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How to monitor environmental pressures of a circular economy: An assessment of indicators

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Abstract

Understanding how a circular economy (CE) can reduce environmental pressures from economic activities is crucial for policy and practice. Science provides a range of indicators to monitor and assess CE activities. However, common CE activities, such as recycling and eco-design, are contested in terms of their contribution to environmental sustainability. This article assesses whether and to what extent current approaches to assess CE activities sufficiently capture environmental pressures to monitor progress toward environmental sustainability. Based on a material flow perspective, we show that most indicators do not capture environmental pressures related to the CE activities they address. Many focus on a single CE activity or process, which does not necessarily contribute to increased environmental sustainability overall. Based on these results, we suggest complementing CE management indicators with indicators capturing basic environmental pressures related to the respective CE activity. Given the conceptual linkage between CE activities, resource extraction, and waste flows, we suggest that a resource-based footprint approach accounting for major environmental inputs and outputs is necessary—while not sufficient—to assess the environmental sustainability of CE activities. As footprint approaches can be used across scales, they could aid the challenging process of developing indicators for monitoring progress toward an environmentally sustainable CE at the European, national, and company levels.

1 INTRODUCTION

In recent years, the circular economy (CE) has gained attention as a response to the increasing global environmental pressures emerging from the current expansive economic system (Korhonen, Honkasalo, & Seppälä, 2018; Maina, Kachrimanidou, & Koutinas, 2017). For instance, the European Union (EU) adopted an action plan for CE in 2015 (European Commission [EC], 2015), followed by the "Circular Economy package" in January 2018 (EC, 2018a). This EU policy aims for long-term economic growth, prevention of resource scarcity, and environmental protection. In terms of environmental sustainability, the action plan states that CE will "help avoid the irreversible damages caused by using up resources at a rate that exceeds the Earth's capacity to renew them [...]" (EC, 2015, p. 2). The action plan also argues that the plan itself will be "instrumental in reaching the Sustainable Development Goals (SDGs) by 2030, in particular Goal 12 of ensuring sustainable consumption and production patterns" (EC, 2015, p. 3). The EU thereby suggests there is a beneficial relationship between CE and sustainability, a statement that is contested in academia. Some studies suggest that CE has a conditional relation to sustainability, whereas others see trade-offs in the relationship to sustainability (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). We know little about the effects current CE efforts actually have on environmental sustainability.

Conceptually, CE relies on the notion that increased resource use efficiency through closed material loops will decrease material extraction, waste disposal, and, in turn, environmental pressures (Ghisellini, Cialani, & Ulgiati, 2016; Haas, Krausmann, Wiedenhofer, & Heinz, 2015; International Resource Panel [IRP], 2017; Tukker et al., 2014). The concept recognizes that environmental pressures are closely related to an overuse of natural resources, resulting in environmental damages that destabilize key earth system processes (IRP, 2017; Tukker et al., 2014; Wijkman & Rockström, 2012). Given the socioeconomic dependence on environmental processes, an essential precondition for a sustainable CE is that resource extraction is kept within levels of regeneration and that waste and emissions are kept within limits that allow ecosystems to continuously support human societies (Pearce & Turner, 1990). Such criteria align with the general understanding of environmental sustainability (Goodland, 1995).

Recent research explains CE as an umbrella concept (Blomsma & Brennan, 2017) for maintaining products and materials at their “highest utility and value” (Bocken, Olivetti, Cullen, Potting, & Lifset, 2017); it often refers to the *3R*: reduce, reuse, and recycle (Ghisellini et al., 2016; Haupt, Vadenbo, & Hellweg, 2017; Huysman, Schaepmeester, Ragaert, Dewulf, & Meester, 2017). Consequently, many CE initiatives focus on a single activity, such as recycling, eco-design, or product service systems (Annarelli, Battistella, & Nonino, 2016; Haupt et al., 2017; Mendoza, Sharmina, Gallego-Schmid, Heyes, & Azapagic, 2017). There is a risk for problem shifting and rebound effects when measures are limited to a single process within long supply chains and complex markets. For instance, Chakravarty, Dasgupta, and Roy (2013) and Zink and Geyer, (2017) suggest that CE can result in rebound effects, as increased resource efficiency would allow for increased production and consumption levels, thereby offsetting the environmental benefits. This is why the linkages between CE and environmental sustainability need to be more explicitly addressed and studied. This article shows if current approaches to assess CE sufficiently capture environmental pressures to monitor the progress toward environmental sustainability; and if not, what a possible approach would look like. Recognizing the importance of well-directed monitoring for policy compliance, we take a system perspective to assess proposed CE indicators and map to what extent and under which assumptions these indicators capture environmental pressures.

In this study, we identify the interrelations between CE activities and environmental pressures through mapping material flows. We review the literature on indicators framed as CE indicators and take a life cycle approach to assess the indicator's capabilities to capture environmental pressures. This feeds into current debates and developments of monitoring tools and guidance for an environmentally sustainable CE at both the microlevel (e.g., improved product design) and the macrolevel (e.g., EU or national strategies). By outlining the challenges of the different indicators and providing suggestions for CE monitoring, this article aims to help structure the development of CE monitoring tools in relation to the question of how to bring environmental sustainability back into CE, as called for by many scholars (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Mayer et al., 2018; Pauliuk, 2018). On the basis of these findings, this article also aims to inform policy discussions about an environmentally sustainable implementation and evaluation of CE policy. To this end, we discuss our results against the EU monitoring framework.

2 METHODOLOGY

This study was conducted based on the four steps shown in Figure 1. First, we defined environmental sustainability and identified *key environmental flows* for such a socioeconomic system. Second, we defined a material flow system model that captures interlinkages between CE activities and key environmental flows. Thereafter, we reviewed the literature to collect an illustrative set of indicators that are proposed to monitor CE; finally, we used the system model and the collected indicators to assess and analyze the indicators according to their characteristics.

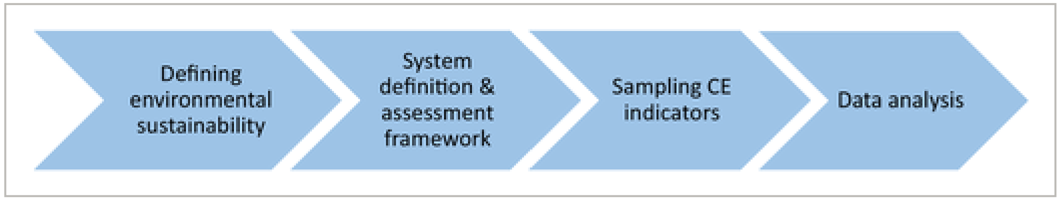

Figure 1

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Steps of the methodological approach used for the assessment of CE indicators

2.1 Defining environmental sustainability: The physical preconditions

Industrial ecology (IE) concepts of closing material loops (Frosch, 1992) and studying the interaction between the society and the environment as the industrial metabolism (Erkman, 1997) have fostered the debate around the CE. By adopting a more systemic, comprehensive, and integrated view of the industrial system and its interaction with the biosphere, and by promoting a transition toward a more sustainable "viable industrial ecosystem" (Erkman, 1997, p. 2), IE significantly influenced the conceptualization of CE (Iung & Levrat, 2014).

