

Circular economy monitoring – how to make it apt for biological cycles?

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Highlights

1. Existing circular economy (CE) monitors, mainly, assess the extent to which resources are looped back in the economy and seem less apt for assessing the circularity of biological cycles.
2. Characteristics of biological cycles, that distinguish them from technical cycles, are their renewability, potential use in cascading, closing the biological nutrient loop, and the environmental impact of biotic resources depletion, land-use and biogenic carbon flows.
3. These characteristics need to be added to CE monitoring criteria, to ensure the sustainable and circular use of natural resources.

Abstract

Circular economy (CE) principles distinguish between technical and biological cycles. Technical cycles involve the management of stocks of non-renewable abiotic resources that cannot be appropriately returned to the biosphere, whereas, biological cycles involve the flows of renewable biotic resources that can safely cycle in and out of the biosphere. Despite this distinction, existing CE monitors are typically developed for technical cycles, and focus mainly on the extent to which resources are looped back in the technosphere. These monitors seem less apt to assess the circularity of biological cycles. This study aims to identify this gap by critically reviewing the CE monitoring criteria and CE assessment tools, and evaluate if they include the four key characteristics of biological cycles.

Firstly, biotic resources, although renewable, require to be harvested sustainably. Secondly, while abiotic resources can be restored and recycled to their original quality, biotic resources degrade in quality with every subsequent use and are, hence, cascaded with every application. Thirdly, biotic resources should safely return as nutrients to the biosphere to support the regeneration of ecosystems. Fourthly, biological cycles have environmental impacts due to resource extraction, resulting from land-use and resource-depletion and biogenic carbon flows. The CE monitoring criteria lack in thoroughly assessing these characteristics. With the growing demand for biotic resources, the gap in the assessment could exacerbate the overexploitation of natural resources and cause the degradation of ecosystems. The study discusses measures to bridge this gap and suggests ways to design a CE assessment framework that is also apt for biological cycles.

Keywords

Bioeconomy, Circular economy indicators, Sustainable sourcing, Cascading, Biological nutrient cycling, Land-use impact, Resource depletion

Glossary

Abiotic resources	Abiotic resources are inorganic (such as metals or minerals), non-living matter (such as fossil fuels) or synthetic material from non-living matter (such as fossil-based plastic). These resources are non-renewable or finite by nature.
Bio-based materials	Materials derived from biomass
Bio-economy	Economy pertaining to production of biotic resources and their conversion into food, feed, biobased material and energy.
Biocomposites	Composites made of a mixture of plastic polymers and natural fibers, such as wood (wood-plastic composites) or agricultural crops.
Biodegradability	Refers to the capability of being degraded under the action of micro-organisms.
Biological cycles	Biological cycles, typically described by the left-hand side of Ellen MacArthur (EMF) butterfly diagram, contain materials that can safely cycle in and out of the biosphere (Ellen MacArthur Foundation, 2017). Hence, in this cycle, the resources are harvested from ecosystems, cascaded through several material-applications, and at the end of their product life decompose to re-enter biosphere and restore the natural capital. Although, it would be more appropriate to refer to it as ‘biogeochemical cycle’ because on decomposition the materials cycle through both biotic (biosphere) and abiotic (lithosphere, atmosphere, and hydrosphere) compartments of earth.
Biotic resources	Biotics resources are living organic matter produced by the biological system using atmospheric carbon and solar energy (e.g. wood, silk). These resources are intrinsically renewable in nature.
Biosphere	Part of the Earth and its atmosphere occupied by living organisms.
Biopolymers	Polymers produced from living organisms.
Dissipative losses	The losses to the environment. The material that is unrecoverable, and thus for which recycling is inherently not feasible.
Material	Material is a substance that constitutes an object. In this paper, the term material is used synonymously with the term substance.
Resource	A ‘resource’ is considered as such when it has an intrinsic ‘value’ or ‘utility’ for humans (Beylot et al., 2020), encompassing abiotic (fossils and minerals) and biotic (biomass) resources.
Resource quality	The definition of resource quality has been derived from the definition proposed by Sirkin and Houten (1994). It is the measure of potential resource utility - the capacity to perform tasks of various degrees of difficulty. It is the potential (re-)usability, recoverability and recyclability of the material. In this paper, the term ‘material-value’ is used synonymously with ‘resource-quality’.
Technical cycles	Technical cycles, typically described by the right-hand side of Ellen MacArthur Foundation butterfly diagram, contain flows of materials that cannot be appropriately returned to the biosphere (Ellen MacArthur Foundation, 2017, 2015). Hence, technical cycles are designed to circulate resources in the technosphere as long as possible, without entering the biosphere
Technosphere	Refers to the human system, i.e. the physical environment built or modified by humans, which is a sub-system to the biosphere.

1. Introduction

Circular Economy (CE) is an approach to promote sustainable use of resources and address environmental challenges. CE has its conceptual roots in industrial ecology, which envisions a material symbiosis between different industries and production processes (Andersen, 2007). Industrial ecology emphasizes that these linkages enable the use of residual waste and by-products of one industry as a feedstock for other industries. This improves overall resource efficiency and hence reduces the use of virgin resources and emissions to the environment.

The CE principles distinguish between technical and biological cycles (Braungart et al., 2007; Ellen MacArthur Foundation, 2015). The distinction between these cycles is well illustrated in the CE 'butterfly diagram' by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015). Technical cycles involve managing non-renewable stocks of abiotic resources and the flows of materials that cannot be appropriately returned to the biosphere. Whereas, biological cycles contain the flows of renewable biotic resources that can safely cycle in and out of the biosphere. Abiotic resources are finite, and hence, technical cycles are designed such that the resources can be looped back in the technosphere for as long as possible. Once mined (in the case of inorganic materials) or produced (in the case of synthetic materials), their value is preserved as much as possible by prioritizing the so-called inner cycles (i.e. maintenance, reuse, repair), maximizing the number of consecutive cycles and increasing the time spent in each cycle (Ellen MacArthur Foundation, 2015). On the other hand, in biological cycles, the products are designed with the intention to be consumed or to be used in cascading and subsequently decompose to re-enter the biosphere (Bocken et al., 2016; Braungart et al., 2007). It should be acknowledged that the distinction between technical and biological cycles is not straightforward. In reality, biotic resources are mixed with abiotic resources to make products. Biotic resources are also used to make products that are not biodegradable, making them characteristic of technical cycles; most notable are the drop-in polymers such as bio-based polyethylene (European Environmental Agency, 2018). On the other hand, there are products of abiotic origin that are bio-degradable, such as fossil-based biodegradable polymer polybutylene adipate-co-terephthalate (PBAT), which is typical of material in biological cycles.

Having had its origins in industrial ecology, CE discussions and assessments today often have a narrow focus on technical cycles. Although the CE concepts have been extended to biological cycles, the CE assessment and monitoring seem insufficiently adapted to biological cycles (Haas et al., 2020; Leipold and Petit-Boix, 2018). A Google Scholar search for the term 'circular economy' combined with 'biological' or 'biobased' (in the title, keywords or abstract) delivers a total of only 25 results (Annex A). The majority of the articles center around (1) the design of products, supply-chain, bio-refineries and business models and (2) the conceptual distinction between technical and biological cycles. Concrete research on CE assessment criteria and monitoring specifically for biological cycles or inclusive of biological cycles seems to be lacking (Haas et al., 2020). In biological cycles, resources should be cascaded in the application and eventually returned to the biosphere to become valuable feedstock for a new cycle (Ellen MacArthur Foundation, 2015). However, most CE monitors mainly assess the extent to which resources are looped back in the economy; little attention has been paid to assessing the cascading use and the extent to which biotic resources at the end of their life decompose, release the nutrients to the biosphere and foster the regeneration of the ecological systems. Robust criteria or comprehensive indicators to quantify the fraction of biotic resources that sustainably close the nutrient cycle are still unavailable (Haas et al., 2020).

This could also be stemming from the popular notion that the use of biotic resources is circular and sustainable by its nature (Haas et al., 2020; Hetemäki et al., 2017). However, this assumption is not

necessarily valid. There are several examples, in particular of bio-fuels (Fargione et al., 2008; Koh and Ghazoul, 2008; Searchinger et al., 2008), wherein shift to biomass has led to overexploitation of forest resources, land-use change, biodiversity loss and increased competition for land for food and feed. Hence, assessing the circularity of biological cycles and their impact on the ecosystem is essential.

Against this backdrop, this study aims to highlight the gaps in current CE monitoring in assessing the circularity of biological cycles and to identify the modifications required to adequately assess them. Identifying and acknowledging this gap is crucial and could then serve as a guideline for designing a thorough framework for assessing the progress towards the CE that is inclusive of biological cycles. This could potentially make way to more sustainable and circular use of natural resources and avoid further degradation of ecosystems.

