whilst still following the aforementioned consequential thinking, the land impacts of determining product feedstocks and market-displaced unconstrained suppliers can vary considerably. For example, feedstocks arising from crops will (typically) have very different landscape impacts to those arising from forestry or macroalgae. To address this, the Bio-ERA Framework defines the landscape impact probabilities for determining products and by-products for all feedstocks as medium (as an “average”) (Fig. 3), placing the onus of environmental risk directly onto the Severity of consequences (Section 2.1.4) — still allowing the full range of low to high risk depending on individual feedstock scenarios (Fig. 2). Similarly, if waste product feedstocks are sourced from the land, they may negatively impact terrestrial carbon stocks if removed from land, so medium probability is also given for the Terrestrial Carbon Storage aspect for waste feedstocks.

2.1.4. Severity of environmental impact — Step 2

As explained above, one of the key factors in estimating the environmental risk posed by bio-based feedstocks is determining the Severity of environmental impact, which pertains to the potential magnitude or intensity of consequences arising from an increased demand for a particular feedstock within the bioeconomy. This study presents the Severity of impact criteria for the seven environmental aspects in Fig. 4, which can guide practitioners to estimate whether increased demand for the bio-based feedstock under consideration is associated with low, medium, or high Severity of impact.

While determining the Severity of impact for determining products is relatively straightforward due to the direct nature of their related (production) impacts, characterising the Severity of impacts for by-products or constrained primary products can be less intuitive as the indirect impacts arising from the (potentially unknown) unconstrained suppliers may not be immediately apparent. The frameworks laid out by Weidema et al. (2009, 1999) can be used to identify the unconstrained suppliers to the market and can facilitate the prediction of potential environmental risks associated with increasing feedstock demand. However, since the Bio-ERA Framework is designed for rapid screening with minimal data, the identification of specific unconstrained suppliers is not necessary; instead, the precautionary principle is recommended to flag possible hotspots that require further investigation after screening. The Severity of impact criteria in Fig. 4 provide a flexible framework for evaluating the environmental risk of bio-based feedstocks based on structured qualitative descriptions that

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[3] The consumer who is least willing to pay the prevailing market price in a supply and demand equilibrium. If the price of the product increases, the marginal consumer will stop buying the product, and vice versa.

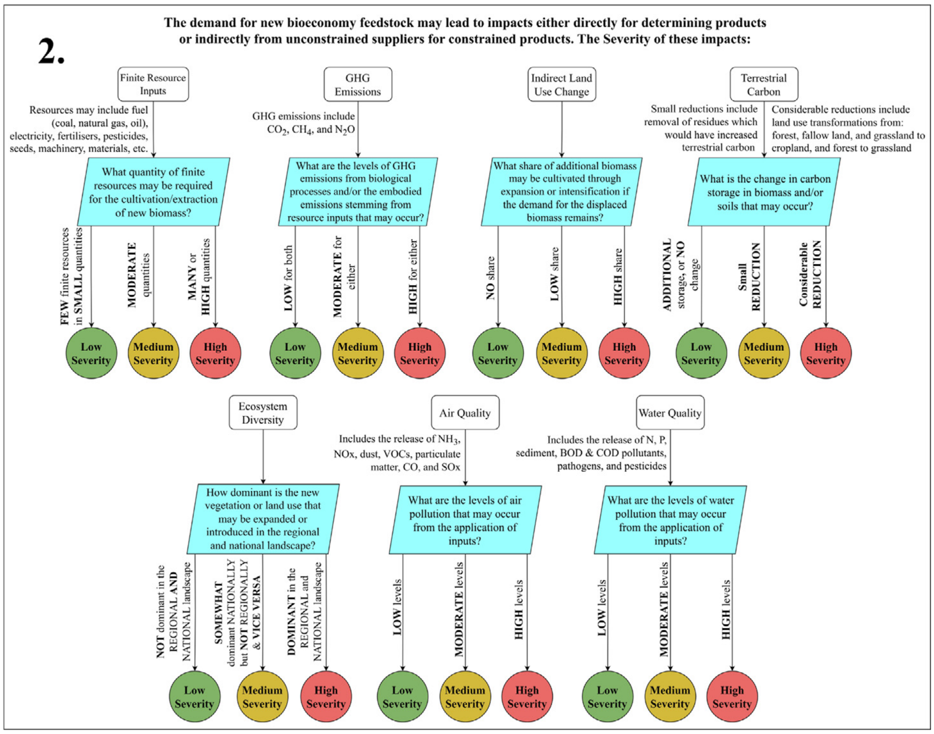

Fig. 4. Step 2 of the Bio-ERA Framework: Criteria applied to determine low, medium, or high Severity of impact across each of the seven environmental aspects (rounded boxes). Questions for each of the environmental aspects are in blue rhomboids. Answers leading to the level of Severity are on the arrows.

can be applied even in cases where data may be limited. However, some value judgements are inevitably involved, and there are likely to be instances where practitioners are unsure on how to rank the Severity of environmental impact associated with a particular feedstock. In such cases of uncertainty, we recommend taking a precautionary approach by selecting the higher severity candidate options. This approach is consistent with the objective of identifying potential risks and risk hotspots across feedstock types, as per the precautionary principle (Kriebel et al., 2001).

2.2. Feedstock examples

To demonstrate the applicability and utility of the Bio-ERA Framework presented in Section 2.1, a number of diverse bio-based feedstocks were screened using the proposed methodology, in the context of Ireland to assess location-specific impact risks (where necessary). These feedstocks were drawn from a wide range of materials, including by-products and wastes, comprising cereals, energy crops, grasses, aquaculture, and bovine products. It is worth noting that this is not an exhaustive list, but rather a diverse sample that provides insight into how the Bio-ERA Framework can be applied in practice. By exploring multiple case studies, insight is provided into the multi-systems thinking necessary to estimate environmental risks arising from increased demand for various bio-based feedstocks, as well providing a benchmark for the allocation of the various levels of environmental risk.