The introducers of the term CE, Pearce and Turner (1990), recognize three economic functions of the environment: the provision of resources, the environment as waste sink, and the utility value of the environment for human pleasure and well-being. The first two functions constitute essential physical preconditions for the sustainability of our society. Hence, the authors suggest a more holistic perspective on the economy—a circular perspective—that includes the economic functions of the environment. They conclude that the Earth is a closed system (except solar energy input) and that the capacity of the environment to comply with its different economic functions is thus limited. Following this, they suggest two main management rules to achieve a system than can sustain itself: First, the use of renewable resources should not exceed the pace of regeneration; second, the waste and emission flows going into the ecosphere should not exceed the limits that allow ecosystems to continuously support human societies (Bringezu, 2000; Goodland, 1995; Pearce & Turner, 1990). We define an environmentally sustainable CE as a system complying with these rules by means of CE activities (e.g., reuse, reduce, and recycle). What is needed is a feasible operationalization of such rules, also in combination with the current SDGs.

To illustrate the physical basis for the two main economic functions of the environment, Figure 2 shows a simplified global model of the dependence of the anthroposphere on the ecosphere, based on Bringezu (2000). The *input flow* represents the extraction of resources and the *output flow* represents waste and emissions going back into the ecosphere. We refer to these flows as the key environmental flows (cf. elementary flows in life cycle assessment [LCA]) of the socioeconomic metabolism, which determine the order of magnitude of environmental pressures. Figure 2 illustrates that biotic resource outputs to the ecosphere can be decomposed and a portion of the resulting nutrients may be taken up by living organisms on land and in water, while other portions (e.g., mineral waste) remain in the environment. Portions of CO_2 emissions may be regenerated into biomass via plant photosynthesis, which can be harvested in agriculture and forestry, while the rest may remain in the ecosphere. Resources that become input flows to the anthroposphere are either mineral (including fossil) or biomass, which consists of regenerated and non-regenerated components (with larger regenerated portions coming from agriculture, forestry, aquaculture, and minor portions from wild catch and logging of wilderness).

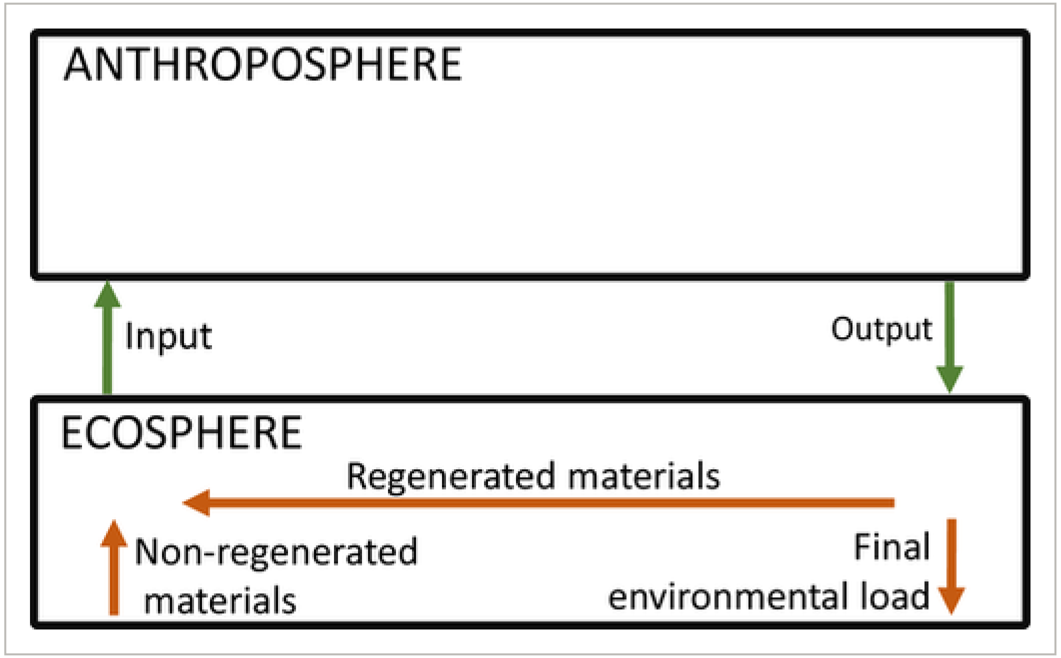

Figure 2

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Simplified model of the dependence of the anthroposphere on the ecosphere. The key environmental flows (input and output) define the interactions between the anthroposphere and the ecosphere. Input defines extraction of primary raw materials. Output defines release of waste and emissions into the ecosphere. Final environmental load describes non-regenerated emission or waste remaining in the environment (adapted from Bringezu, 2000)

Given the current pace of resource exploitation and environmental pressures, the key environmental flows must decrease to prevent unacceptable environmental changes (IRP, 2017; Ripple et al., 2017). This implies that extraction of non-regenerated materials as well as release of waste and emissions into the environment must decrease. Given the mass balance principle, material inputs (I) to a system always equal material outputs (O) plus net accumulation of stocks. Hence, in a period of time when the material stock in the anthroposphere is increasing (as is currently the case), I > O applies. This, in turn, limits the possibility of meeting material demand through CE activities (which redirect flows back to the societal stock instead of causing output flows to the environment).

2.2 System definition and assessment framework

To assess the capability of CE indicators to capture the physical preconditions for a sustainable CE, we identify which material flows each indicator addresses and how these relate to the key environmental flows. A generic material flow system model (Figure 3) forms the basis of our analysis. To support the assessment of diverse indicators, the system represents material flows and processes. It visualizes which life cycle stages different indicators address, irrespective of scale (e.g., product system, region, nation) or temporal scope (e.g., product lifetime, a year, a century). The model combines key elements of economy-wide material flow accounting (EW-MFA) and substance flow analysis (SFA), such as those developed by Graedel et al. (2011). To clarify how our system model relates to EW-MFA, Table 1 provides the corresponding EW-MFA indicators, given an EW application of the system in Figure 3. The model follows a simplified scheme of the industrial phases: extraction of raw materials, production, use, and waste management and recycling. Production refers both to material production and manufacturing (cf. Graedel et al., 2011; Pauliuk, 2018). To ensure that the key environmental flows capture all material flows causing environmental pressures, we consider as input flows to the anthroposphere the total material requirement (TMR)—the total extraction of primary materials, including both used and unused extraction from mining and biomass harvest, soil excavation, and dredging (Bringezu, Schütz, Steger, & Baudisch, 2004). One main component of TMR is the raw material input (RMI), which only includes the used parts of the extraction. Subsequently, the output flow—the final waste disposal (FWD)—consists of solid waste and gas emissions occurring from all anthropogenic processes: from raw material extraction to waste management.