2. Methods and materials

2.1. Research design

The methodology followed a series of steps, a graphical representation of which is in Fig. 1. The first step, to achieve the research objective, was to identify the criteria for assessing and monitoring CE (step 1 in Fig. 1), i.e. the criteria validating the progress towards CE. This was based on the definition of CE principles. However, there is no one agreed definition of CE. Thus, the CE definitions by themselves were not sufficient to derive the CE monitoring criteria. A study of CE practices, adopted by various stakeholders, was needed to deduce the guiding principles for CE implementation strategies (i.e. what should the CE strategies aim to achieve) and determine the widely accepted CE assessment criteria (i.e. what measures indicate the transition towards a CE). This was done by studying the CE implementation strategies (Kalmykova et al., 2018) and the CE assessment criteria (Corona et al., 2019; Elia et al., 2017) identified by the CE review papers.

The second step was to identify the characteristics of biological cycles. This literature-based study started with the key sources Bocken et al. (2016), Ellen MacArthur Foundation(2017, 2010), European Environmental Agency (2018), Hetemäki et al. (2017). These sources provide guidelines for the design of the biological cycle to enable closing the biological nutrient loop. The search was then followed by a semi-structured snowballing literature study. The snowballing started with shortlisting the fundamental characteristics that distinguish biological cycles from technical cycles, based on the sources mentioned above. These characteristics were then studied in depth by a systematic review of literature from that specific field.

The third step was to evaluate if the CE monitoring criteria are sufficient to assess the characteristics of biological cycles. The study was further extended to analyze the current CE monitors - to study if they inherently assess the characteristics specific to the biological cycle (step 4). Step 3 and step 4 enable to highlight the gaps in current CE monitoring criteria and serve as a guideline for the adaptation required to make them inclusive of the biological cycle.

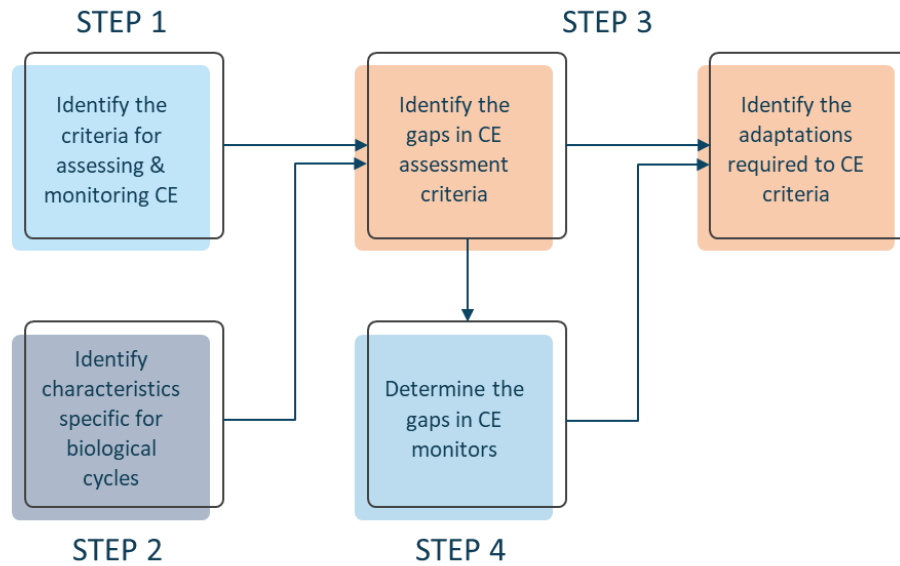


Figure 1: Research design – Illustration of steps followed to evaluate if (1) current criteria for CE monitoring are apt for assessing circularity of biological cycles (2) current CE monitors consider the characteristics of the biological cycle in the circularity assessment

2.2. Reviewing existing CE monitors

Numerous monitoring tools of circularity assessment – in the form of indicators, metrics, frameworks – have been developed in the last few years. The question relevant for this study is - how many of these CE monitors evaluate the criteria for circularity of biological cycles. Additionally, the CE monitors that evaluate those criteria do so to what extent.

Firstly, the current CE monitors were listed, which was done by a systematic literature review (Annex B provides the complete list of indicators studied). Here, a monitor is defined as a quantitative measure of progress towards achieving an objective. Consequently, the search included broad fields of quantitative assessments of CE, i.e. CE indices, indicators, metrics. The identification of CE metrics started with the search of the literature on the circular economy via Scopus and Google Scholar, using combinations of search words: ‘circular economy’, ‘circularity’, ‘evaluation’, ‘assessment’, ‘measure’, ‘indicators’, ‘indices’, ‘index’, and ‘metrics’ for the database search in title, abstract and keywords fields.

TITLE-ABS-KEY (("Circular economy" OR "Circularity") AND ("measure" OR "metric" OR "evaluation" OR "assessment" OR "indicators" OR "indices" OR "index"))

In addition to the literature search, review papers on CE indicators were studied to ensure the completeness of the list (Corona et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019; Rossi et al., 2020; Saidani et al., 2019). The most extensive list of CE indicators was published by Saidani et al. (2019), who reviewed 55 CE monitors. Some sources, mainly, Parchomenko et al. (2019) and Corona et al. (2019) consider even those indicators that are not specific to CE assessment but could potentially be useful for CE monitoring. These indicators were not included in this study, to maintain the focus only on CE monitors.

The analysis resulted in 59 sets of CE metrics, coming from 40 journal papers, 12 technical reports, and 7 websites. The search for CE monitors was kept broad to include the CE monitors at different levels of implementation (micro, meso and macro), in different sectors (construction, manufacturing etc.), and across different countries. The CE monitors specific to technical cycles were also included.

Out of the 59 indicators, 23 indicators were developed for a specific industry or were demonstrated using a case study from a particular industry. Out of these, 21 were on material or industry of technical sectors. For example, Graedel et al. (2011) focus on the recycling rate for metals. Only two referred to a bio-based industry, which was the food sector. Despite being specific for technical cycles, these monitors were included to evaluate if the underlying criteria are relevant for biological cycles. Additionally, it also highlights the inequality in the number of CE monitors existing specifically for each cycle, with a clear weightage towards technical cycles.

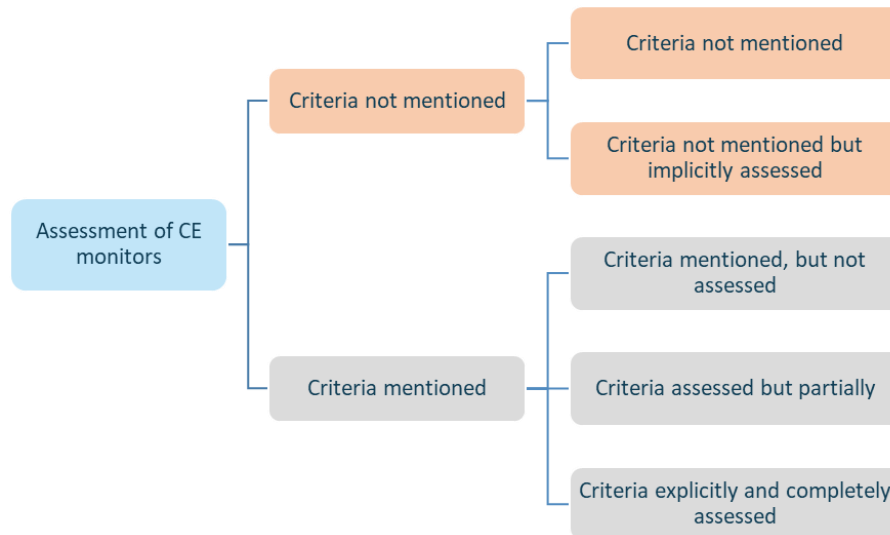


Figure 2: The framework for the evaluation of CE monitors - to validate if the CE monitors measure the parameters critical for assessing the circularity of biological cycles

CE monitors were then examined to validate whether each criterion relevant for biological cycles, as derived from the literature study, was considered. The framework for this evaluation is illustrated in Fig. 2. The first step was to examine whether there is a mention of the criterion. In case there is a mention, the second step was to determine whether the criterion is assessed and if assessed is it being assessed completely (marked in the results 'explicitly & completely assessed') or only partially (marked as 'explicitly & partially assessed'). Even in the case where there is no mention of the criterion, the next step was to determine whether it is assessed (marked as 'implicitly assessed'). There are cases where there is no mention of the criteria, but it is implicitly measured none the less. This framework accounts not only if the criteria are assessed but also to what extent are they being completely assessed.

3. Results and Discussion

3.1. CE monitoring criteria specific for biological cycles

The contours of CE are highly contested (Korhonen et al., 2018). The concept has been promoted by governments, academics and businesses (Kalmykova et al., 2018). However, there is no one agreed definition across these bodies. Several CE definitions exist. The most renowned definition has been framed by the Ellen MacArthur Foundation:

CE as an economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2010).

A recent literature review by Kirchherr et al. (2017) found 114 CE definitions. Kirchherr et al. (2017) synthesized these definitions and proposed a uniting definition:

CE is defined as “an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations”.

This study uses these two definitions of the CE concept to deduce the guiding principles for CE practices and implementation strategies (i.e. the aspects CE strategies should strive to achieve). Since the study focused on the material circularity in technical and biological cycles, only the first sentence of the definition by Kirchherr et al. (2017) is considered. The analysis suggests that CE implementation strategies mainly aim at closing the material loop and fall into five main categories:

1. Reducing the **input of resources**
2. Minimizing the **waste** and **losses** produced
3. Increasing the input of **recycled materials**
4. Maximizing **value**, utility and durability of products

It has been assumed in this study that these requirements for CE strategies form the basis of the CE monitoring criteria, i.e. the measures that indicate the transition towards a CE.