3. Results

3.1. Barley

Using the proposed Bio-ERA Framework, an increase in demand for barley grain in Ireland could pose high environmental risks across Finite Resource Inputs, GHG Emissions, Air Quality, Water Quality, Terrestrial Carbon storage, and Indirect Land Use Change, with Ecosystem Diversity carrying medium risk within an Irish context (Table 1). Specifically, as barley grain is the determining product of the production activity (Step 1 of Bio-ERA Framework), to meet any increased demand, barley production would be expanded or intensified. While direct intensification is unlikely in Ireland, given the already intensive crop systems, it may occur indirectly through displacement of production pressures overseas. In this scenario we assume that expansion of barley cropping area occurs, which could exacerbate the pressure on finite resources, particularly synthetic fertilisers, pesticides, and agricultural machinery (Lovarelli et al., 2020) (Fig. 5). These inputs carry notable upstream GHG burdens, as well as possible emissions from fuel combustion, nitrogen fertilisation, and liming (Guo et al., 2022). Additionally, the loss of nutrients and pesticides from these inputs into water bodies could lead to considerable water pollution, while the release of air pollutants such as particulate matter from fuel combustion and nitrogen oxides from fertiliser application could significantly impact air quality (Del Hierro et al., 2021). Increasing the demand for barley grain could lead to the conversion of natural ecosystems or (most likely in Ireland) agricultural grassland to cropland, resulting in the release of carbon from soil and vegetation (Mukumbuta and Hatano, 2020), as well as the possibility of Indirect Land Use Change from the displacement of livestock produced on grassland converted to cropland (Fig. 5). As a determining product and carrying high Probability of risk (Fig. 3) and high Severity of impact (Fig. 4), high risk is assigned to these environmental aspects for barley grain (Fig. 2). However, as barley crops (spring + winter) only cover about 186 kha of land in Ireland out of an agricultural area of circa 4.4 Mha (CSO, 2023), barley is not considered a dominant land cover. Thus, increasing barley production could potentially enhance Ecosystem Diversity at a landscape level. However, if new barley cultivation was concentrated in arable "pockets" it could introduce a monoculture aspect that reduces biodiversity in specific localities. Specific context is critical here, and uncertainty is captured in our assessment by attributing a medium risk of depleting Ecosystem Diversity (Figs. 2, 4).

If the increased demand for barley grain was achieved through enterprise swapping, *i.e.*, where a shift was made from another crop to

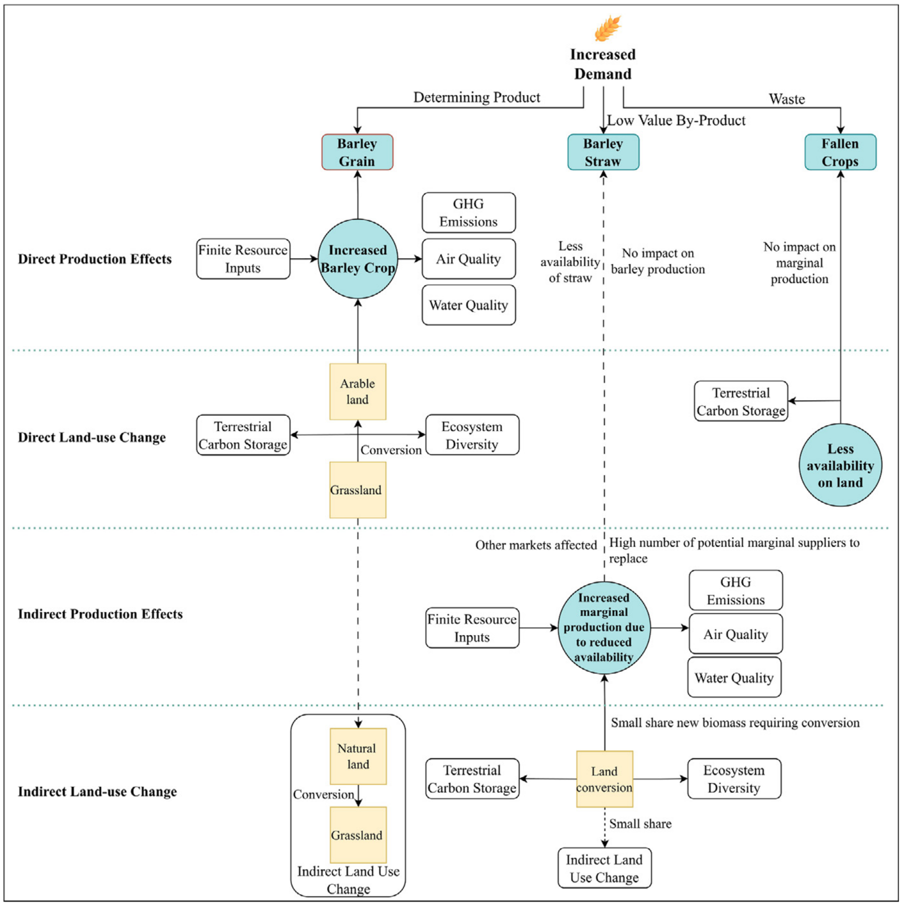

Fig. 5. Consequential thinking applied to the increased demand for three barley feedstocks, separated into direct and indirect production effects and land use change. Solid lines represent direct impacts, dotted lines signify indirect market impacts. Rounded boxes denote the seven environmental aspects covered.

Table 1
Environmental risk scores associated with an increased demand for various barley crop products. Risk scores: 3 = high risk (red), 2 = medium risk (yellow), 1 = low risk (green). Maximum overall environmental risk score is 21. CPP: constrained primary product; DP: determining product. LVBP: low-value by-product. W: waste.

Feedstock	Type	Finite resource inputs	GHG emissions	Indirect land use change	Terrestrial Carbon Storage	Ecosystem Diversity	Air Quality	Water Quality	Overall Environmental Risk	Actions
Barley grain	DP	3	3	3	3	2	3	3	**20**	Full consequential LCA urgently required to determine if downstream “credits” can mitigate high risks.
Barley straw	LVBP	2	2	2	2	2	2	2	**14**	Further investigation needed to determine consequences of displacing existing uses of straw.
Barley fallen crops	W	1	1	1	2	1	1	1	**8**	Low risk, proceed to next steps in planning. Soil C effects should be accounted for in full LCA (in due course).
Willow (woody stems)	DP	2	2	3	1	1	2	2	**13**	Further investigation needed to prepare indirect land use change mitigation actions and verify if carbon sequestration offsets risks.
Willow root system	W	1	1	1	2	1	1	1	**8**	Low risk, proceed to next steps in planning. Ensure full LCA accounts for soil carbon impacts at a later stage.
Willow bark	LVBP	2	2	2	2	2	2	2	**14**	Further investigation needed to determine consequences of displacing existing uses of willow bark.
Perennial ryegrass	DP	3	3	3	1	3	3	3	**19**	Urgent need for full consequential LCA to evaluate: (i) the potential for downstream “credits” to offset risks, and (ii) risk mitigation strategy efficacy.
White clover	DP	2	2	3	1	1	2	2	**13**	Develop detailed planning measures to minimise indirect land use change risks, demonstrated through full consequential LCA.
Beef meat	DP	3	3	3	2	3	3	3	**20**	Immediate need for consequential LCA to determine feasibility of downstream mitigation and risk mitigation strategies.
Beef hide	LVBP	2	2	2	2	2	2	2	**14**	Further investigation needed to determine consequences of displacing existing uses of hide.
Wild brown seaweed (unconstrained)	DP	2	2	1	1	1	2	2	**11**	Proceed to next project stage. Ensure sustainable harvesting practices and quantify downstream emissions impacts through a full LCA later.
Wild brown seaweed (constrained)	CPP	3	3	1	1	1	3	3	**15**	Investigate site-specific constraints and assess potential trade-offs of cultivation scenarios via full consequential LCA.