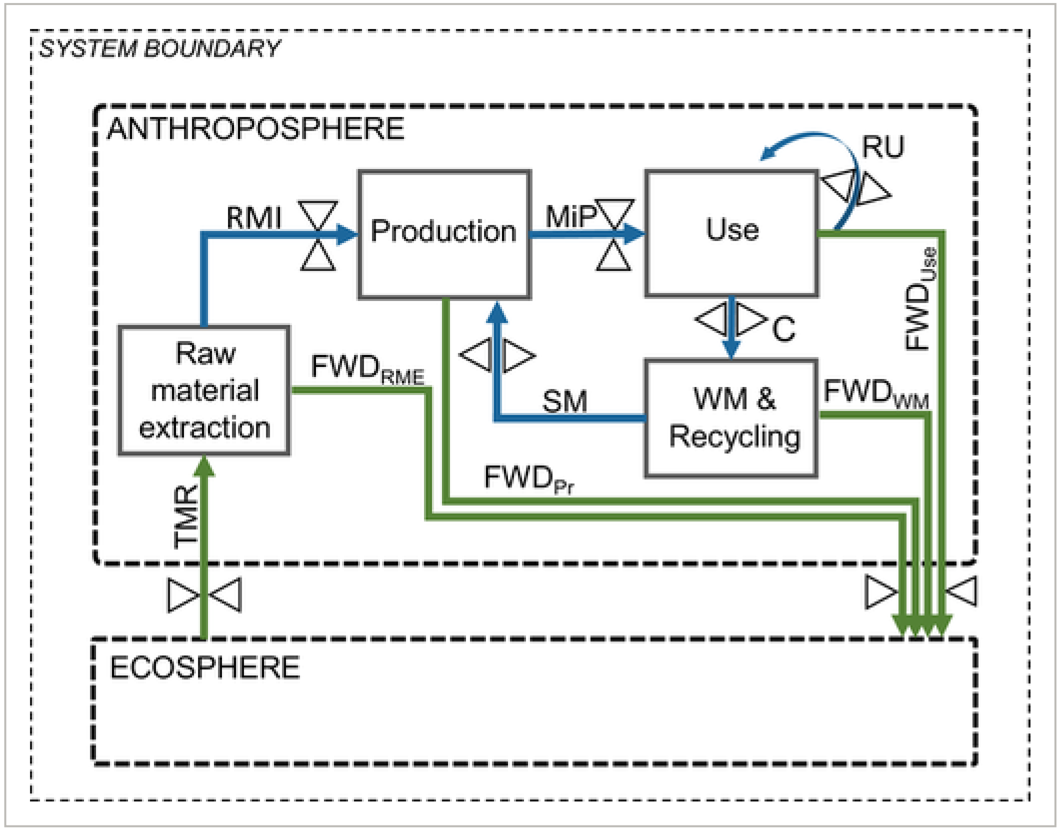

Figure 3

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Simplified system model defining material flows and processes relevant for a circular economy. Green arrows indicate key environmental flows and blue arrows represent material flows mainly related to CE activities within the anthroposphere. Desired decrease or increase in material flows are indicated by triangles. The use phase is central for CE in terms of time delay within this process, defining the durability of a product or material. C, materials collected for recycling; FWD_{Pr}, FWD from production; FWD_{RME}, final waste disposal from raw material extraction; FWD_{Use}, FWD from the use phase; FWD_{WM}, FWD from waste management and recycling; MiP, materials in product; RMI, raw material input; RU, reuse (redistribution for reuse or refurbishment); SM, secondary materials; TMR, total material requirement

Table 1. Denotation of flows, acronyms, and their corresponding indicator for economy-wide material flow accounting (EW-MFA) based on Fischer-Kowalski et al. (2011), Mayer et al. (2018), and Organisation for Economic Co-operation and Development (OECD, 2008)

Flow	Indicator in EW-MFA
Total material requirement (TMR)	TMR
Raw material input (RMI)	RMI
Materials in product (MiP)	n.a.
Reuse (RU)	n.a.
Secondary materials (SM)	SM
Final waste disposal from processing (FWD_{Pr} + FWD_{Use} + FWD_{WM})	Domestic processed output (DPO)
Final waste disposal (FWD_{Pr} + FWD_{Use} FWD_{WM} + FWD_{RME})	Total domestic output (TDO)

Note. FWD_{RME} is the disposal of the unused extraction; FWD along extraction–production–consumption–recycling chains may be spread across different countries, whereas DPO and TDO relate to a specific country.

If we were to avoid further increasing the environmental burdens of TMR and FWD, a greater use of materials and products is only possible by increasing durability in use, reuse rates (RU), and flows of secondary materials (SM) from recycling, or by reducing the RMI for products and services. The desired changes in material flows are indicated in Figure 3 by triangles, pointing toward the flow in the case of decrease and away from the flow in the case of increase. Increased durability in use improves resource efficiency because a longer (or more intense) use phase leads to less material per functional unit and possibly postpones the demand for new products, which slows down material cycles.

If the object of analysis is a certain product system, a number of market mechanisms play a role. For instance, decreasing metal use in one product system may result in an increase of this metal in another product system due to scrap market dynamics. Likewise, price fluctuations, substitution of materials, rebound effects, and other mechanisms can lead to burden shifting (Zink & Geyer, 2017).

Therefore, the implications of the sectoral scope as well as the aggregation level of the analysis should be carefully assessed, particularly at product level.

The generic system model can also be applied to an economic system defined through political or geographical boundaries (e.g., country or region). In this case, import and export flows need to be taken into account, including their upstream or downstream flows.

2.3 Sampling CE indicators

Monitoring metrics to assess the progress toward CE are being debated (Elia, Gnoni, & Tornese, 2017; Mayer et al., 2018; Pauliuk, 2018) and recent attempts to develop general metrics differ in aim and scope, resulting in diverse coverage and focus (Elia et al., 2017; Iacovidou et al., 2017; Linder, Sarasini, & van Loon, 2017; Pauliuk, 2018; Tecchio, McAlister, Mathieux, & Ardente, 2017). Given the wide range of perspectives, formats, and scales, Saidani, Yannou, Leroy, Cluzel, and Kendall (2018) suggest a taxonomy of different CE indicators. However, many reviews address specific aspects of CE, such as resource efficiency (Huysman et al., 2015), eco-innovation (Smol, Kulczycka, & Avdiushchenko, 2017), or resource recovery from waste (Iacovidou et al., 2017). At the product and organizational levels, possible metrics are discussed by Tecchio et al. (2017) and Pauliuk, (2018), respectively. At an EW level, Moriguchi (2007) suggests indicators for a "sound material-cycle society" and Takiguchi and Takemoto (2008) present indicators for the Japanese 3R Policies. Mayer et al. (2018) suggest a set of indicators for the EU based on material flow analysis with the premise that CE "should contribute to the reduction of environmental pressures instigated by resource use" (p. 2).

EU policy suggests a monitoring framework focusing on waste (e.g., waste generation and food waste) and recycling (e.g., recycling rates [RRs], contribution of recycled materials to raw materials demand), complemented with more economic and socially oriented indicators (EC, 2018b). The list of indicators for measuring progress toward SDG 12, which the CE policy aims to support, includes material footprints and domestic material consumption, both per capita and per GDP (SDG 12.2), as well as national RRs and tons of materials recycled (SDG 12.5).

For the purpose of our analysis, we generated a sample of indicators that represents current approaches to measure and assess CE. Given the broad field of indicators that are related to different aspects of the CE, we created an illustrative set of indicators that reflects current CE discourses at various scales. As the starting point for our analysis are current EU policy efforts for the realization and monitoring of a CE, we expect that approaches and indicators directly referring to the term CE are most likely to be recognized as relevant in policy debates. We conducted a literature search focusing on the key term "circular economy" to ensure that all publications clearly refer to CE. We searched for peer-reviewed journal articles, reviews, and editorials dealing with indicators monitoring CE. The search was done in Web of Science, covering publications available in English up until December 1, 2017. We combined the CE keywords with “framework,” “methodology,” “indicators,” “implementation,” or “review.” For a more specific coverage, we added “sustainability,” “sustainable,” “consumption,” “reduction,” “recycling,” “reuse,” “remanufacturing,” “environmental,” “extraction,” “resources,” “raw material*,” or “material*.” This resulted in 354 articles, which we then screened to select papers explicitly addressing CE indicators. Cross-references from selected papers were used to capture indicators broadly accepted as CE indicators coming from gray literature. The review resulted in 10 CE indicators from 10 papers that aim to illustrate CE discourses (see results, Table 2).