Because of non-consensus over agreed definitions of CE, the CE definitions themselves were insufficient to deduce the CE monitoring criteria. Hence, the list of CE monitoring criteria was complemented with the monitoring criteria identified by Corona et al. (2019) and Elia et al. (2017), who based their analysis on the CE strategies and practices. Elia et al. (2017) built on the results of the European Environmental Agency (2018) and added the criteria ‘increasing share of renewable resources’ and ‘reducing emission levels’ in addition to the above mentioned four criteria. Additionally, Corona et al. (2019) proposed to add three more criteria reflecting economic prosperity and social equity. Those are creating local jobs at all skill level, value-added creation and distribution and increase social wellbeing. To complete the list of CE assessment criteria, but yet maintain the focus on material circularity, the criteria - increasing share of renewable resources and reducing emission levels – have been included in this study. While the other three criteria, evaluating economic and social impact, have been considered out of scope for this study.

The question then arises whether these CE assessment criteria are adequate to evaluate the circularity of biological cycles. In answering that question, firstly, the characteristics of biological cycles in the context of CE were identified, in particular, those that are not assessed by existing CE monitoring criteria. These are:

1. **Renewability**, however, limited by its regeneration rate
2. Potential for **cascading** use of material
3. At the end-of-life, biodegrade and return to the biosphere to **close the nutrient cycle**
4. Environmental impact of biological cycles associated with **resource extraction** and biogenic **carbon flows**

These features have been discussed in-depth in the next sections. The aspects of biological cycles, assessed already by the existing CE monitoring criteria, are not included in the discussion. For example,

the production or use phase of biological cycles also have an environmental impact but are not included, as it is assessed by an existing CE monitoring criterion (namely, reducing emission levels).

The next step was to evaluate if these characteristics are assessed by the CE monitoring criteria mentioned above. Each trait of the biological cycle is analyzed corresponding to the CE monitoring criteria to validate the extent to which they are aligned. The results of this analysis are described in sections 3.1.1.- 3.1.4 and summarized in section 3.1.5.

3.1.1 Renewability

Biotic resources are intrinsically renewable. Hence, the primary principle of CE 'to reduce the input of virgin resources' is less critical for these resources. This has been widely accepted, as can be seen with the growing emphasis on the bio-economy (European Commission, 2012; European Environmental Agency, 2018). The substitution of fossil-based resources by biotic resources is being encouraged. However, the renewability of these resources can only be ensured by sustainably producing and harvesting these resources (Hetemäki et al., 2017; Sikkema et al., 2017); by extracting resources at a rate lower than their regeneration capacity (Hilborn et al., 1995). In the forestry sector, this principle is termed 'sustained yield' (Muys et al., 2014). However, albeit essential, this is not sufficient to sustain the long-term productivity of the ecosystems. The harvesting or extraction processes could affect the ecosystem quality and capacity of biomass provisioning. Increasing agriculture and forestry productivity could lead to loss of species and landscape diversity, nutrient depletion or habitat loss (Muys et al., 2013). Some fishing techniques, e.g. dynamite fishing, trawling and dredging, could destroy habitat and deplete fish stock (Airoldi and Beck, 2007; Woods et al., 2016). These factors have an impact on the intrinsic capability of renewal and affect the long-term yield. The forestry sector has thus widened the concept of 'sustained yield' into a broader concept of 'sustainable yield', which aims at maintaining the ecosystem services and long-term productivity of forest ecosystems by safeguarding biodiversity and monitoring soil productivity (Muys et al., 2014). The fisheries sector defines the 'Maximum Sustainable Yield' (MSY) as the limit that can safely be removed from the fish stock while maintaining its capacity to produce sustainable yields in the long term (Maunder, 2008). The forestry and fisheries sectors have long histories of concern about sustainability. However, the CE discussions seem to be lagging in their consideration of sustainable exploitation of biotic resources (Hennig et al., 2016).

The growing need to reduce the dependency on fossil-based resources will see a shift towards biotic resources. A promising green alternative is lignin, one of the building blocks of biomass. It can substitute fossil-based resources in many sectors and products - fuels, resins, pharmaceuticals (Liao et al., 2020; Smolarski, 2012). The commercialization of lignin represents an opportunity to meet climate targets but could increase demand for biomass. Currently, lignin is abundantly available as residues in the paper and pulp industry and is used mainly for energy (Cline and Smith, 2017). But using lignin for material applications would mean finding alternative sources for energy supply, which could further increase the biomass demand.

The increasing demand for biomass may exacerbate the overexploitation of natural resources and cause further degradation of ecosystems (Ceccherini et al., 2020; European Environmental Agency, 2018; Hetemäki et al., 2017; Worm et al., 2006). The CE assessments should validate the renewability of the resources. The aim should be to minimize the use of biotic resources, along similar lines as abiotic resources. But, more importantly, ensure that it is within sustainable limits. In addition to validating that the extraction of biotic resources is below their natural regeneration rate, the CE monitors should also ensure that the ecosystem production capacity remains stable over-time.

3.1.2 *Potential of cascading use of material*

Bio-based materials, i.e. materials derived from biomass, are biodegradable by nature, and it is harder to preserve the value of biodegradable materials (European Environmental Agency, 2018). Recycling these materials to their original form is difficult. They degrade in quality with each subsequent application (Jarre et al., 2020), resulting in lower structural properties and utility. This limits the applicability of the core CE principles – recycling and maximizing the utility – to biological cycles. The use of biotic resources is, thus, optimized by using it in cascades.

Cascading is the sequential use of resources as long, as many times and as efficiently as possible for material applications and only to recover energy from them when no other material application is feasible (Essel et al., 2008; Sirkin and Houten, 1994). The use of waste streams – post-consumer waste and industrial residual streams - for innovative products is encouraged. For example, wood, from construction and demolition waste, is used for particleboard production (Höglmeier et al., 2013; Merrild and Christensen, 2009). Inedible and unavoidable food waste and food residues are considered potential feedstocks for bioplastics, organic acid, essential oils (Teigiserova et al., 2019). Lignin, a by-product of pulp mills, is burned for low-grade energy. Better yet would be to use it for material applications, such as chemicals or pharmaceuticals (Smolarski, 2012), instead of being incinerated. Even after incineration or biodegradation, the emission capture and utilization technologies (Thomsen and Zhang, 2020) could extend the time these resources are in use. Cascading aims to maximize the value retrieved from the material over the multiple life-cycles. Value or material-quality here refers to the potential resource utility based on the inherent and intrinsic material properties, such as structural organization and chemical composition (Campbell-Johnston et al., 2020; Sirkin and Houten, 1994). The objective of maximizing the material-value is achieved by starting the use of resources for high-quality products, using the waste streams as much as possible, increasing the life-time of each application and hence overall life-time, and minimizing quality loss with each application (Brunet-Navarro et al., 2018; Fraanje, 1997; Keegan et al., 2013). These practices could enhance resource use efficiency, increase resource availability for other material uses, reduce dependency on virgin resources and reduce the environmental burden associated with resource use (Bais-Moleman et al., 2017; Fraanje, 1997; Höglmeier et al., 2015; Sikkema et al., 2013).

The majority of CE research has concentrated on material re-use and recycling. Little attention has been paid to assessing cascading. Assessing cascading would require considering the material-quality and rate of material-quality degradation along the material value chain (Haberl and Geissler, 2000), with a lower rate of quality loss signifying a more circular value-chain. The assessment should determine the highest value pathway for the material by assessing multiple-use phases and across multiple-material streams (i.e. virgin feedstock, waste and residues) and prioritize the use of materials for the highest quality application possible (Campbell-Johnston et al., 2020; Fraanje, 1999; Sirkin and Houten, 1994). High-quality material should not be allocated to low-quality applications. An integrated assessment of cascading - considering quality degradation over multiple-use phases and multiple streams - is generally lacking in CE monitoring and is essential to extract the maximum potential of the biological cycle.

The cascading principles have primarily belonged to the biomass domain (Kalverkamp et al., 2017) because, unlike metals and minerals, bio-based materials cannot be recycled to their original form. Natural fibers in bio-based material degrade in structural properties during the recycling process. However, the materials from abiotic resources also face quality degradation during the recycling processes, although the mechanisms might differ. Metals degrade in quality during recycling because they get mixed with undesirable elements or lower grade materials, resulting in lower-quality recycled material, i.e. material with lower inherent properties such as lower mechanical properties (Koffler and

Florin, 2013). This has been referred to as downcycling in CE discussions, which is recycling that results in products or materials of lower value. Yet, CE assessment has paid limited attention to considering material value (Campbell-Johnston et al., 2020), which merely necessitates its assessments for both technical and biological cycles.

3.1.3 Closing the biological nutrient cycle: biodegrade and return to the biosphere

Bio-based materials are typically biodegradable and support the regeneration of the ecosystem after their decomposition. Hence, the core principle of CE, i.e. reduce waste and increase recycling, seems essential but not sufficient for biological cycles. Additionally, ensuring 'closure of the biological nutrient cycle' is fundamental. It is essential to validate whether the biotic resources after decomposition feed the regeneration of the ecological systems.