barley, the directly associated environmental risks could be a somewhat moderated compared to those listed in Table 1 — because overall agricultural inputs in the rotation, and arable land areas required, may remain similar. However, if the demand for the original displaced crops remains within the wider market, the risk of significant environmental impacts arising from Indirect Land Use Change, from pressure to cultivate the replaced crop elsewhere, would increase.

An increase in demand for barley straw may present medium risk for all environmental aspects (Table 1). The production of straw is constrained by the production of the barley grain and has relatively low market value, making it a low-value by-product (Fig. 3). As such, an increase in demand for barley straw would not lead to an increase in the production of barley but could result in a reduced availability of the straw for other uses (*e.g.*, water treatment, horticulture, animal bedding, soil carbon sequestration mitigation action, etc.). Consequently, additional production of equivalent functional products by unconstrained suppliers may be incurred by diversion of barley straw to the new bioeconomy use (Ekvall and Weidema, 2004), linked with medium Probability of environmental risk (Figs. 3, 5). Due to the low value of the barley straw, it may have lower market demand but be highly suitable for a wide range of applications. This could result in a high number of potential unconstrained suppliers, and so the "average" marginal production activity will carry medium Severity for all environmental aspects (Figs. 4, 5).

Fallen barley crops are typically considered waste products. As such, if there is an increase in demand for them as a bioeconomy feedstock, it is unlikely to result in the additional production of new biomass. Consequently, the environmental risks associated with Finite Resource Inputs, GHG Emissions, Air Quality, Water Quality, Ecosystem Diversity, and Indirect Land Use Change are considered low (Table 1). However, fallen crops are usually left on the field, where a portion of the carbon content of the crop can become sequestered in the soil (Chowdhury et al., 2021). Thus, removing this source of carbon input presents a medium environmental risk associated with Terrestrial Carbon storage (Fig. 5). As the nutrient content of the straw is also removed from the soil, the farmer may counter this with the application of additional synthetic fertiliser, though this is deemed outside the scope of this risk assessment.

3.2. *Willow*

An increase in demand for willow stems, as the determining product, could pose medium environmental risks across Finite Resource Inputs, GHG Emissions, Air Quality, and Water Quality, with high potential risk of Indirect Land Use Change, and low risk for Ecosystem Diversity and Terrestrial Carbon storage (Table 1). Despite the high Probability of risk occurrence for Finite Resource Inputs, GHG Emissions, Air Quality, and Water Quality (Fig. 3), the Severity of the environmental aspects within these aspects are low (Fig. 4). The cultivation of willow stems, a fast-growing and high-yield crop, requires relatively small inputs of fertilisers and fossil fuels, resulting in low environmental releases compared with most other crops (Yang et al., 2020) (Fig. 4). Willow crops also have a high potential to sequester carbon, especially in the above-ground biomass, whilst maintaining high soil carbon stocks (as a perennial crop), resulting in a low risk of negative Terrestrial Carbon Storage impacts (and indeed, possibility of an increase in terrestrial carbon storage) (Yang et al., 2020). Additionally, the potential for negative Ecosystem Diversity impacts from increasing willow (stem) production is considered low, given that willow is not a dominant "crop" within Ireland, even regionally, covering just 589 ha of national land area (Girón Domínguez and Gaffey, 2024). Nevertheless, like any crop, the expansion of willow production carries the potential for indirect land use change. Accurately predicting the type and impact of indirect land use change can be challenging. The Severity of these indirect land use impacts depends on the type of land displaced by the willow crop. For instance, arable land displacement may have a high Severity, productive grassland may have a medium Severity, and rough grassland may have a low Severity, due to varying amount of production that may be displaced (Fig. 4). Nonetheless, due to the uncertainty surrounding the exact land that would be affected, applying the precautionary principle suggests considering a high environmental risk of indirect land use change (Table 1).

Similar to by-product and waste products of barley (Section 3.1), increasing the demand for the low-value bark of willow carries medium environmental risk for all aspects considered, while the root system from felled trees has low risk for all aspects, except Terrestrial Carbon Storage. In this latter case, the sequestration of a portion of root carbon into the soil may be prevented, and increased soil disturbance will increase oxidation of soil carbon (Table 1). However, it is important to note that willow roots will only be available in relatively small quantities as a "waste" product at the end of plantation lifetimes, as willow is coppiced repeatedly for about 19–25 years (Harayama et al., 2020).

3.3. *Grass and clover*

Perennial ryegrass and white clover are widely used in pasture and forage systems in Ireland, but despite their similar uses, they have very different characteristics and potential environmental impacts. The proposed Bio-ERA Framework indicates that increasing demand for perennial ryegrass could pose high environmental risk across all environmental aspects covered except for Terrestrial Carbon, which carries low risk (Table 1). Perennial ryegrass has the potential to sequester considerable carbon in its below-ground biomass, though this does depend on where it is grown. For example, if the grass is grown on organic soils or previously wooded areas, there is high risk of carbon loss. However, in the context of Ireland, an increase in grass demand would likely be met primarily through the intensification of rough grazing or low input grassland. The intensive inputs required for perennial ryegrass production, such as synthetic fertilisers and agricultural machinery, will contribute significantly to GHG emissions, air, and water pollution, and may exacerbate pressure on constrained land, leading to indirect land use change if animal production is displaced (precautionary principle) — *e.g.*, if the grass was used as a feedstock in a biorefinery as opposed to feeding ruminants. Furthermore, the expansion of perennial ryegrass is likely to have negative impacts on Ecosystem Diversity, as it is the most common biomass arising in Ireland, covering over 3.3 Mha of land area in Ireland (Girón Domínguez and Gaffey, 2024). In contrast, an increase in demand for white clover may pose medium environmental risks across Finite Resource Inputs, GHG Emissions, Air Quality, and Water Quality, with high risk of Indirect Land Use Change, and low risk of negative impacts on Ecosystem Diversity and Terrestrial Carbon Storage (Table 1). As a determining product, while white clover carries a high Probability of impact occurrence (Fig. 3), it has low input requirements, as it can fix nitrogen from the air into a form that can be used by the plant (as well as the surrounding plants and soil) (Enriquez-Hidalgo et al., 2015). As such, the crop requires very low inputs of fertiliser application, and thus minimises environmental releases. High Probability with low Severity translates into medium risk scores (Fig. 2). Like perennial ryegrass, clover manifests a low risk for Terrestrial Carbon loss, and because clover is not a dominant land cover (Girón Domínguez and Gaffey, 2024), Ecosystem Diversity is also low risk. However, increasing white clover production could lead to indirect land use change should it displace animal production (*e.g.*, if not used for grazing) which may need to be produced elsewhere.