Table 2. Summary of indicators showing name, description, objective, covered material flows, and choice of unit

Life cycle phase	Indicator	Description	Objective	Flows/processes							
				TMR	RMI	MiP	RU	Use	C	SM	FWD
Production	Value-based resource efficiency (VRE; Di Maio et al., 2017)	Value added/value of inputs	Decouple economic growth from material input (particularly addressing scarce materials) and decrease environmental impacts.		M	M					
	Product-level circularity (PLC; Linder et al., 2017)	Economic value of recirculated parts/economic value of all parts	Increase the use and demand of secondary raw materials in products, particularly of expensive and scarce materials. Decouple economic growth from environmental degradation.			M				M	

Life cycle phase	Indicator	Description	Objective	Flows/processes							
				TMR	RMI	MiP	RU	Use	C	SM	FWD
	Circularity index (CI;	Function of (a) recycled	Support development toward a		X					X	

Note. Indicators are grouped according to life cycle phases (left). The objective describes the desired future development reflected in each article. Definitions of flows are found in Figure 3.

Abbreviations: C, materials collected for recycling; FWD, final waste disposal; MiP, material in product; RMI, raw material input; RU, reuse; SM, secondary materials; TMR, total material requirement. Units are indicated with letters: E, energy; E_X, exergy; M, monetization; T, time; X, mass.

2.4 Data analysis

Indicators collected from the literature review were structurally assessed using the generic system model in Figure 3. For each indicator, the addressed material flows and ratios were identified and formulated according to the definitions of flows suggested in Figure 3. Several indicators do not measure physical material flows or do not solely focus on material flows but include, for instance, aggregated environmental impacts or economic value. In these cases, the most central flows or processes contributing to this measure were identified. For instance, product value relates to the flow materials in product (MiP), as this describes the phase when the product is purchased (Figure 3). Depending on the system definition used by the authors, flows must be interpreted to fit our system definition. When the system model or flow definition in the articles is considerably different, this is pointed out in the results. However, the interpretation of flows through our system model provides a sufficiently accurate picture of which parts of the system each indicator addresses.

To understand the underlying rationale and context of the indicators' development processes, we aimed to capture the authors' CE visions by analyzing the characteristics of the indicators, such as units, the proposed aim, and the motivation of usage. An overall picture of the CE vision reflected in each article and through the design of the respective indicator was summarized as its objective. The choice of unit was added as a separate characteristic. To facilitate the assessment of direct and indirect connections between material flows in the anthroposphere and the key environmental flows, we grouped the indicators according to the addressed life cycle phase(s). Based on Tecchio et al. (2017), we defined the life cycle phases as production phase, use phase, and end of life. For simplicity, we included extraction of raw material in the production phase. This resulted in an analytical framework consisting of four characteristics:

1. Addressed material flow(s)
2. Objective(s)
3. Unit(s)
4. Addressed life cycle phase(s)

3 RESULTS

This section presents the CE indicators in relation to the addressed flows, objectives, and units of measure, and is structured according to the life cycle phases (Table 2).

3.1 Production phase: Reducing input flows?

The three indicators in this category assess relations of flows entering or leaving the production phase and calculate ratios in relation to the material use in production: value-based resource efficiency (VRE; Figure 4a), product-level circularity (PLC; Figure 4b), and circularity index (CI; Figure 4c).

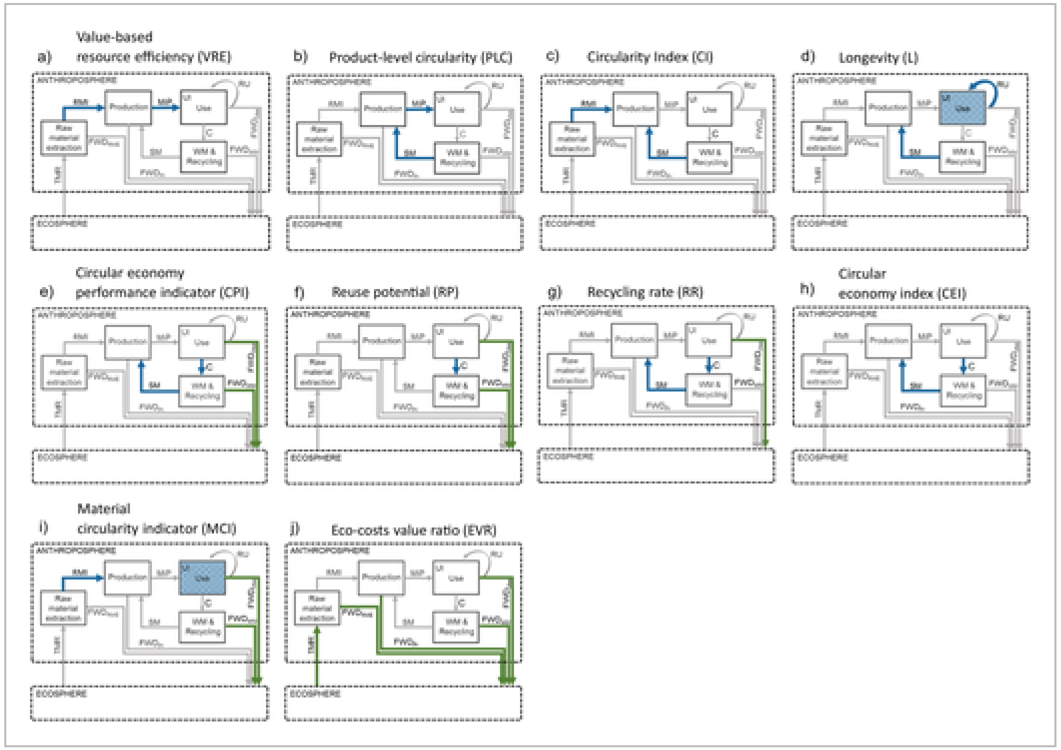

Figure 4 Open in figure viewer | PowerPoint

Illustration of the covered flows by each indicator. Green and blue arrows indicate the coverage of the indicator. Green arrows reflect key environmental flows and blue arrows are flows representing CE activities within the anthroposphere. (a) Value-based resource efficiency (VRE). (b) Product-level circularity (PLC). (c) Circularity index (CI). (d) Longevity (L). (e) Circular economy performance indicator (CPI). (f) Reuse potential (RP). (g) Recycling Rate (RR). (h) Circular economy index (CEI). (i) Material circularity indicator (MCI). (j) Eco-costs value ratio (EVR). C, materials collected for recycling; FWD, final waste disposal; MiP, materials in product; RMI, raw material input; RU, reuse; SM, secondary materials; TMR, total material requirement

VRE, suggested by Di Maio, Rem, Baldé, and Polder (2017), measures resource efficiency in terms of economic value, namely the economic value of the product over the economic value of the input flow. PLC, suggested by Linder et al. (2017), addresses the ratio of the economic value of recycled content to the economic value of the final product. This aims to stimulate producers and consumers to increase the portion of recycled materials and increase the demand for recycled materials in production. Both papers argue that economic value better reflects resource availability and is therefore an appropriate unit for resource efficiency. In addition, Di Maio et al. (2017) argue that externalized environmental costs should be addressed by governmental measures and covered by appropriate taxes.