Firstly, bio-based products are not necessarily biodegradable. A clear example of this is bio-based polymers (such as bio-polypropylene and bio-polyethylene; Bocken et al., 2016). These are typical drop-in bio-based polymers. They have the same structure as their fossil counterparts and hence are not biodegradable (Shogren et al., 2019). Additionally, mixing biotic resources with abiotic resources, a frequently-used method for enhancing the material properties of products, can hamper the biodegradability of the biotic resources. For example, bio-composites may not necessarily be biodegradable (Jiang et al., 2020). The aim of CE should be to enhance the separability of the material of biotic and abiotic origin, to enhance the biodegradability of bio-based materials. When materials from biotic and abiotic sources cannot be separated or when the bio-based materials are non-biodegradable, they should be treated as part of technical cycles, focusing on enhancing their reusability and recyclability.

Bio-based alternatives to fossil-based products face several challenges even when biodegradable. For instance, bio-based plastic polylactic acid (PLA), which is biodegradable but has an appearance similar to that of fossil-based alternative (polyethylene terephthalate PET). Hence, these two fractions get collected together in the waste streams, posing two problems. Firstly, the biodegradable fraction should be composted (after cascading uses if possible). Mixing the two streams increases the difficulty of eventually composting this fraction. Secondly, the presence of PLA seriously hinders the existing recycling process of PET (Alaerts et al., 2018). Hence, bio-based materials or products should be collected separately - for recycling or composting purposes. Separation of bio-based materials or products from their abiotic counterparts is crucial for the closure of both technical and biological cycles.

Yet another challenge is the dissipative losses, i.e. the losses to the environment that are not recoverable. The products that result in dissipative losses during use (such as lubricants, tires or paint) should be made compatible with biological systems (Bocken et al., 2016; Braungart et al., 2007). They should degrade and not accumulate in nature. However, this is not always the case. The emissions to the environment contain non-biodegradable materials, also of abiotic origin. They gradually accumulate in the biosphere over-time and interfere with the ecosystem functioning (Thomsen et al., 2012). If toxic in nature, it could severely impact plant, animal or human health. For instance, industrial emissions contain toxic pollutants that spread on agricultural land and are becoming part of food-systems (Marini et al., 2021; Pizzol et al., 2010). Hence, the presence of non-biodegradable or abiotic resources in dissipative emissions should be avoided. Secondly, if unavoidable, the toxicity and impact on ecosystem functioning as a result of their occurrence should be minimized. Moreover, even if they were biodegradable, whether these resources are feedstock for the regeneration of the ecosystems is less known.

Non-hazardous biodegradable bio-based materials that do safely decompose are assumed to return as nutrients to the biosphere. However, these nutrients do not necessarily feed the regeneration of the ecosystem. Nutrients are extracted from the biosphere as harvested food, energy and material, and are discharged back into the biosphere when it decomposes. The nutrients not returned to the place or at a rate at which ecosystems absorb the nutrients can disrupt the nutrient cycles (Skene, 2018). Without adequate measures to ensure nutrient cycling, shortages are created at the source of biomass, and nutrient excess in the ecosystems where the biomass is consumed or discharged (De Oliveira Garcia et al., 2018; European Environmental Agency, 2018). This is especially true in the case of agricultural systems where the urban areas are becoming concentrators of nutrients (Chowdhury et al., 2014; Kalmykova et al., 2012; Papangelou et al., 2020) and the rural soils are degrading and relying increasingly on synthetic fertilizers (Lathuillière et al., 2014). This disruption of the nutrient system is damaging at both places (Battye et al., 2017). It causes environmental issues like eutrophication (Chowdhury et al., 2014; Lassaletta et al., 2014), where the nutrients are concentrated and discharged into waste streams. At the sites where nutrients are extracted, the soil fertility is reduced; increasing the dependency on synthetic fertilizers. Excessive use of fertilizer, causing fertilizer run-off from the agricultural system to water-bodies, can also lead to increased toxicity levels and further reduce the capacity of soil to support growth (Coppens et al., 2016; Dalin and Rodríguez-Iturbe, 2016; Lassaletta et al., 2014; Smil, 2011). Modern agricultural practices, such as excessive tillage and the use of heavy machinery, accelerate this process by increasing erosion and water runoff, carrying nutrients out of the soil and into water systems. Other than the farming practices, megatrends such as globalization, international trade (Dalin and Rodríguez-Iturbe, 2016; Lassaletta et al., 2014; Schipanski and Bennett, 2012), and urbanization further contribute to the relocation of nutrients and disruption of nutrient balance (Ellen MacArthur Foundation, 2017).

These nutrient imbalances have a severe impact on human and ecosystem functioning. The Stockholm Resilience Center has highlighted that the biogeochemical nutrient cycle (of nitrogen and phosphorus) is one of the planetary boundaries that has already been transgressed. There is sufficient evidence to say that this has been, radically, caused by human industrial and agricultural processes (Steffen et al., 2015). Hence, an assessment of a system's capability to close the biological nutrient cycle and maintain the ecosystem's regenerative capacity is crucial and essential.

To summarize, CE concepts assume that the biomass that decomposes and returns to the biosphere contributes to closing the biological nutrients loop (Haas et al., 2020). However, it is evident that this is not always true. Hence, the CE monitors should assess the following aspect - Firstly, the biodegradability of bio-based materials; secondly, the occurrence and toxicity of hazardous substances in the emissions to the environment as a result of biodegradation; and thirdly, validate if the place and rate of decomposition of the material sustain the regeneration of ecosystems (Reijnders, 2008; Skene, 2018). This assessment should also include the biodegradable material of abiotic origin, while the non-biodegradable bio-based materials should be in the CE monitoring of technical cycles.

3.1.4 Environmental impact specific to biological cycles

Primary sectors producing biotic resources - agriculture, forestry and fisheries - have substantial impacts on the environment. The biotic resource use impacts the quantity and quality of ecosystems, natural capital (soil, water and air), biodiversity and landscape amenity value. The planetary boundaries developed by Stockholm Resilience Center point out that impact on five out of nine have a direct link to the bio-based economy: biogeochemical (nitrogen and phosphorus) cycle balance, land system change, freshwater consumption and the global hydrological cycle, loss of biosphere integrity (biodiversity loss and extinctions) and climate change (Steffen et al., 2015). Hence, biological cycles should not be inherently assumed to be environmentally friendly.

The biotic resource use damages the environment, mainly, through the local ecosystem impact of resource extraction, resulting from resource depletion and land-use or ocean use interventions, and global climate impact of carbon emissions.

The biotic resource extraction impacts the capacity and quality of ecosystem functioning due to resource depletion. This is not the case with abiotic resource extraction, for which the impact occurs due to resource extraction and not due to depletion or scarcity. Abiotic resource depletion could impact resource availability for the future generation but does not affect the ecosystem health or functioning (Heijungs et al., 1997). Overexploitation of biotic resources could lead to a reduction or extinction of species, challenging their future availability. But more importantly, it causes indirect biodiversity loss (Crenna et al., 2018), for example, through trophic interactions (Chapin et al., 2000). Both direct and indirect biodiversity loss diminishes the total biomass available for ecosystem functioning, which could impact the ecosystem health, affecting the production capacity of the ecosystem (i.e. provisioning of resources) as well as other life-supporting functions (e.g. climate regulation, flood control). An example of this is the potential threat to coastal water quality and ecosystem stability due to the overexploitation of marine resources; by altering food web structures and reducing the population of non-target species (Woods et al., 2016; Worm et al., 2006). The resource depletion is an impact category relevant for extraction of non-cultivated biotic resources from the natural environment, e.g. hunting in the wild, timber from natural forest, fishing from oceans; and not for cultivation, i.e. harvesting from farms and plantations, for which the impacts are mainly due to land-use or ocean-use (Heijungs et al., 1997).

The impacts originating from land-use interventions are of two types - land occupation and land transformation. Land occupation is the continuous use of land for a specified land-use type for a certain period. Land transformation is modifying land to suit it for the intended use. Such as converting forest to agricultural land, draining land to establish arable fields, intensifying farmland production (Koellner et al., 2013). These interventions degrade ecosystem services due to a decline in vegetation, biodiversity, soil- and water quality (Foley et al., 2005; Saad et al., 2013; UNEP, 2019). The ocean-based activities damage the marine ecosystems, through habitat destruction (from fishing techniques, disturbances - dynamite fishing, fishery bottom trawling and dredging) and biodiversity loss (from habitat loss, by-catches; Kaiser et al., 2002; Woods et al., 2016). So far, concern about the impact of biotic resources extraction on ecosystem services has been limited in CE assessment. However, to ensure sustainable use of natural resources and to avoid burden shifting by moving from fossil-based to biotic resources, the impact of biotic resources extraction on ecosystem health, resulting from direct and indirect land-use impacts and resource depletion, needs to be accounted.