3.4. *Cattle*

Cattle-derived feedstocks, such as beef and hide can have varying degrees of environmental risk when their demand increases (Table 1). If there was an increase in demand for beef, as the determining product, cattle numbers would likely increase to satisfy the demand. This increase would have significant implications for direct GHG emissions and environmental releases from the animals, particularly from enteric methane and manure management emissions of methane and nitrous oxide (Mazzetto et al., 2020). Additionally, the increase would require increased production inputs (and thus increased emissions) and necessitate greater land area requirements (if intensification alone were not possible). This conversion of land into grass feed, specifically in the context of Ireland, presents similar potential risks identified for perennial ryegrass in Table 1, though with the additional animal emissions. Although manure deposits on land can enhance Terrestrial Carbon storage by sequestering a portion of the carbon within the soil, it is important to note that this carbon originates from the biomass consumed by the animals. If the biomass were left in place or if other biomass were allowed to grow, the potential for carbon storage could be greater. Consequently, Terrestrial Carbon Storage was assigned medium risk in this context.

Hide is a low-value by-product, constrained by the production of beef, that carries a medium Probability of environmental risk across all environmental aspects when its demand is increased (Fig. 3). An increased demand may result in increased supply of equivalent unconstrained functional products, leading to medium environmental risk for all aspects, as explained in Sections 3.1 and 3.2. However, it has been suggested that the current demand for hide may be lower than its production, effectively rendering it a 'waste' product (Porto Costa et al., 2023). As a result, if the feedstock demand is not high, it could pose low environmental risk across all aspects.

3.5. Wild seaweed

Wild seaweed in Ireland provides a distinctive, non-land-based case study. Despite the limited availability of wild resources, it has been noted that currently wild brown seaweed in Ireland is largely underextracted, suggesting that the resource is unconstrained (at least for now) (Mac and Morrison, 2020). With this in mind, although carrying high Probability of risk as a determining product, wild brown seaweed requires minimal inputs and generates low levels of emissions during production/extraction, resulting in medium environmental risk for Finite Resource Inputs, GHG Emissions, Air Quality, and Water Quality (Table 1). Further, increasing the demand for this widely available feedstock is likely to have minimal risk of Indirect Land Use Change, Ecosystem Diversity, and Terrestrial Carbon storage (Table 1). This is because the (unconstrained) wild seaweed does not need or compete with agricultural land or resources, so it is unlikely to result in the conversion of other land types for its production, though it may have positive impacts on marine biodiversity.

However, if the demand for wild brown seaweed were to increase to the point where the macroalgae become constrained, a similar scenario to the one described in Section 2.1.3 could arise, wherein an increase demand for the constrained feedstock increases wild seaweed price, the marginal consumers may choose the more affordable unconstrained farmed seaweed suppliers (or other potential suppliers that supply the same functioning product). This could significantly increase the upstream environmental risks associated with an increased demand for the brown seaweed, compared with the unconstrained impact risks (Table 1). Finite resource requirements and related emission risks from farmed seaweed account for these changes in risk (Collins et al., 2022). However, risks associated with Ecosystem Diversity would remain low as increasing brown seaweed production may provide valuable food and habitats for marine life. This case study further illustrates the context specificity of risk scores and suggests that screening scores for particular feedstocks will need to be reviewed and updated as markets evolve.

4. Discussion

4.1. Use of the Bio-ERA framework

The Bio-ERA Framework introduced in this study enables stakeholders to conduct early screening of potential environmental risks associated with increased demand for bio-based feedstocks in relevant (specific) contexts. By incorporating the principles of consequential life cycle thinking and considering the potential indirect effects across pertinent environmental aspects, Bio-ERA aims to equip stakeholders, such as prospective bio-industry managers, with a more comprehensive understanding of the environmental risks linked to feedstock sourcing decisions. This awareness raising can help to improve strategic consideration of bioeconomy risks and opportunities before significant resources are directed towards scoping studies — at a much earlier stage than when full consequential LCA may be undertaken. For example, where Bio-ERA identifies low environmental risk scores for a specific feedstock in a particular context (supported by transparent documentation of decision flows), this could provide confidence for stakeholders to justify initial investment in a scoping study for use of that feedstock for a particular purpose, to ascertain business viability. These studies can continue with project development without requiring immediate consequential LCA, though does not remove the need for consequential LCA entirely. Conversely, a feedstock identified as having a higher environmental risk could either be avoided, or ear-marked for early consequential LCA appraisal to validate the potential for upstream impacts and to ascertain whether these impacts could be offset by downstream benefits. Importantly, by providing timely insight into often hidden risks, Bio-ERA can avoid misallocation of resources to the development of risky feedstocks (or at least identify where additional information, or full consequential LCA, should be prioritised before any additional investment). This is important given that full consequential LCA is limited not just by time and funding, but by data availability, so that detailed results are often only generated after detailed planning has been undertaken to spec all processes (Holden, 2022) - at which point it may be too late to redirect the overall investment.

Holden (2022) proposed a stage-gate framework to guide bioeconomy innovation, delineating four key stages: (1) ideation, (2) prototyping, (3) validation, and (4) implementation. In this stage-gate framework, it proposed that in the initial ideation stage, which involves developing a bioeconomy concept, **life cycle thinking** should be introduced. It is not until the validation stage, which involves testing the innovation in an operational environment, that a **full consequential LCA** was recommended to be undertaken (Holden, 2022). The Bio-ERA Framework aligns with these principles by providing a tool for early environmental screening of potential bio-based feedstocks, grounded in consequential life cycle thinking, to support informed decision-making during the ideation stage. Like Holden (2022), we advocate for a full consequential LCA later in the project development cycle, informed by the early screening provided by the Bio-ERA Framework.