CI, suggested by Cullen (2017), aims to assess the circularity of a system, taking into account both the quality and quantity of end-of-life materials. The quantity is assessed as the ratio of recycled materials to RMI, whereas the quality is quantified by calculating the energy requirement for material recovery in relation to the energy requirement for raw material extraction. The product of the two gives the CI. A perfect CE would have a CI = 1, which should be seen as a theoretical benchmark. Due to entropy and material losses, this is physically impossible (Cullen, 2017).

Although VRE focuses on resource efficiency of raw materials, PLC and CI aim to improve the use of recycled materials in production. Following the authors' argumentation, a common underlying objective of the three indicators seems to be to decrease input flows to the anthroposphere. Yet none of them captures TMR. In order for these indicators to give an indication of TMR, waste flows from raw material extraction and production must be insignificant, which is an unrealistic assumption.

3.2 Use phase: Managing stocks?

Only one indicator focuses on the use phase of a product, namely the longevity (L), suggested by Franklin-Johnson, Figge, and Canning (2016). Longevity assesses how long the materials in a product remain within the anthroposphere by computing the sum of three time periods: product lifetime, refurbished/reused lifetime, and recycled lifetime (Figure 4d). Even though the calculation depends on several life cycle stages (e.g., recycling and redistribution after the first life cycle), the measure addresses the total time the product or material is in use, which is why it is categorized as focusing on the use phase.

Franklin-Johnson et al. (2016) argue that longevity seeks to determine the degree to which a system is circular. A perfectly circular system would have a longevity equal to infinity, where materials circulate (e.g., are reused, repurposed, remanufactured, or recycled) indefinitely in the anthroposphere. Based on our system perspective, the underlying objective is to improve the use and management of the anthropogenic stock. The longevity of products and materials contributes to a decrease in input flows under the condition that the stock of materials replaces the raw materials entering production. This also directly postpones and/or decreases output flows.

3.3 End of life: Reducing output flows?

The end-of-life indicator group focuses on flows leaving the use phase, either by being collected for recycling (flow C) or by going directly into the environment as FWD. It includes the CE performance indicator, reuse potential (RP), RR, and circular economy index (CEI; see Figure 4e–h).

Circular economy performance indicator (CPI), suggested by Huysman et al. (2017), aims to define the performance of a plastic waste treatment process in relation to the best available treatment option in terms of environmental benefits. CPI is defined as the ratio of the environmental benefits of the current treatment to the environmental benefits of the best available treatment option for the assessed waste flow. Benefits are measured in exergy and computed according to the principle of substitution (i.e., avoided impacts from extraction). Accordingly, the ideal CE would be CPI = 1. Figure 4e shows the scope of the indicator in terms of addressed flows. As the quality of some flows from the use phase might be too low for recycling, they go to FWD, possibly through incineration (Figure 4e).

RP, suggested by Park and Chertow (2014), focuses on assessing the quality of a waste flow. It thereby aims to answer how “resource-like” or “waste-like” a certain flow is. Focusing on waste flows, RP calculates the portion of waste that can be economically recovered with existing technologies. This means that RP measures the physical flow of generated material surplus (corresponding to the sum of the materials leaving the use phase in our system model—see Figure 4f) and captures design elements in terms of material choices. Thus, it does not assess any particular CE activity such as recycling, but only the potential that a certain material flow offers to implement a profitable CE activity.

Both RR suggested by Haupt et al. (2017) and CEI suggested by Di Maio and Rem (2015) assess RRs, but have some fundamental differences. First, RR calculates the ratio of material recovered through the recycling process to the total amount of waste flows, including waste not collected for recycling (the sum of C and FWD in Figure 4g). CEI, on the other hand, solely includes the materials going into the recycling facility (measured at point of collection, Figure 4h). However, CEI is based on a system definition that does not differentiate between the material going into the recycling facility and the material needed for (re)producing a new product, meaning they assume that all end-of-life products can be recycled to the same quality. Second, they differ in choice of unit. RR measures the ratio in mass, whereas CEI measures the economic value, meaning the ratio of economic value of recycled parts to economic value of materials needed for (re)producing the same product (they assume the same flow for end-of-life products as for materials for recycling).

The four end-of-life indicators have different objectives and scopes. CPI addresses the environmental burden of waste treatment (Huysman et al., 2017) and RR seeks to minimize material losses and optimize materials and energy consumption (Haupt et al., 2017). In contrast, the objectives of RP and CEI include economic profitability as a central aspect of CE. However, the overarching objective of RR, RP, and CEI is to redirect waste toward production.

In terms of their ability to capture the key environmental flows (inputs and outputs), CPI, RR, and RP capture FWD in terms of solid waste but not emissions to air, water, or soil. CEI captures the solid waste part of FWD only under the unrealistic condition that all end-of-life materials are collected. Under the condition that recycled materials substitute for raw materials, the rate of material recovery can affect RMI and in turn TMR, the input material flows from the environment.

3.4 Across life cycle phases: Capturing the whole picture?

Two of the assessed indicators measure material flows across several life cycle phases. As Figure 4i,j demonstrates, material circularity indicator (MCI) and eco-costs/value ratio (EVR) cover flows in various phases of the life cycle.

MCI, suggested by Ellen MacArthur Foundation and GRANTA DESIGN (2015), is defined through a function of virgin feedstock, waste generation, and product utility (see indicated flows/processes in Figure 4i; for detailed function, see Ellen MacArthur Foundation & GRANTA DESIGN, 2015). It is a comparative indicator where the utility factor is defined in relation to an average product. It assumes that recovered material can be processed into a similar quality as the original virgin material.

Scheepens, Vogtlander, and Brezet (2016) suggest EVR as a CE indicator. EVR was developed as an indicator for eco-efficiency and was first introduced by Vogtländer, Brezet, and Hendriks (2001) and updated in 2007 and 2012 (Scheepens et al., 2016). Based on LCA, it calculates the environmental impacts in relation to economic value of the product. The environmental impacts, measured as "eco-costs," are calculated as the costs of preventing environmental damages. The EVR calculates the eco-costs over the economic value of the product.

Looking at the objective behind the indicators, MCI simultaneously addresses the key environmental flows and the utility of the resources. EVR measures economic value in relation to environmental burden with the motivation that, given current consumption patterns, economic value accounts for the risk of rebound effects of savings. Thus, their overarching objective is the net reduction of environmental impacts (Scheepens et al., 2016).

In terms of addressed key environmental flows, MCI does not capture input flows but includes RMI and output flows. For EVR, the cradle-to-grave approach aims to capture key environmental flows emerging along the whole life cycle of products or services. However, system boundaries are not defined in a way that explicitly captures the TMR. Therefore, neither the environmental impacts nor the associated costs of resource extraction are sufficiently reflected in either of these indicators.

4 DISCUSSION

The results show that the majority of the indicators capture only parts of the material cycles (Figure 4). Although key environmental flows between the anthroposphere and ecosphere are addressed by some indicators, they are not captured sufficiently. EVR aims to capture the key environmental flows in terms of monetized values, but it fails to directly address input flows in terms of TMR. None of the indicators accomplish this; as for output-oriented indicators, most ignore emissions to air, water, and soil. Subsequently, none of the proposed indicators can judge the net environmental pressures of CE activities; thus, they lack the perspective of physical preconditions for a sustainable CE.

In the following sections, we discuss these results in light of the methodological approach, addressing gaps, needs, and possible indicators that can support a sustainable CE transition; subsequently, we reflect upon the monitoring framework suggested by the EU, followed by conclusions.

4.1 A systems perspective on material management and environmental flows

The selection of papers illustrates different aspects novel CE indicators address. While recognizing that CE relevant indicators are not necessarily framed in CE terms, the selection criteria provide a set of indicators that reflects some general tendencies in CE discourses. We discuss these in light of the physical preconditions for a sustainable economy and current CE debates.