Another aspect unique to biological cycles is the climate impact of biogenic carbon. Biological cycle carbon management differs from that of the technical cycle in a way that carbon is both sequestered from and emitted to the biosphere in biological cycles. Carbon dioxide is absorbed from the atmosphere through photosynthesis and stored in biomass, and further on, in bio-based products. CO₂ is emitted to the atmosphere when the biomass is incinerated or decomposes. The emissions balance out the initial carbon sequestration. The carbon storage in the bio-based products, even if temporary, contributes to delaying the emissions. Hence, carbon emissions from biogenic sources are often assumed to be 'carbon neutral'. Wood products have officially been accounted for as carbon sinks under the Kyoto Protocol (UNFCCC, 2012), and the use of bio-based products is seen as a climate mitigation strategy. However, the 'climate neutrality' assumption holds if the rate of carbon emission is lower than sequestration. Harvesting a tree that grows over several years and using it for bio-energy could create a 'carbon debt'. So, the biotic resources should be harvested at a rate below the rate of sequestration. Their use in long-lasting products and in cascading enhances their climate mitigation

potential. Validating ‘carbon neutrality’ by evaluating time-explicit account of carbon flux – i.e. not only net carbon emission, but more importantly considering the rate of carbon sequestration, time over which carbon is stored and the rate of release of biogenic carbon - is essential to conclude the climate benefits of biological cycles.

The biological cycles also have an environmental impact in other phases of the product life-cycle, i.e. production, use and end-of-life. However, these impacts are not specific to biological cycles and also occur in technical cycles. They are not discussed in this study as the criteria to reduce the environmental impact associated with these phases is already included in the existing CE monitoring frameworks. The aim was to identify the additional criteria required to assess biological cycles.

3.1.5 Summary

Table 1 summarizes the results of this evaluation. Each of the characteristics of the biological cycle (mentioned in the column header of Table 1) is reviewed and compared to the CE monitoring criteria (listed in the row headers) to showcase the extent to which they are aligned. The contradictions between the two or the aspects where CE monitoring criteria fall short of including the biological cycle (highlighted in bold) lay the ground for the adaptations required to these criteria to integrate biological cycles in the current CE assessments.

Table 1: Summary of the evaluation of the characteristics of the biological cycle and comparing them with the CE monitoring criteria to validate the extent to which they are aligned (the gaps are highlighted in bold)

Biological cycles' characteristics	Renewability	Cascading use of material	Closing of the biological nutrient cycle	Environmental impact
CE monitoring criteria				
Reducing input of resources	Important but not sufficient. Essential that resources are sustainably sourced			
Reducing waste			More importantly, the need to validate biodegradability, presence of hazardous substances & if decomposition sustains regeneration	
Increasing recycled resource		Additionally, should optimize the cascading use of material		
Increasing the use of renewable resources	In contradiction with the criteria to reduce input. Validating if resources are sustainably sourced becomes more crucial			
Reducing emissions (GHG)				In addition to the environmental

				impact associated emissions, it is crucial to assess impacts of resource extraction and assess the temporal aspect of emission
Maximizing value, utility & time in use		Additionally, should assess the quality degradation over multiple-uses		

It is evident that current CE monitoring criteria fall short of assessing the key characteristics of biological cycles. Based on the gaps highlighted in Table 1, it can be suggested that CE monitoring should include, along with criteria applicable to technical cycles, the following criteria for accurately gauging transition towards circular biological cycles:

1. To ensure ‘renewability of biotic resources’, the additional CE assessment criterion should be increasing the use of **sustainably-sourced** resources
2. To optimize the ‘cascading use of biotic resources’, the criterion should be **maximizing the value** by identifying the best utilization pathway considering multiple-uses and multiple streams
3. To ‘close the nutrient cycle’, the criteria should be to ensure that
 1. Enhancing **separability** and **biodegradability** of bio-based biological materials
 2. Reducing the **presence of hazardous substances** in the emissions to the environment
 3. Increasing the **return of nutrients**, in place and at a rate, that sustains the regeneration of the ecosystem
4. To minimize the ‘environmental impact’, the criterion for CE monitoring should be to assess the **impacts of biotic resource extraction on ecosystem services**, in particular, that resulting from land-use interventions and resource depletion and global climate impact of **carbon balance**, by accounting carbon sequestration, storage and release of biogenic carbon

3.2. Gaps in existing CE monitors

The existing CE monitors were evaluated to determine whether they assess the circularity criteria relevant to biological cycles. The study reviewed 59 CE monitors - the summary of the results is provided in Table 2 and Figure 3. Annex B provides the complete list of CE monitors and evaluation results for each monitor, while Table 2 in the shortlist of only those monitors that assess at least one of the criteria.

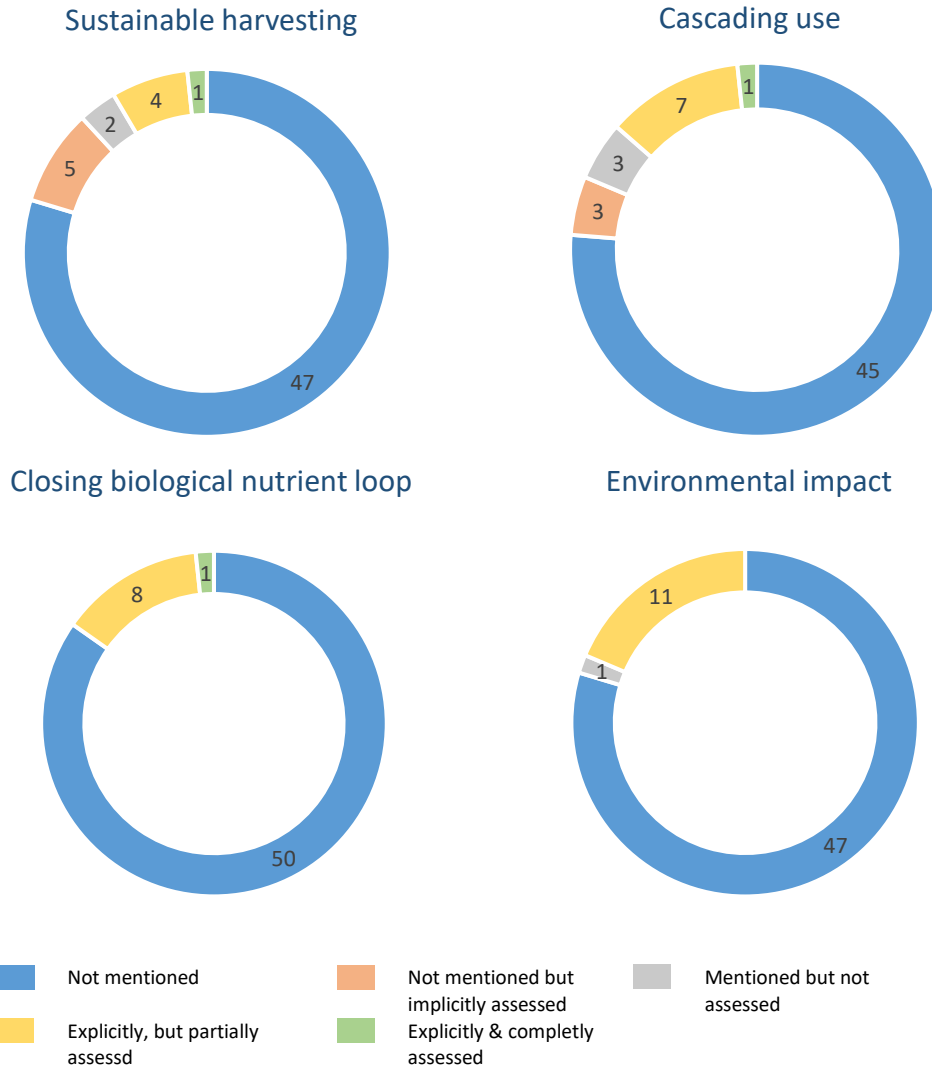


Figure 3: Results of the CE monitors evaluation

1 Table 2: Summary of the evaluation of CE monitors – validation if the CE monitors consider the criteria specific for circularity of biological cycle. This table includes only those CE monitors that
 2 consider at least one of the criteria. Empty cell represent that the criteria is '(not mentioned &) not assessed'

CE monitor	Source	Sustainable sourcing	Cascading use	Closing the biological nutrient cycle	Environmental impact specific to biological cycles
Assessing circular trade-offs	Circle economy, Camacho-Otero and Ordoñez, 2017	Explicitly but partially assessed Including criticality (using resource price) and renewability	Mentioned (but not assessed)	Explicitly but partially assessed Assess share of material biodegradable	Explicitly but partially assessed (The aspects assessed are not known)
Value-based resource efficiency	Di Maio et al., 2017	Implicitly assessed Considered economic value of stressed resources			
Product-level-circularity-metric	Linder et al., 2017	Implicitly assessed Include the cost of recirculated resources	Implicitly assessed Include the cost of recirculated resources		
Hybrid LCA Model	Genovese et al., 2017	Implicitly assessed LCA includes land-use change and resource scarcity			Explicitly but partially assessed, using LCA , which is a methodology to study environmental impact. However, impact on resource depletion on ecosystem services and time-dependent carbon flows is rarely studied
Integrative Evaluation on the Development of CE	Qing et al., 2011	Implicitly assessed Includes per capita green area			
Eco-efficiency index	Laso et al., 2018	Implicitly assessed Include the cost of raw material			
Circular economy toolbox	"Measuring Circular Economy U.S. Chamber of Commerce Foundation," n.d.	Explicitly but partially assessed	Explicitly but partially assessed	Explicitly but partially assessed Assess share of material biodegradable	