It should be emphasised that a high overall environmental risk score assigned to a particular feedstock should not automatically disqualify that feedstock from being considered as a potential source for bioeconomy products. Rather, it places the responsibility on producers using that feedstock to demonstrate effective risk mitigation strategies in the areas where high environmental risk is flagged, applying detailed consequential LCA to validate the environmental credentials of the entire project (value chain). For example, we show that increasing demand for grass feedstock can carry high risk due to land displacement (Table 1) — but a strategy to improve grassland productivity could mitigate this. Alternatively, linking feedstock supplies with systems transformation, such as introducing grass into crop rotations for soil improvement (Englund et al., 2023) or sourcing grass from land spared from excess livestock production (Bishop et al., 2024) could ensure low environmental risk compared with the appropriate counterfactual situation. In general, downstream environmental "credits" arising from new bio-based value chains can be maximised (and thus more likely outweigh any upstream impacts) where cascading uses of biomass can be realised to achieve multiple substitutions (and therefore credits) along the value chain. The Bio-ERA Framework recognises the importance of such value chains through the consequential logic applied, and encourages sourcing bioeconomy feedstocks from wastes or low-value by-products which tend to incur the lowest environmental risks due to no or small upstream production burdens. Previous research has highlighted that utilisation of waste feedstocks can have some of the best relative environmental performance of bio-based materials (*e.g.*, (Bishop et al., 2022; Osman et al., 2021; Styles et al., 2016)). Crucially, while the Bio-ERA Framework provides an early-stage "in-house" screening tool to inform internal (company) decision-making, it is not intended to replace the need for a full consequential LCA. At later stages of project development, producers bear the responsibility to conduct a comprehensive, independently verified consequential LCA and disclose the results to the public. Although Bio-ERA documentation may be less relevant for public consumption in early stages, it can be used to convey low environmental risk during project development if adequate documentation is provided.

Bio-ERA complements Strategic Environmental Assessment (SEA), which evaluates the environmental effects of policies, plans, and programs. While SEA provides a broad, policy-level assessment, the Bio-ERA Framework offers a more granular, feedstock-specific analysis, enabling stakeholders to identify upstream environmental risks early in the decision-making process. Unlike SEA, which typically focuses on broader strategic issues, Bio-ERA hones in on the potential impacts of specific bio-based feedstocks. Bio-ERA may also be useful to periodically (re-)assess environmental risks after particular bioeconomy investments have been made. The information generated could help companies to fulfil materiality responsibilities (Baumuller and Sopp, 2022) and support forthcoming detailed corporate reporting requirements across a broad range of environmental, social, and governance issues under the updated European Sustainability Reporting Standards (EFRAG, 2021). The insights generated through the screening process could also support the identification of environmental hotspots in existing supply chains, guiding stakeholders to target environmental sustainability actions and allocate resources effectively.

4.2. Limitations

The Bio-ERA Framework has some limitations. Firstly, while we have included several important environmental aspects, we recognise that the list is not exhaustive. For instance, we have not accounted for environmental risks from, *inter alia*, biodiversity loss or introduction of invasive species, human health, or water depletion, as well as other sustainability risks from social and economic aspects. However, considering the goal of the framework, which is to support rapid environmental screening at an early stage of feedstock sourcing decisions, with limited data availability, these areas are excluded. More comprehensive follow-on studies for priority feedstocks should consider these impacts. It is important to note that Bio-ERA does not consider any environmental aspect as more important than another, so equal weighting of the environmental aspects is proposed within the score summation step. In future iterations, differential weighting could be introduced if it is clearly documented, transparently justified, and rigorously validated to avoid the risk of greenwashing or biasing results

Secondly, the scope of the Bio-ERA Framework is limited to potential upstream impacts only (Fig. 1). The downstream impacts (negative or positive), which can include displaced fossil fuel production and other (expanded boundary) substitutions, can be substantial. As such, an assessed low environmental risk for a particular feedstock does not necessarily equate to good overall environmental performance for the bio-product produced from it, which depends on effects arising over the entire value chain. Rather, Bio-ERA results are intended to identify where more detailed assessment is required, and to support feedstock sourcing decisions at an early stage.

Thirdly, categorising feedstocks in terms of product types may be challenging as the classification of by-products and wastes can vary by location, industry, and market conditions. A by-product that is considered low-value in one market may be high-value (or a waste) in another market, depending on the balance between supply and demand, production costs, and the potential for value-added activities to increase its value. Even where a waste is correctly identified, Prosman and Sacchi (2016) noted that increasing the demand for waste feedstocks can create ripple effects in waste handling markets given that wastes are typically constrained — if you increase the demand for a waste, the waste-producing activity won’t increase production to accommodate this demand. This may limit specific waste feedstock availabilities in certain contexts, although given the scale of waste generation worldwide (Kaza et al., 2018), many waste sources may remain effectively unconstrained in many contexts in the near term. Should we ever reach a critical juncture where “waste” has been fully exploited, the bioeconomy goal of promoting systems transformation to a truly circular bioeconomy will have been achieved (European Commission, 2018a). Nevertheless, when a waste stream becomes valorised or there is innovation in its use, this could impact on the potential demand. While supply is judged to be relatively inelastic in the default position, there is likely a threshold where the increased utilisation affects the value of “waste”, impacting not just on territorial flows but a reconsideration of the supply chains from which the waste arises, and a reclassification away from “waste” to “by-product”. This context and temporal dependency can be reflected by ensuring feedstock classifications are appropriate to the place and the time horizon of analysis, considering prospective technologies for “waste” conversion where relevant for forward-looking investment decisions. Further, in line with consequential LCA, Bio-ERA screening should be undertaken for the anticipated scale and time horizon of production, *e.g.*, over the coming five-ten years, so as to capture the medium- to long-term and scale-related effects. In the short-term (one year), it may be possible to meet the increased demand for specific bio-based feedstocks without incurring indirect effects. However, an imbalance of supply and demand will manifest over time, changing the market equilibrium between supply and demand across the feedstock in question and also across potentially related (substitutable) materials.