The results present diverse uses of the term CE. Indicators claiming to address the CE often solely address specific parts of what a CE comprises. For instance, CPI addresses waste treatment of plastic and CI measures RRs in material value: Although these indicators address operational aspects of the circular system that Pearce and Turner (1990) describe as an expansion of the traditionally constructed economic system, they do not take a sufficiently wide system perspective. Depicting only selected sections of the socioeconomic metabolism bears the risk of problem shifting. There is a need to operationalize the management rules for sustainability through indicators that can (a) be attributed to CE activities in production and consumption, (b) be influenced by actors (through product design, policy regulations, etc.), and (c) represent basic environmental pressures. From a metabolic perspective, output flows are determined by input flows and the net accumulation of material stocks. Thereby, CE activities can be seen as means to improve the material management to reduce input and output flows. For instance, the overarching objective of most end-of-life indicators is to redirect waste toward production (e.g., CI and PLC). Similar to the objectives of longevity, these measures would subsequently contribute to prolonging material maintenance. However, to match material input to production with end-of-life materials, the stock needs to be constant over time and all materials need to be recovered. This would imply that the flows are in a dynamic equilibrium (I = O at all times) and correspond to a steady-stock society (Bringezu & Bleischwitz, 2009). With today's growing anthropogenic stock, not even 100% recycling would meet the demand for raw materials (cf. Haas et al., 2015). In this sense, a system perspective including key environmental flows is necessary to assess the contribution of CE to environmental sustainability. RRs and other indicators measuring CE activities are insufficient to capture the physical preconditions for a sustainable CE. Therefore, any monitoring of progress toward a sustainable CE needs to link CE activities to the sustainability of the overall economy, including possible contributions or countereffects from CE activities.

To differentiate between indicators that measure CE activities (e.g., recycling, life-time extension), which dominate our sample, and the CE aspects that aim at sustainable levels of key environmental flows (cf. Pearce & Turner, 1990), we see the need to clarify the CE terminology. We suggest referring to CE activities as improved material management in the anthroposphere and to its indicators—like RR and secondary input rate—as *CE management indicators*. In this context, CE management equates with: (a) redirecting societal stocks that would go to FWD back into production and/or (b) increasing material use efficiency and effectiveness through material reduction, extended lifetime, and/or increased use intensity. It is worth pointing out that this definition implies that reusability, recyclability, and other ex ante valuations such as "reuse potential" are not considered CE management. Nevertheless, ex ante valuations are helpful in the anterior stages of planning and design for circularity. As previous research shows (Zink & Geyer, 2017) and our forgoing discussion concludes, CE activities do not necessarily contribute to decreased environmental pressures. If CE is to play a role in environmental sustainability, CE management indicators must be complemented with objective-oriented CE indicators, quantifying key environmental flows per time unit, and thus measuring the *environmental performance* resulting from the CE activity. CE environmental performance indicators should reflect basic environmental pressures related to the CE activities (TMR and FWD in Figure 3).

4.2 Monitoring CE environmental performance: Gaps and needs

Given the conceptual and political objectives of CE (EC, 2015; Pearce & Turner, 1990), indicators should capture the sustainability management rules for resource use, waste, and emission (Goodland, 1995). Monitoring TMR corresponds directly to the rate of resource use. Yet, to monitor the state of the environment and the subsequent environmental impacts, which in turn affect the carrying capacity, environmental pressures provide a limited amount of information: place- and context-dependent environmental impacts play a crucial role. The DPSIR framework describes these causal networks in terms of drivers, pressures, states, impacts, and responses (European Environment Agency [EEA], 1999). In this framework, drivers relate to *CE management* indicators and include indicators for recycling, eco-efficiency, and other CE activities (e.g., VRE, PLC, CI, L, CEI, RR). Measures of the key environmental flows, TMR and FWD, are pressure indicators. They are associated with the extraction of mineral and biomass resources (e.g., landscape changes) as well as pressures associated with the final release of emissions into the soil, water, and air (e.g., greenhouse gas emissions).Pressures defined by the key environmental flows can also be classified as “inventory-oriented resource footprints” (input flows) and “inventory-oriented emission footprints” (output flows; Fang et al., 2016). The extent to which such pressure-oriented footprints measure environmental sustainability is disputed. Verones, Moran, Stadler, Kanemoto, and Wood (2017) showed that there are significant differences between pressure and impact indicators at national and global level. Similarly, pressure footprints have been criticized for neglecting aspects such as scarcity or criticality (Fang et al., 2016). However, material scarcity or criticality in its original understanding is an economic issue rather than an environmental problem (EC, 2018c; Graedel, Harper, Nassar, Nuss, & Reck, 2015). Material footprints, nevertheless, not only are aggregate results of an inventory but also carry a meaning with regard to environmental pressure. Steinmann, Schipper, Hauck, and Huijbregts (2016) assessed the capacity of resource footprints to reflect environmental impacts. They showed that the footprints of fossil energy, land, material, and water affect the magnitude of various impact bundles; the four footprints captured 84% of the specific environmental impacts addressed by 135 mostly output-oriented LCA indicators (Steinmann et al., 2016).

In this sense, the four resource-based footprints constitute a valid tool to reflect the environmental pressures instigated from resource use. Moreover, environmental footprints are applicable at different scales, for instance, using life cycle tools to capture whole life cycles of products (Fang & Heijungs, 2015) or input–output analysis at a macroscale (Lutter, Giljum, & Bruckner, 2016), which is commonly on a “cradle-to-use” basis for the consumed products and also includes the resources required for domestic waste management and recycling. Whether the system of interest is a product system or service system, an infrastructure, or a whole economy, we suggest that resource-based footprints are suitable to monitor CE environmental performance.

To monitor progress toward an environmentally sustainable CE, we need to define an acceptable level of environmental change and related target values. The well-known concept of “planetary boundaries” (Steffen et al., 2015) provides benchmarks for environmental footprints (Fang, Heijungs, & De Snoo, 2015; Laurent & Owsianiak, 2017). These have shown to be applicable, for instance, through an assessment of the environmental footprints of Switzerland (Dao, Peduzzi, & Friot, 2018). For the four footprints, estimations or suggestions for science-based targets at different scales exist (Bringezu, 2015; Fang, Heijungs, Duan, & De Snoo, 2015; Hoekstra & Mekonnen, 2012; Ridoutt & Pfister, 2010; Tukker et al., 2014) and will be further developed.

4.3 Supporting monitoring of policy implementation

In processes related to resource efficiency policies, appropriate targets and indicators have played a central role for decades (IRP, 2017). However, essential elements of these processes have not yet fed into the EU monitoring framework for the CE. For instance, the suggested monitoring framework for the CE in the EU focuses on RRs and other waste-related activities; it does not adopt a sufficiently comprehensive system perspective, nor does it outline targets (EC, 2018b). This narrow focus is criticized in a motion arguing that the framework fails to address the relationship between economic activities and resource use and that it lacks "an indicator measuring whether the overall consumption of primary raw material declines with increasing use of secondary raw material" (European Parliament, 2018, p. 4). Furthermore, the monitoring framework does not account for major waste flows, in particular from mining activities. On the other hand, the list of indicators for SDG 12.2, aiming for a sustainable management and efficient use of natural resources, includes the previously suggested indicator of material footprints. Thus, environmental performance indicators for sustaining a CE may eventually be adopted by policy, but need to be further developed and included in the CE monitoring framework. If the framework aims to monitor the progress toward an environmentally sustainable CE in the EU, we argue that it would greatly benefit from a system perspective that captures all key environmental flows. Even though RRs are an important CE activity, our analysis shows that RRs and other activity-oriented indicators do not reveal information about the net environmental benefits for the socioeconomic system.