CE monitor	Source	Sustainable sourcing	Cascading use	Closing the biological nutrient cycle	Environmental impact specific to biological cycles
		Includes share of resources from certified sources	Assess closed-loop and open-loop recycling rates		
Resource productivity indicator	Wen and Meng, 2015		Implicitly assessed Include industrial added value per unit material input		
Resource duration indicator	Figge et al., 2018; Franklin-Johnson et al., 2016		Implicitly assessed Include time in use of a resource		
Indicators for Material input for CE	European Environment Agency EEA, 2016	Mentioned (but not assessed)	Mentioned (but not assessed)		Mentioned (but not assessed)
Material circularity indicator	Ellen MacArthur Foundation, 2015	Mentioned (but not assessed) Suggests use of complementary risk indicator ' material scarcity '			
Product circularity indicators	Bracquené et al., 2019		Mentioned (but not assessed)		
Recycling and collection rates	Haupt et al., 2017		Explicitly but partially assessed Assess closed-loop and open-loop recycling rates		
End-of-life Recycling rates	Graedel et al., 2011		Explicitly but partially assessed Assess functional and non-functional recycling rates		
Circularity index	Cullen, 2017		Explicitly but partially assessed		

CE monitor	Source	Sustainable sourcing	Cascading use	Closing the biological nutrient cycle	Environmental impact specific to biological cycles
			Assess the energy required for material & virgin material		
Circular economy index	Di Maio et al., 2015		Explicitly but partially assessed Assess market value		
Material recycling index	Reuter and Van Schaik, 2016		Explicitly but partially assessed Assess recycle composition		
Circular economy toolkit	Evans and Bocken, 2014			Explicitly but partially assessed Assess share of material biodegradable	
Circular pathfinder	https://rescomd58.eurostep.com/idealco/pathfinder			Explicitly but partially assessed Assess share of material biodegradable	
Input-output balance sheet	https://www.capcon.it/en/measure-the-circularity-of-a-product/			Explicitly but partially assessed Assess share of material biodegradable	
Circular Economy Monitoring Framework	https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework			Explicitly but partially assessed Assess share of material biodegradable	
EU Resource efficiency scoreboard	European Commission, 2015b			Explicitly but partially assessed Assess area under organic farming, soil erosion, nutrient balance	Explicitly but partially assessed Assess greenhouse gas emissions per capita , index of common farmland bird species , land fragmentation , pollutant emissions

CE monitor	Source	Sustainable sourcing	Cascading use	Closing the biological nutrient cycle	Environmental impact specific to biological cycles
CE-enterprise-index	Li and Su, 2012				Explicitly but partially assessed Assess output per unit land, water and energy consumption, emissions per unit output
Circular economy indicator system of China	Geng et al., 2012				Explicitly but partially assessed Assess energy consumption, water withdrawal , and emissions per unit output
Regional Circular Economy Development Index	Guogang and Jing, 2011				Explicitly but partially assessed Assess water, energy and chemical fertilizers consumption
Environmental Protection Indicators in a context of CE	Su et al., 2013				Explicitly but partially assessed Assess water, energy per unit output
Cradle to cradle certification program	The Cradle to Cradle Products Innovation Institute, 2014			Explicitly assessed	Explicitly but partially assessed Asses energy and water consumption
Circular economy performance indicator	Huysman et al., 2017		Explicitly assessed		
CE indicator system	Zhou et al., 2013				Explicitly but partially assessed, measures environment damage cost based on the economic impact of

CE monitor	Source	Sustainable sourcing	Cascading use	Closing the biological nutrient cycle	Environmental impact specific to biological cycles
					environmental pollution (such as air pollution, water pollution, light pollution, noise, solid waste)
Eco-efficient value ratio	Scheepens et al., 2016				Explicitly but partially assessed, using LCA , which is a methodology to study environmental impact. However, impact on resource depletion on ecosystem services and time-dependent carbon flows is rarely studied
Measuring Regional CE–Eco-Innovation	Smol et al., 2017				
Circulytics	Ellen MacArthur Foundation, 2016	Explicitly assessed (Considers if the biotic resources are sustainably sourced)		Explicitly but partially assessed Assess whether the outflow of material are suitable for biological cycle	
Global Resource Indicator	Adibi et al., 2017	Explicitly but partially assessed Assess the renewability rate while considering resource scarcity			
Circularity material indicator	Pauliuk, 2018		Explicitly but partially assessed, using weighted factor (based on purity, quality, and recoverability of material) to calculate circularity index		

CE monitor	Source	Sustainable sourcing	Cascading use	Closing the biological nutrient cycle	Environmental impact specific to biological cycles
EU Raw materials scoreboard	European Commission, 2018	Explicitly but partially assessed Considers growing stock and forest-felling (utilization) rate			

3

5 The study evaluated whether CE monitors assess the sustainable sourcing of biomass; harvested in a
6 way that preserves the ecosystem functioning and long-term provision of resources. Out of 59 CE
7 monitoring frameworks, only 1 considers this aspect. 2 indicators mention the need to consider
8 sustainable harvesting but do not assess it. Whereas 5 indicators implicitly assess it, albeit partially.
9 Out of these 5 indicators, 3 indicators assess the criticality of resources based on economic value (Di
10 Maio et al., 2017; Laso et al., 2018; Linder et al., 2017). The assessment based on economic value is
11 considered as an implicit assessment of renewability because, in principle, increased resource scarcity
12 or compromised renewability of resources would reflect on its economic value. However, the use of
13 monetary values has its disadvantages. Market values and prices fluctuate heavily over time. Problems
14 also arise when prices are missing or distorted due to monopolies or government interventions, such
15 as subsidies. Another CE monitor that is considered an implicit assessment is *Hybrid LCA*, offered by
16 Genovese et al. (2017). *Hybrid LCA* is a framework to integrate the top-down environmental input-
17 output model and bottom-up Life cycle assessment (LCA) model. It has been considered an implicit
18 assessment because the criteria 'sustainable sourcing' will be included if the underlying LCA
19 incorporates the relevant impact categories. The one other indicator that implicitly assesses
20 renewability is 'per capita green area' (Yang et al., 2011). It has been considered an implicit (and
21 partial) assessment because this could ensure that a certain amount of green areas are maintained.

22 The 4 monitors that explicitly, but partially, assess sustainable sourcing are circularity assessment tool
23 suggested by Circle Economy (Camacho-Otero and Ordoñez, 2017), the EU raw material scoreboard
24 (European Commission, 2018), the global resource indicator (Adibi et al., 2017) and the CE metric
25 proposed by the U.S. Chamber of Commerce Foundation and. The circularity assessment tool of Circle
26 Economy evaluates the renewability and criticality of resources. The EU resource raw material
27 scoreboard considers the growing stock and forest-felling rate. The global resource indicator uses
28 scarcity, recyclability and criticality, wherein scarcity is measured based on renewability rate (Adibi et
29 al., 2017). As discussed in the earlier section (Section 3.1.1), consideration of renewability rate is no
30 guarantee for long-term yield, so these indicators have been considered a partial assessment. The CE
31 metric used by the U.S. Chamber of Commerce Foundation includes a measure of the share of
32 resources from a certified source of that resource, for example, the amount of FSC-certified wood
33 supplied to the furniture and paper industry. Many of the certifications target sustainable
34 management of resources, in particular FSC, which aims for forest management that ensures timber
35 harvesting without affecting the biodiversity, forest productivity and other ecosystem services (FSC,
36 2015). However, this monitor mentions only FSC certification, which covers forest ecosystems, and it
37 is not clear if the certifications relevant to other ecosystems aim for sustainability in sourcing. The CE
38 monitor has, thus, been marked as a partial assessment.

39 The only tool that explicitly and completely validates sustainable sourcing of biotic resources is the
40 circularity measurement tool 'Circulytics' developed by Ellen MacArthur Foundation (2020) for
41 companies. It considers the share of virgin resources from renewable and sustainable sources and
42 ensures that the resources are grown in a way that preserves the ecosystems.