Finally, although the Bio-ERA Framework provides a clear structure for decision making, practitioners will be required to apply value-judgements on specific aspects (*e.g.*, Severity of impact) that may often be difficult to validate, especially for indirect risks. Although we have provided guidelines for Severity risk ranking, it may be tempting to assign “high risk” to every environmental aspect if considering the worst-case scenario for each selection (or vice versa, depending on user perspective). As this methodology does not require the identification of specific unconstrained suppliers for the constrained feedstocks, it is important to consider a relative assessment of the environmental risks, using the precautionary principle only in cases where there are marginal differences between rankings. In any case, maintaining a focus on transparency and documentation is the over-riding priority to allow for scrutiny and refinement of judgement over time. Scoring may evolve through user experience, so is best suited for relative screening, especially as results are highly scenario specific. As such, it should be emphasised that the Bio-ERA framework is not intended to demonstrate compliance with regulation or conformance with particular standards, nor to supplant LCA, but is intended for use as a decision support tool to facilitate sustainable feedstock acquisition and to raise awareness around potentially under-appreciated environmental impact pathways. Ultimately it is up to users to adhere to the Framework’s principles and documentation requirements in order to derive meaningful value from it, and to convince stakeholders of the validity of any disseminated screening results. It is essential to recognise that the screening process is both time and context-specific, offering insights rather than definitive “answers” on environmental sustainability. Thus, the main strength of this Framework lies not in the scores themselves but in the *process* it facilitates, serving as a valuable decision-support tool for enhancing critical awareness of systems thinking and the environmental sustainability risks associated with feedstock selection in the bioeconomy.

5. Conclusion

The Bio-ERA Framework provides a structured approach to guide a broad audience of stakeholders through consequential life cycle thinking, revealing indirect environmental impacts stemming from future market signals associated with particular feedstock sourcing decisions. Addressing seven critical environmental aspects, Bio-ERA provides stakeholders with a broad, multi-dimensional evaluation of potential environmental risks associated with increasing demand for any particular bio-based feedstock. This can empower decision makers to make informed judgements at the nascent stages of project development, underscoring the framework's aim in guiding strategic and sustainable investment decisions in the bioeconomy. While the Bio-ERA Framework facilitates rapid screening and awareness of potential environmental risks, it is essential to acknowledge its complementary nature to detailed consequential LCA (which is typically undertaken at later stages of project development). Despite the structured approach, final scores are ultimately subject to value judgement and some degree of uncertainty. Thus, Bio-ERA does not avoid the need for detailed LCA evaluation of promising bioeconomy projects, but instead promotes deeper interrogation and awareness of potential environmental risks at an early stage of project conceptualisation, in a manner that is accessible to all stakeholders. It could therefore guide more strategic and sustainable early scoping of investment decisions in the bioeconomy. This approach avoids the risk of undertaking consequential LCA in high-risk projects only after considerable resources have been committed, when it might be too late to redirect investment towards more sustainable options. Through awareness-raising and early integration into decision-making, Bio-ERA could support strategic, responsible, and efficient utilisation of often constrained bio-based resources as society strives to develop a sustainable, circular bioeconomy.

CRediT authorship contribution statement

George Bishop: Writing – original draft, Visualization, Methodology, Conceptualization. **Carmen Girón-Domínguez:** Writing – review & editing, Validation. **James Gaffey:** Writing – review & editing, Validation, Funding acquisition. **Maeve Henchion:** Writing – review & editing, Validation. **Réamonn Fealy:** Writing – review & editing, Validation. **Jesko Zimmermann:** Writing – review & editing, Validation. **Wriju Kargupta:** Writing – review & editing, Validation. **David Styles:** Writing – review & editing, Validation, Methodology, Conceptualization.

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.

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References

2.-0 LCA Consultants, 2015. Determining or dependent co-products? [WWW Document].

Awerunse, O.S., Olorunsola, H.A., Ahuekwe, E.F., Obembe, O.O., 2023. Towards a sustainable bioeconomy in a post-oil era Nigeria. Resour. Environ. Sustain. 11, 100094. http://dx.doi.org/10.1016/J.RESENV.2022.100094.

Baumuller, J., Sopp, K., 2022. Double materiality and the shift from non-financial to European sustainability reporting: review, outlook and implications. J. Appl. Account. Res. 23, 8–28. http://dx.doi.org/10.1108/JAAR-04-2021-0114.

Bishop, G., Duffy, C., Prudhomme, R., Cowie, A., O'Donoghue, C., Cain, M., Lanigan, G.J., Styles, D., 2024. Defining national net zero goals is critical for food and land use policy. Commun. Earth Environ. 5, 1–11. http://dx.doi.org/10.1038/s43247-024-01275-0, 1 5.

Bishop, G., Styles, D., Lens, P.N.L., 2022. Land-use change and valorisation of feedstock side-streams determine the climate mitigation potential of bioplastics. Resour Conserv. Recycl. 180, http://dx.doi.org/10.1016/j.resconrec.2022.106185.

Brandão, A.S., Gonçalves, A., Santos, J.M.R.C.A., 2021. Circular bioeconomy strategies: From scientific research to commercially viable products. J. Clean. Prod. 295, 126407. http://dx.doi.org/10.1016/J.JCLEPRO.2021.126407.

Chowdhury, S., Bolan, N., Farrell, M., Sarkar, B., Sarker, J.R., Kirkham, M.B., Hossain, M.Z., Kim, G.H., 2021. Role of cultural and nutrient management practices in carbon sequestration in agricultural soil. Adv. Agron. 166, 131–196. http://dx.doi.org/10.1016/BS.AGRON.2020.10.001.

Collins, N., Kumar Mediboyina, M., Cerca, M., Vance, C., Murphy, F., 2022. Economic and environmental sustainability analysis of seaweed farming: Monetizing carbon offsets of a brown algae cultivation system in Ireland. Bioresour. Technol. 346, 126637. http://dx.doi.org/10.1016/J.BIORTECH.2021.126637.

CSO, 2023. Crops and Livestock Provisional 2023 [WWW Document]. Central Statistics Office, URL https://www.cso.ie/en/releasesandpublications/ep/p-clsjp/cropsandlivestockprovisionaljune2023/ (accessed 3.8.24).

Dallendörfer, M., Dieken, S., Henseleit, M., Siekmann, F., Venghaus, S., 2022. Investigating citizens' perceptions of the bioeconomy in Germany – High support but little understanding. Sustain. Prod. Consum. 30, 16–30. http://dx.doi.org/10.1016/J.SPC.2021.11.009.

Del Hierro, Ó., Gallejones, P., Besga, G., Artetxe, A., Garbisu, C., 2021. A comparison of IPCC guidelines and allocation methods to estimate the environmental impact of barley production in the basque country through life cycle assessment (LCA). Agriculture 11, 1005. http://dx.doi.org/10.3390/AGRICULTURE11101005.