5 CONCLUSIONS

If political and scientific efforts aim to promote a CE that contributes to environmental sustainability, it is important to carefully examine the interrelations between CE activities and environmental pressures. We argue that this engagement is pivotal and urgent because the CE is conceptualized very broadly in political and scholarly debates, and scientists and policymakers closely relate it to the achievement of the SDGs. Hence, CE may turn into a new focal point for political sustainability efforts in the EU. To support such engagement, we took a system perspective to assess to what extent this interrelation is captured by indicators framed as CE indicators. Conceptually, a CE recognizes that environmental pressures are closely related to material use and if we want to lower environmental pressures, materials need to be circulated and efficiently used. At the same time, researchers have shown that there is a risk of burden shifting and that CE activities do not necessarily contribute to decreased environmental pressures. Our analysis shows that most of the assessed indicators address a single activity or a part of the material or product's life cycle. This risks obscuring possible burden shifting. To ensure that the imposed CE activity is contributing to the aim of environmental sustainability, the suggested indicators should be complemented with measures of environmental pressures. Because of the conceptual link between CE, resource use, and environmental pressures, we suggest that a material- and resource-based footprint approach, accounting for major environmental inputs and outputs, is necessary—while not sufficient—to assess the environmental sustainability of CE activities. Footprints can be used at different scales, depending on the CE activity they aim to assess. Thus, it can be used inter alia by companies, cities, and national and supranational bodies for monitoring and evaluation to support resource governance and waste management.

Considering that many scholars call to bring environmental sustainability back in to CE, our findings suggest that a crucial step toward adequate indicators is to ensure that monitoring can support a CE transformation toward a sustainable exchange between the ecosphere and human societies. Full information on the actual exchange is a step toward this end.

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AUTHOR CONTRIBUTIONS

All authors were responsible for the conception and design of the study. Sina Leipold conceived the original idea of the article. Hanna Helander undertook data collection and analysis and took the lead in writing the manuscript. Anna Petit-Boix, Sina Leipold, and Stefan Bringezu provided substantial input during framework development, data collection, analysis, and interpretation and critically revised the draft for important intellectual content. All authors gave their final approval to the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Annarelli, A., Battistella, C., & Nonino, F. (2016). Product service system: A conceptual framework from a systematic review. *Journal of Cleaner Production*, **139**, 1011– 1032. https://doi.org/10.1016/j.jclepro.2016.08.061
Crossref | Web of Science® | Google Scholar

Blomsma, F., & Brennan, G. (2017). The emergence of circular economy: A new framing around prolonging resource productivity. *Journal of Industrial Ecology*, **21**(3), 603– 614. https://doi.org/10.1111/jiec.12603
Wiley Online Library | Web of Science® | Google Scholar

Bocken, N. M. P., Olivetti, E. A., Cullen, J. M., Potting, J., & Lifset, R. (2017). Taking the circularity to the next level: A special issue on the circular economy. *Journal of Industrial Ecology*, **21**(3), 476– 482. https://doi.org/10.1111/jiec.12606
Wiley Online Library | Web of Science® | Google Scholar

Bringezu, S. (2000). *Ressourcennutzung in Wirtschaftsräumen: Stoffstromanalysen für eine nachhaltige Raumentwicklung. Springer eBook collection*. Berlin: Springer.
Crossref | Google Scholar

Bringezu, S. (2015). Possible target corridor for sustainable use of global material resources. *Resources*, **4**(1), 25– 54. https://doi.org/10.3390/resources4010025
Crossref | Google Scholar

Bringezu, S., & Bleischwitz, R. (2009). *Sustainable resource management: Global trends, visions and policies*. New York, NY: Routledge.
Google Scholar

Bringezu, S., Schütz, H., Steger, S., & Baudisch, J. (2004). International comparison of resource use and its relation to economic growth. *Ecological Economics*, **51**(1–2), 97– 124. https://doi.org/10.1016/j.ecolecon.2004.04.010
Crossref | Web of Science® | Google Scholar

Chakravarty, D., Dasgupta, S., & Roy, J. (2013). Rebound effect: How much to worry? *Current Opinion in Environmental Sustainability*, **5**(2), 216– 228. https://doi.org/10.1016/j.cosust.2013.03.001
Crossref | Web of Science® | Google Scholar

Cullen, J. M. (2017). Circular economy: Theoretical benchmark or perpetual motion machine? *Journal of Industrial Ecology*, **19**(5), 23. https://doi.org/10.1111/jiec.12599
Google Scholar

Dao, H., Peduzzi, P., & Friot, D. (2018). National environmental limits and footprints based on the planetary boundaries framework: The case of Switzerland. *Global Environmental Change*, **52**, 49– 57. https://doi.org/10.1016/j.gloenvcha.2018.06.005
Crossref | Web of Science® | Google Scholar

Di Maio, F., & Rem, P. C. (2015). A robust indicator for promoting circular economy through recycling. *Journal of Environmental Protection*, **6**(10), 1095–1104. https://doi.org/10.4236/jep.2015.610096
Crossref | Google Scholar

Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources, Conservation and Recycling*, **122**, 163– 171. https://doi.org/10.1016/j.resconrec.2017.02.009
Crossref | Web of Science® | Google Scholar

European Commission (EC). (2015). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Closing the loop—An EU action plan for the circular economy*. Brussels.
Google Scholar

European Commission (EC). (2018a). *Circular economy: Implementation of the circular economy action plan*. Retrieved from http://ec.europa.eu/environment/circular-economy/index_en.htm
Google Scholar

European Commission (EC). (2018b). *Measuring progress towards circular economy in the European Union—Key indicators for a monitoring framework: Accompanying the document*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social

Committee and the Committee of the Regions on a Monitoring Framework for the Circular Economy, Strassbourg. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018SC0017&from=EN
Google Scholar

European Commission (EC). (2018c). *Report on critical raw materials and the circular economy*. Luxembourg. Retrieved from https://publications.europa.eu/en/publication-detail/-/publication/d1be1b43-e18f-11e8-b690-01aa75ed71a1/language-en
Google Scholar

European Environment Agency (EEA). (1999). *Environmental indicators: Typology and overview* (Technical Report No. 25). Copenhagen, Denmark: Author.
Google Scholar

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, **142**(4), 2741– 2751. https://doi.org/10.1016/j.jclepro.2016.10.196
Crossref | Web of Science® | Google Scholar

Ellen MacArthur Foundation, & GRANTA DESIGN. (2015). *Circularity indicators: An approach to measuring circularity—Methodology*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Methodology_May2015.pdf
Google Scholar

Erkman, S. (1997). Industrial ecology: An historical view, *5*(1–2), 1–10. https://doi.org/10.1016/S0959-6526(97)00003-6
Google Scholar

European Parliament. (2018). *Draft motion for a resolution: Pursuant to Rule 133 of the Rules of Procedure on monitoring framework for the circular economy*. B8-0000/2018. Retrieved from http://www.europarl.europa.eu/meetdocs/2014_2019/plmrep/COMMITTEES/ENVI/RE/2018/06-20/1155453EN.pdf
Google Scholar