43 To fill the current gap in CE monitors, they should essentially include a renewability score and assess
44 if harvesting is at a level that can preserve the long-term quantity and quality ecosystem functioning.
45 One way of doing that is by adopting methodologies or indicators from other sectors, such as fisheries,
46 forestry. As mentioned earlier, the fisheries sector uses a 'maximum Sustainable Yield' (MSY) as the
47 limit to the fish stock that can be harvested. The sustainable forest management (SFM) indicators,
48 used across Europe, include increment and felling to assess the provisioning functions of the forests.
49 They additionally use indicators, such as soil conditions, forest damage, land degradation, to monitor

50 the overall forest health and vitality (Forest Europe, 2015). Another methodology that can be
51 integrated within CE monitoring is LCA. LCA already has resource depletion as an impact category,
52 based on resource stock, harvest rate and regeneration rate (Guinée and Heijungs, 1995; Heijungs et
53 al., 1997; Klinglmair et al., 2014). The recent developments in the LCA include the assessment of the
54 renewability potential of biotics resources based on the recovery time, restoration time and renewal
55 time (Crenna et al., 2018). These factors are affected by the magnitude of the pressure the ecosystems
56 are subject to and are an indication of ecosystems' health and capacity. To emphasize this issue,
57 Dewulf et al. (2015) suggest that instead of having 'natural resources' as an area of protection, LCA
58 could have 'provisioning capacity of natural resources' as a safeguard subject. These assessments and
59 underlying goals are some of the proposals that could be considered in the CE monitoring frameworks
60 to ensure the sustainable use of biotic resources.

61 *3.2.2. Optimized cascading use*

62 The second evaluation of CE tools was validating if it assesses 'cascading use'. This evaluation validated
63 if CE monitors assess resource-quality degradation and if this assessment is performed over multiple-
64 uses of the material and over multiple-streams.

65 Relative to other requirements, a higher number of CE metrics displayed consideration for this
66 category. 14 indicators, out of 59, consider the assessment of cascading. Out of the 3 indicators that
67 implicitly assess it, 2 assume economic value as a proxy for material quality (Linder et al., 2017; Wen
68 and Meng, 2015), while the third one, *resource duration indicator* or the *longevity* indicator, measures
69 the contribution to material retention based on the time a resource is in use (Figge et al., 2018;
70 Franklin-Johnson et al., 2016). Increasing the duration of use supports increasing the value-extraction,
71 one of the primary principles of cascading, and has been considered an implicit (and partial)
72 assessment. Amongst the 10 indicators that stress the need to assess material quality instead of mere
73 recycling index, 3 indicators either do not specify the means to do so (Bracquené et al., 2019;
74 Camacho-Otero and Ordoñez, 2017) or highlight that, currently, no data is available to create this
75 indicator (European Environment Agency, 2016).

76 Among the indicators that explicitly assess cascading, *Recycling rates* proposed by Haupt et al., 2017
77 and the *Circular economy toolbox* by the U.S. Chamber of Commerce Foundation measure closed-loop
78 and open-loop recycling rates. Closed-loop recycling implies using the secondary resources to produce
79 the same product, while open-loop recycling is to produce something that differs from the preceding
80 product. Similarly, Graedel et al. (2011) split recycling rates into end-of-life functional recycling rate
81 and non-functional recycling rate. The functional recycling rate is the portion of resources that are
82 separated and recycled to retain their functions. The non-functional recycling rate describes the share
83 of collected resources recycled to be part of a larger material stream as impurity elements. This
84 prevents the dissipation of this material into the environment but represents the loss of the material's
85 functional properties. Both these indicators acknowledge that often the material loses its quality
86 during recycling, the information regarding which is not captured in the recycling rate. However, none
87 of these indicators considers the extent of quality loss.

88 *Circularity index* explicitly considers quality during recycling based on the ratio of the energy required
89 to recover the material from secondary sources (i.e. waste streams) relative to the energy required to
90 produce the material from primary sources (i.e. nature; Cullen, 2017). It is regarded as a partial
91 assessment because the energy required for recovery is technology-specific and might not always
92 represent the material-quality. Another CE tool that explicitly assesses cascading, *Circular Economy*
93 *Index*, assumes market value as an indicator of material-quality and measures the ratio of the material
94 market value produced by the recycler by the intrinsic value entering the recycling facility (*Di Maio et*

95 *al., 2017*). *Material recycling index* considers recycle quality as a function of product design and
96 recycle composition (Van Schaik and Reuter, 2016). However, the product design could be a proxy
97 and not an actual parameter for material quality. These indicators, which explicitly assess cascading,
98 focus on single-step of recycling and appear ineffective for assessment for multiple lifecycles of the
99 material. *Circularity material indicator* considers a weighted factor based on quality, purity and
100 recoverability to assess the circularity of material (Pauliuk et al., 2017).

101 *Circular Economy Performance Indicator (CPI)* is the only metric that successfully evaluates the quality
102 of material flows. CPI indicator is built on the existing recyclability benefit rate (RBR), which is a ratio
103 of environmental benefit from recycling a product over the environmental burden related to
104 production from virgin resources followed by disposal. To integrate the quality loss during recycling
105 into the assessment, the study proposed CPI as the ratio of the actual obtained environmental benefit
106 over the ideal environmental benefit according to quality (Huysman et al., 2017). The latter is the
107 environmental benefit when the waste is re-directed to the state-of-the-art waste treatment option
108 best suited to the waste stream according to its composition or quality. CPI is 1 when the waste is
109 used to the best of its quality (assuming the impact and losses during recycling are minimal). Value of
110 CPI lower than 1 would indicate that the waste stream is not utilised to the best of its technical
111 capability (or the recycling process has a significant material loss or environmental burden). This tool
112 can be aptly used to determine the most appropriate use of waste streams based on their quality,
113 which is one of the key principles of cascading.

114 The selection of the highest-value application for a material stream, the aspect currently lacking in CE
115 assessment, can be done based on a guiding principle, such as the one adopted by the EU Waste
116 Framework Directive (European Commission, 2008). It provides a waste hierarchy, which set priorities
117 for waste handling techniques. Several other frameworks could aid in this selection process, for
118 example, Lansink's Ladder, Van Gerven's Ladder, Bio-based pyramid (Odegard et al., 2012), food waste
119 hierarchy (Teigiserova et al., 2020). However, these frameworks only set preferences for applications
120 or processes. They do not state the application best suited for the resource based on the inherent
121 resource properties and the application that necessitates these properties the most. Methodologies
122 that evaluate the intrinsic material properties, such as statistical entropy analysis (SEA) or exergy
123 analysis, could support filling this gap. SEA has been put forward as a method to quantify resource
124 quality (Laner et al., 2017) based on the concentration of a substance in a flow (Rechberger and
125 Graedel, 2002). The higher the concentration of a substance in a flow, the higher is its availability and,
126 hence, the higher is the potential utility. SEA could also quantify quality based on other physical
127 properties that determine the material utility. For example - for wood, the size of the wooden element
128 defines its utility. Sawn-wood has a higher utility than wood chips. SEA applied to the entire lifecycle
129 of material, as done in Laner et al. (2017) and Rechberger and Graedel (2002), reflects changes in the
130 resource quality over time. The resource-use pathway that maximally preserves quality and material-
131 value over time can be considered the most desirable material trajectory. SEA includes all the three
132 aspects – quality degradation, multiple life cycles & multiple streams – relevant for cascading and,
133 thus, could be a powerful tool for assessing it. Exergy analysis uses the thermodynamic-based exergy
134 concept, which is the maximum potential work that can be obtained from the resource when bringing
135 it into equilibrium through reversible processes with the natural environment (Dewulf et al., 2008).
136 Resource-quality degradation is represented with the loss of potential energy, and hence the exergy
137 approach too could be viable to study cascading. The use of exergy analysis to study cascading use has
138 already been demonstrated by Risse et al. (2017). While SEA and exergy analysis can identify the
139 highest-value material trajectory, complementary methods, such as LCA, support improve the
140 resource-efficiency and reduce the environmental burden of that material trajectory (Dewulf et al.,
141 2008; Kaufman et al., 2008; Rechberger and Brunner, 2002). Methods such as these should be

142 integrated into the CE assessment frameworks to ensure the cascading use of biotic resources is
143 optimized.

144 *3.2.3. Closing the biological nutrient cycle*

145 The third aspect that was evaluated refers to the closing of the biological nutrient cycle and validates
146 if the CE monitors assess:

- 147 1. The biodegradability of the bio-based material – i.e. it safely returns to the biosphere and
148 does not accumulate in the environment
- 149 2. The presence and toxicity of hazardous substances in the emissions to the environment as
150 a result of biodegradation
- 151 3. The biotic resources returning to the biosphere as nutrients sustain the regeneration of the
152 ecological systems

153 It is observed that out of 59 CE indicators that were studied, only 1 indicator completely studied the
154 end-of-life of biotic resources. Additional 8 indicators assess only a part of the criteria of biological
155 nutrient loop closing.

156 The indicators that partially assess the end-of-life of bio-based material validate whether it is
157 biodegradable or compostable. The circularity measurement tool ‘Circulytics’, developed by Ellen
158 MacArthur Foundation (2020), evaluates the share of the total output flows, products and waste that
159 are suitable for the biological cycle, i.e. that degrade and not cause harm to human health or the
160 environment during or after their use. *EU Resource efficiency scoreboard* (European Commission,
161 2015) evaluates whether the nutrients from end-of-life return as feedstock to the ecosystems. The
162 indicators for that are area under organic farming, soil erosion and gross nutrient balance in agricultural
163 land. The scoreboard focuses on the agricultural systems, and the evaluation of other biomass
164 production systems, such as forestry and marine, is overlooked. The only indicator that evaluates
165 biological nutrient loop closing is the *Cradle to Cradle Certification Program*. The assessment for this
166 certification validates if the companies pursuing certification define components of their products as
167 biological or technical nutrients, and design pathways for nutrient recovery and re-utilization (The
168 Cradle to Cradle Products Innovation Institute, 2014).