EFRAG, 2021. Proposals for a Relevant and Dynamic EU Sustainability Reporting Standard Setting. Brussels, European Financial Reporting Advisory Group.

Ekvall, T., 2019. Attributional and consequential life cycle assessment. Sustainability Assessment at the 21st century 395, 1–22. http://dx.doi.org/10.5772/INTECHOPEN.89202.

Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. Life Cycle Assess. 9, 161–171. http://dx.doi.org/10.1007/BF02994190.

Englund, O., Mola-Yudego, B., Börjesson, P., Cederberg, C., Dimitriou, I., Scarlat, N., Berndes, G., 2023. Large-scale deployment of grass in crop rotations as a multifunctional climate mitigation strategy. GCB Bioenergy 15, 166–184. http://dx.doi.org/10.1111/GCBB.13015.

Enriquez-Hidalgo, D., Gilliland, T.J., Hennessy, D., 2015. Herbage and nitrogen yields, fixation and transfer by white clover to companion grasses in grazed swards under different rates of nitrogen fertilization. Grass Forage Sci. 71, 559–574. http://dx.doi.org/10.1111/GFS.12201.

European Commission, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General Guide for Life Cycle Assessment - Detailed Guidance. Luxembourg.

European Commission, 2018a. A sustainable bioeconomy for Europe : strengthening the connection between economy, society and the environment : updated bioeconomy strategy. Luxembourg.

European Commission, 2018b. Bioeconomy: the European way to use our natural resources. http://dx.doi.org/10.2777/79401, Action plan 2018. Brussels.

European Commission, 2018c. PEFCR Guidance Document, - Guidance for the Development of Product Environmental Footprint Category Rules (PEFCRs) 1–238.

European Commission, 2019. The European Green Deal. COM/2019/640 final. Brussels.

European Commission, 2020. A New Circular Economy Action Plan. COM(2020) 98 final. Brussels.

European Commission, 2022. European Bioeconomy Policy – Stocktaking and Future Developments – Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Publications Office of the European Union.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J Env. Manag. 91, 1–21. http://dx.doi.org/10.1016/J.JENVMAN.2009.06.018.

Gaffey, J., McMahon, H., Marsh, E., Vehmas, K., Kymäläinen, T., Vos, J., 2021. Understanding consumer perspectives of bio-based products—A comparative case study from Ireland and The Netherlands. Sustainability 13 (6062), http://dx.doi.org/10.3390/SU13116062.

Giri, S., Qiu, Z., 2016. Understanding the relationship of land uses and water quality in twenty first century: A review. J. Env. Manag. 173, 41–48. http://dx.doi.org/10.1016/J.JENVMAN.2016.02.029.

Girón Domínguez, C., Gaffey, J., 2024. Quantification of Biological Raw Materials for Ireland's Bioeconomy. Ireland.

Guo, C., Liu, X., He, X., 2022. A global meta-analysis of crop yield and agricultural greenhouse gas emissions under nitrogen fertilizer application. Sci. Total Environ. 831, 154982. http://dx.doi.org/10.1016/J.SCITOTENV.2022.154982.

Harayama, H., Uemura, A., Utsugi, H., Han, Q., Kitao, M., Maruyama, Y., 2020. The effects of weather, harvest frequency, and rotation number on yield of short rotation coppice willow over 10 years in northern Japan. Biomass Bioenergy 142, 105797. http://dx.doi.org/10.1016/J.BIOMBIOE.2020.105797.

Heimann, T., 2019. Bioeconomy and SDGs: Does the bioeconomy support the achievement of the sdgs? Earths Futur. 7, 43–57. http://dx.doi.org/10.1029/2018EF001014.

Holden, N.M., 2022. A readiness level framework for sustainable circular bioeconomy. EFB Bioeconomy J. 2, 100031. http://dx.doi.org/10.1016/J.BIOECO.2022.100031.

Igos, E., Benetto, E., Meyer, R., Baustert, P., Othoniel, B., 2019. How to treat uncertainties in life cycle assessment studies? Int. J. Life Cycle Assess. 24, 794–807. http://dx.doi.org/10.1007/s11367-018-1477-1.

Ingrao, C., Wojnarowska, M., 2023. Findings from a streamlined life cycle assessment of PET-bottles for beverage-packaging applications, in the context of circular economy. Sci. Total Environ. 892, 164805. http://dx.doi.org/10.1016/J.SCITOTENV.2023.164805.

Isbell, F., Adler, P.R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D.K., Liebman, M., Polley, H.W., Quijas, S., Scherer-Lorenzen, M., 2017. Benefits of increasing plant diversity in sustainable agroecosystems. J. Ecol. 105, 871–879. http://dx.doi.org/10.1111/1365-2745.12789.

ISO, 2020a. ISO 14044:2006/Amd 2:2020 - Environmental Management — Life Cycle Assessment — Requirements and Guidelines — Amendment 2. International Organization for Standardization, Geneva, Switzerland.

ISO, 2020b. ISO 14040:2006/Amd 1:2020 - Environmental Management — Life Cycle Assessment — Principles and Framework — Amendment 1. International Organization for Standardization, Geneva, Switzerland.

Kaza, S., Yao, L., Bhada-Tata, P., Van Woerden, F., 2018. What a Waste 2.0 a Global Snapshot of Solid Waste Management to 2050. Washington, DC.

Kriebel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., Loechler, E.L., Quinn, M., Rudel, R., Schettler, T., Stoto, M., 2001. The precautionary principle in environmental science. Environ. Health Perspect. 109, 871–876. http://dx.doi.org/10.1289/EHP.01109871.

Lasarte-López, J., Grassano, N., M'barek, R., Ronzon, T., 2023. Bioeconomy and resilience to economic shocks: insights from the COVID-19 pandemic in 2020. Bio-based Appl. Econ. 12, 367–377. http://dx.doi.org/10.36253/BAE-14827.

Liobikienė, G., Miceikiene, A., 2023. Contribution of the European bioeconomy strategy to the green deal policy: Challenges and opportunities in implementing these policies. Sustainability 15, 7139. http://dx.doi.org/10.3390/SU15097139.

Lovarelli, D., Garcia, L.R., Sánchez-Girón, V., Bacenetti, J., 2020. Barley production in Spain and Italy: Environmental comparison between different cultivation practices. Sci. Total Environ. 707, 135982. http://dx.doi.org/10.1016/J.SCITOTENV.2019.135982.

Lucas, P.U., Gamborg, C., Lund, T.B., 2022. Sustainability concerns are key to understanding public attitudes toward woody biomass for energy: A survey of Danish citizens. Renew. Energy 194, 181–194. http://dx.doi.org/10.1016/J.RENENE.2022.05.075.

Mac, Monagail M., Morrison, L., 2020. The seaweed resources of Ireland: a twenty-first century perspective. J. Appl. Phycol. 32, 1287–1300. http://dx.doi.org/10.1007/S10811-020-02067-7/FIGURES/3.

Mazzetto, A.M., Bishop, G., Styles, D., Arndt, C., Brook, R., Chadwick, D., 2020. Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems. J. Clean. Prod. 277, http://dx.doi.org/10.1016/j.jclepro.2020.124108.

Mukumbuta, I., Hatano, R., 2020. Do tillage and conversion of grassland to cropland always deplete soil organic carbon? Soil Sci. Plant Nutr. 66, 76–83. http://dx.doi.org/10.1080/00380768.2019.1676135.

Osman, A.I., Mehta, N., Elgarahy, A.M., Al-Hinai, A., Al-Muhtaseb, A.H., Rooney, D.W., 2021. Conversion of biomass to biofuels and life cycle assessment: a review. Environ. Chem. Lett. 19 (6), 4075–4118. http://dx.doi.org/10.1007/S10311-021-01273-0.

Pawelzik, P., Carus, M., Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., Weiss, M., Wicke, B., Patel, M.K., 2013. Critical aspects in the life cycle assessment (LCA) of bio-based materials - reviewing methodologies and deriving recommendations. Resour. Conserv. Recycl. 73, 211–228. http://dx.doi.org/10.1016/j.resconrec.2013.02.006.

Pelton, R.E.O., Smith, T.M., 2015. Hotspot scenario analysis. J. Ind. Ecol. 19, 427–440. http://dx.doi.org/10.1111/JIEC.12191.

Porto Costa, M., Saget, S., Zimmermann, B., Petig, E., Angenendt, E., Rees, R.M., Chadwick, D., Gibbons, J., Shrestha, S., Williams, M., Styles, D., 2023. Environmental and land use consequences of replacing milk and beef with plant-based alternatives. J. Clean. Prod. 424, 138826. http://dx.doi.org/10.1016/J.JCLEPRO.2023.138826.

Prosman, E.J., Sacchi, R., 2016. New environmental supplier selection criteria for circular supply chains: Lessons from a consequential LCA study on waste recovery. J. Clean. Prod. 172, 2782–2792. http://dx.doi.org/10.1016/J.JCLEPRO.2017.11.134.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9, http://dx.doi.org/10.1126/SCIADV.ADH2458/SUPPL_FILE/SCIADV.ADH2458_SM.PDF.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., De Wit, C.A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature http://dx.doi.org/10.1038/461472a.

Ronzon, T., Sanjuán, A.I., 2020. Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. J. Clean. Prod. 254, 119832. http://dx.doi.org/10.1016/J.JCLEPRO.2019.119832.

Santos, J., Pizzol, M., Azarijafari, H., 2022. Life cycle assessment (LCA) of using recycled plastic waste in road pavements: Theoretical modeling. Plast. Waste Sustain. Asph. Roads 27, 3–302. http://dx.doi.org/10.1016/B978-0-323-85789-5.00014-9.

Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., Benetto, E., 2021. Attributional & consequential life cycle assessment: Definitions, conceptual characteristics and modelling restrictions. Sustainability 13, 7386. http://dx.doi.org/10.3390/SU13137386.

Schippers, P., van der Heide, C.M., Koelewijn, H.P., Schouten, M.A.H., Smulders, R.M.J.M., Cobben, M.M.P., Sterk, M., Vos, C.C., Verboom, J., 2015. Landscape diversity enhances the resilience of populations, ecosystems and local economy in rural areas. Landsc. Ecol. 30, 193–202. http://dx.doi.org/10.1007/S10980-014-0136-6/FIGURES/3.

Schmidt, J.H., Weidema, B.P., Brandão, M., 2015. A framework for modelling indirect land use changes in life cycle assessment. J. Clean. Prod. 99, 230–238. http://dx.doi.org/10.1016/j.jclepro.2015.03.013.

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Sci. (1979) 347, 1259855. http://dx.doi.org/10.1126/science.1259855.

Styles, D., Dominguez, E.M., Chadwick, D., 2016. Environmental balance of the UK biogas sector: An evaluation by consequential life cycle assessment. Sci. Total Environ. 560–561, 241–253. http://dx.doi.org/10.1016/j.scitotenv.2016.03.236.

Tonini, D., Hamelin, L., Astrup, T.F., 2016. Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes. GCB Bioenergy 8, 690–706. http://dx.doi.org/10.1111/gcbb.12290.

UNEP, 2011. Global Guidance Principles for Life Cycle Assessment Databases. A Basis for Greener Processes and Products. United Nations Environmental Programme, UNEP/SETAC Life Cycle Initiative, Paris/Pensacola.

Verghese, K.L., Horne, R., Carre, A., 2010. PIQET: The design and development of an online streamlined LCA tool for sustainable packaging design decision support. Int. J. Life Cycle Assess. 15, 608–620. http://dx.doi.org/10.1007/S11367-010-0193-2/FIGURES/5.

Wang, Y., Levis, J.W., Barlaz, M.A., 2021. Development of streamlined life-cycle assessment for the solid waste management system. Environ. Sci. Technol. 55, 5475–5484. http://dx.doi.org/10.1021/ACS.EST.0C07461/ASSET/IMAGES/LARGE/ES0C07461_0008.JPEG.

Weidema, B.P., Ekvall, T., Heijungs, R., 2009. Guidelines for Application of Deepened and Broadened LCA. Rome, ENEA, The Italian National Agency on new Technologies, Energy and the Environment.

Weidema, B.P., Frees, N., Nielsen, A.M., 1999. Marginal production technologies for life cycle inventories. Int. J. Life Cycle Assess. 4, 48–56. http://dx.doi.org/10.1007/BF02979395/METRICS.

Weidema, B.P., Pizzol, M., Schmidt, J., Thoma, G., 2018. Attributional or consequential life cycle assessment: A matter of social responsibility. J. Clean. Prod. 174, 305–314. http://dx.doi.org/10.1016/j.jclepro.2017.10.340.

WHO, 2006. Air Quality Guidelines: Global Update 2005 : Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. World Health Organization, Germany.

Yang, S., Volk, T.A., Fortier, M.O.P., 2020. Willow biomass crops are a carbon negative or low-carbon feedstock depending on prior land use and transportation distances to end users. Energies 13, 4251. http://dx.doi.org/10.3390/EN13164251.