169 CE monitors should include, equivalent to the recyclability score for technical cycles, a biodegradability
170 score for end-of-product-life bio-based materials. The monitors should also assess any potential risk
171 of the presence of non-biodegradable elements in the waste streams re-introduced in the biosphere
172 or atmosphere. Additionally and more importantly, for the streams that safely return to the biosphere,
173 the CE assessment should assess the extent to which nutrients contribute to biomass regeneration.
174 The monitor could be by evaluating regional-scale management of organic waste, i.e. plant nutrients,
175 sewage sludge and livestock manure (Mayer et al., 2019), and assessing the ecosystem services, such
176 as soil fertility, water quality and availability, biodiversity. Both places – where resources are extracted
177 and where nutrients are deposited – should be monitored to avoid damaging the ecosystems at either
178 location.

179 *3.2.4. Assess the environmental impact associated with biological cycle*

180 The fourth element evaluated in this study is whether the environmental impacts, associated with
181 biotic resource extraction and the temporal aspect of carbon fluxes, are being assessed in the CE
182 monitoring frameworks. The study evaluated whether the environmental impact assessments
183 considered impacts of biotic resource extraction, resulting from land-use interventions and resource
184 depletion, on ecosystem services. And concerning the environmental impact due to biogenic carbon
185 emissions, the study evaluated if the CE monitors validate carbon-neutrality of biological cycles, by

186 accounting for the rate of carbon sequestration, the amount of time over which carbon is stored and
187 the rate of release of biogenic carbon.

188 Only 11 out of 59 CE monitors assess environmental impact, but even they are not are complete. The
189 framework defined by the European Environmental Agency mentions that the use of bio-based
190 material can damage biodiversity and ecosystem services, and contribute to climate change, however,
191 does not assess it (European Environment Agency, 2016). Other CE assessment frameworks do
192 evaluate the environmental impact of biotic resource use but do so insufficiently. Many of them
193 measure ecological efficiency in terms of land area, water consumption, energy consumption and
194 emissions (especially SO₂) per unit output (Geng et al., 2012; Li and Su, 2012; Su et al., 2013; The Cradle
195 to Cradle Products Innovation Institute, 2014). The *Regional Circular Economy Development Index*
196 developed by Guogang and Jing (2011), in addition, also measures the amount of chemical fertilizers
197 applied per unit planted area. These indicators are insufficient to gauge the total ecosystem impact of
198 biotic resource depletion and land-use. Additionally, carbon accounting is not present in these listings.
199 The *EU Resource efficiency scoreboard* has a comparatively wider range of indicators, including an
200 index of common farmland bird species, the extent of land fragmentation and soil erosion. This
201 scoreboard does include greenhouse gas (GHG) emissions, but the emissions from the use of biomass
202 and stock changes in forests are not included. The CE indicator system developed by Zhou et al. (2013)
203 assesses the external environment damage cost caused due to the production process, i.e. the
204 ecological damage originating from the over-consumption of natural resources. This metric assesses
205 the impact on ecosystem services, but it is also incomplete.

206 The remaining indicators base their assessment on LCA methodology (Genovese et al., 2017;
207 Scheepens et al., 2016; Smol et al., 2017). For instance, Scheepens et al. (2016) apply the *LCA-based*
208 *Eco-costs Value Ratio* (EVR) model to analyze the potentially negative environmental effects of
209 business initiatives. LCA is a widely used methodology to assess environmental impact. However, the
210 environmental impacts associated with land use and biotic resources depletion is not always fully
211 integrated or widely applied in many LCA studies (Heijungs et al., 1997; Koellner et al., 2013;
212 Wagendorp et al., 2006). For the aspect of carbon balance, contribution to climate change (in LCA
213 terminology – global warming potential GWP) is often a central part of LCA, but consideration of the
214 temporal aspect of emissions is often lacking (Levasseur et al., 2010). This suggests a clear need to
215 explicitly include these aspects in CE monitoring for a complete assessment of the impact of bio-based
216 materials or biological cycles.

217 There are increasing attempts to evaluate impacts on biodiversity and ecosystem quality. Existing
218 indicators, such as ecological footprint, agricultural land footprint, forest footprint, could be adopted
219 in the CE monitors to close the current gap. Even for the LCA approach, concrete proposals have been
220 put forward to incorporate the impact of biotic resource extraction, resulting from land-use & land-
221 use change and resource depletion, on biodiversity and ecosystem health. Impact due to land-use
222 interventions is based on the type of landscape that is disturbed and the duration of the disturbance
223 (Heijungs et al., 1997), which considers the current occupation of land and change in land-use, which
224 affects the natural regeneration time and biodiversity (Koellner et al., 2013; Lindeijer, 2000).
225 Wagendorp et al., 2006 provided an LCA based assessment for land use impact based on ecosystem
226 thermodynamics. Human impact, such as reduced biomass, is indicated in this study by a decrease of
227 exergy, which is converse to what the ecosystem strives to achieve. Schmidt et al. (2015) provided a
228 framework for evaluating the indirect land-use change. Koellner et al. (2013) proposed structured
229 guidelines to assess the damages caused by land-use interventions on biodiversity and ecosystem
230 services. This framework includes two impact pathways - biodiversity damage potential, based on the
231 functional diversity of species in ecosystems, and ecosystem services damage potential, based on the

232 impact on the potential of the ecosystem to produce biomass, the impact on climate and the impacts
233 on water and soil quantity and quality.

234 Crenna et al. (2018) evaluated the consequence of biotic resources depletion on ecosystem quality.
235 Crenna et al. (2019) showcases, using the preliminary LCA based impact assessment framework, the
236 role of EU food consumption in the current biodiversity decline. They studied the impact of the food
237 system on different impact categories (climate change, eutrophication etc.) and then measured the
238 rate of species lost in a particular area of land or volume of water during a particular time due to these
239 impacts. A different perspective has been proposed by Dewulf et al. (2015) to acknowledge this issue.
240 They recommend that instead of having 'natural resources' as an area of protection, LCA could have
241 the 'ecosystem functions or services' as a safeguard subject. For instance, instead of considering wood
242 from the forest as an asset to be protected, the functions trees provide to the ecosystem (e.g. climate
243 regulation, water purification) should be protected. These are proposals for bridging the gaps in LCA,
244 but could also be relevant for CE monitoring.

245 Concerning carbon accounting in LCA, carbon sequestration during biomass growth is commonly
246 accounted as negative emissions. But the temporal profile of carbon sequestration, storage and
247 emissions are not often considered (De Rosa et al., 2017). The attention towards this time-dependent
248 accounting of biogenic carbon flows has recently increased (Levasseur et al., 2010). Several
249 methodologies aim to integrate it in mainstream LCA (De Rosa et al., 2017), building on a time-
250 dependent life-cycle inventory data, which details emissions and sequestrations through time (i.e.,
251 the amount of carbon released or absorbed at every given time-step). The dynamics of carbon flux
252 significantly influence the LCA results, and therefore it is crucial to integrate the time-frames to
253 accurately assess the global warming impact of the use of bio-based materials and biological cycles.

254 4. Conclusion

255 The use of biotic resources is not necessarily circular and sustainable. Thus, a critical evaluation of the
256 biological cycles is essential in the context of CE, which is currently lacking. For more circular biological
257 systems, biotic resources should be sourced at a rate that ensures their long-term yields, should follow
258 an optimized cascading use pathway and should decompose at the end of their product life and return
259 to the biosphere to support the regeneration of the ecosystem. The processed bio-based materials
260 that do not decompose should be treated as part of a technical cycle and should be looped back in the
261 technosphere to maintain their material-value for as long as possible. Additionally, the biological
262 cycles have an environmental impact, specifically from resource extraction and biogenic carbon
263 emissions. Biotic resource extraction has a damaging effect on biodiversity, ecosystem health and
264 functioning, due to resource depletion and direct and indirect land-use change. These impacts should
265 be closely monitored within circularity frameworks. The use of bio-based materials is being
266 encouraged because of their potential environmental benefit over their fossil counterpart, which will
267 likely increase the demand for biotic resources. The circularity of biological cycles should be analyzed
268 to avoid overexploitation of natural resources and further degradation of ecosystems.

269 Therefore, a thorough CE monitoring of the biological cycles should assess (1) sustainable sourcing (2)
270 cascading use of materials (3) the extent to which nutrients effectively re-enter the biological cycles
271 and (4) the environmental impact of sourcing biotic resources and carbon fluxes. These assessments
272 do not necessarily have to be newly developed. Existing indicators and assessment frameworks from
273 different sectors could assist in filling the gap. This study highlights that bridging the gaps in current
274 CE assessment and making them apt also for biological cycles is crucial and would be a step forward
275 in ensuring sustainable and circular use of natural resources.

276 Declaration of interest

277 The authors declare that they have no known competing financial interests or personal relationships
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284 CRediT author statement

285 **Kranti Navare:** Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing.
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287 Supervision. **Karel Van Acker:** Writing - Review & Editing, Supervision, Project administration.

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