Fang, K., & Heijungs, R. (2015). Rethinking the relationship between footprints and LCA. *Environmental Science & Technology*, **49**(1), 10– 11. https://doi.org/10.1021/es5057775
Crossref | CAS | PubMed | Web of Science® | Google Scholar

Fang, K., Heijungs, R., Duan, Z., & De Snoo, G. R. (2015). The environmental sustainability of nations: benchmarking the carbon, water and land footprints against allocated planetary boundaries. *Sustainability*, **7**(8), 11285– 11305. https://doi.org/10.3390/su70811285
Crossref | CAS | Web of Science® | Google Scholar

Fang, K., Heijungs, R., & De Snoo, G. R. (2015). Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework. *Ecological Economics*, **114**, 218– 226. https://doi.org/10.1016/j.ecolecon.2015.04.008
Crossref | Web of Science® | Google Scholar

Fang, K., Song, S., Heijungs, R., Groot, S., Dong, L., Song, J., & Wiloso, E. (2016). The footprint's fingerprint: On the classification of the footprint family. *Current Opinion in Environmental Sustainability*, **23**, 54– 62. https://doi.org/10.1016/j.cosust.2016.12.002
Crossref | Web of Science® | Google Scholar

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., … Weisz, H. (2011). Methodology and indicators of economy-wide material flow accounting. *Journal of Industrial Ecology*, **15**(6), 855– 876. https://doi.org/10.1111/j.1530-9290.2011.00366.x
Wiley Online Library | Web of Science® | Google Scholar

Franklin-Johnson, E., Figge, F., & Canning, L. (2016). Resource duration as a managerial indicator for circular economy performance. *Journal of Cleaner Production*, **133**, 589– 598. https://doi.org/10.1016/j.jclepro.2016.05.023
Crossref | Web of Science® | Google Scholar

Frosch, R. A. (1992). Industrial ecology: A philosophical introduction. *Proceedings of the National Academy of Sciences*, **89**(8), 3669. https://doi.org/10.1073/pnas.89.8.3669c
Crossref | Google Scholar

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy—A new sustainability paradigm? *Journal of Cleaner Production*, **143**, 757– 768. https://doi.org/10.1016/j.jclepro.2016.12.048
Crossref | Web of Science® | Google Scholar

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, **114**, 11– 32. https://doi.org/10.1016/j.jclepro.2015.09.007
Crossref | Web of Science® | Google Scholar

Goodland, R. (1995). The concept of environmental sustainability. *Annual Review of Ecology and Systematics*, **26**, 1– 24.
Crossref | Web of Science® | Google Scholar

Graedel, T. E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B. K., … Sonnemann, G. (2011). What do we know about metal recycling rates? *Journal of Industrial Ecology*, **15**(3), 355– 366. https://doi.org/10.1111/j.1530-9290.2011.00342.x
Wiley Online Library | CAS | Web of Science® | Google Scholar

Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P., & Reck, B. K. (2015). Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(14), 4257– 4262. https://doi.org/10.1073/pnas.1500415112
Crossref | CAS | PubMed | Web of Science® | Google Scholar

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the World in 2005. *Journal of Industrial Ecology*, **19**(5), 765– 777. https://doi.org/10.1111/jiec.12244
Wiley Online Library | Web of Science® | Google Scholar

Haupt, M., Vadenbo, C., & Hellweg, S. (2017). Do we have the right performance indicators for the circular economy? Insight into the Swiss Waste Management System. *Journal of Industrial Ecology*, **21**(3), 615– 627. https://doi.org/10.1111/jiec.12506
Wiley Online Library | Web of Science® | Google Scholar

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(9), 3232– 3237. https://doi.org/10.1073/pnas.1109936109
Crossref | CAS | PubMed | Web of Science® | Google Scholar

Huysman, S., Sala, S., Mancini, L., Ardente, F., Alvarenga, R. A. F., Meester, S. D., … Dewulf, J. (2015). Toward a systematized framework for resource efficiency indicators. *Resources, Conservation and Recycling*, **95**, 68– 76. https://doi.org/10.1016/j.resconrec.2014.10.014

Crossref | Web of Science® | Google Scholar

Huysman, S., Schaepmeester, J. D., Ragaert, K., Dewulf, J., & Meester, S. D. (2017). Performance indicators for a circular economy: A case study on post-industrial plastic waste. *Resources, Conservation and Recycling*, **120**, 46– 54. https://doi.org/10.1016/j.resconrec.2017.01.013
Crossref | Web of Science® | Google Scholar

Iacovidou, E., Velis, C. A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., ... Williams, P. T. (2017). Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. *Journal of Cleaner Production*, **166**, 910– 938. https://doi.org/10.1016/j.jclepro.2017.07.100
Crossref | Web of Science® | Google Scholar

International Resource Panel (IRP). (2017). *Assessing global resource use: A systems approach to resource efficiency and pollution reduction*. A Report of the International Resource Panel. Nairobi, Kenya: United Nations.
Google Scholar

Iung, B., & Levrat, E. (2014). Advanced maintenance services for promoting sustainability. *Procedia CIRP*, **22**, 15– 22. https://doi.org/10.1016/j.procir.2014.07.018
Crossref | Google Scholar

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its limitations. *Ecological Economics*, **143**, 37– 46. https://doi.org/10.1016/j.ecolecon.2017.06.041
Crossref | Web of Science® | Google Scholar

Laurent, A., & Owsianiak, M. (2017). Potentials and limitations of footprints for gauging environmental sustainability. *Current Opinion in Environmental Sustainability*, **25**, 20– 27. https://doi.org/10.1016/j.cosust.2017.04.003
Crossref | Web of Science® | Google Scholar

Linder, M., Sarasini, S., & van Loon, P. (2017). A metric for quantifying product-level circularity. *Journal of Industrial Ecology*, **21**(3), 545– 558. https://doi.org/10.1111/jiec.12552
Wiley Online Library | Web of Science® | Google Scholar

Lutter, S., Giljum, S., & Bruckner, M. (2016). A review and comparative assessment of existing approaches to calculate material footprints. *Ecological Economics*, **127**, 1– 10. https://doi.org/10.1016/j.ecolecon.2016.03.012
Crossref | Web of Science® | Google Scholar

Maina, S., Kachrimanidou, V., & Koutinas, A. (2017). From waste to bio-based products: A roadmap towards a circular and sustainable bioeconomy. *Current Opinion in Green and Sustainable Chemistry*. https://doi.org/10.1016/j.cogsc.2017.07.007
Crossref | PubMed | Web of Science® | Google Scholar

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2018). Measuring progress towards a circular economy: A monitoring framework for economy-wide material loop closing in the EU28. *Journal of Industrial Ecology*, **132**(Supp. C), 1. https://doi.org/10.1111/jiec.12809
Google Scholar

Mendoza, J. F., Sharmina, M., Gallego-Schmid, A., Heyes, G., & Azapagic, A. (2017). Integrating backcasting and eco-design for the circular economy: The BECE framework. *Journal of Industrial Ecology*, **3**(3), 343. https://doi.org/10.1111/jiec.12590
Google Scholar

Moriguchi, Y. (2007). Material flow indicators to measure progress toward a sound material-cycle society. *Journal of Material Cycles and Waste Management*, **9**(2), 112– 120. https://doi.org/10.1007/s10163-007-0182-0
Crossref | Web of Science® | Google Scholar

Organisation for Economic Co-operation and Development (OECD). (2008). *Measuring material flows and resource productivity: Volume I. The OECD guide*. Retrieved from https://www.oecd.org/environment/indicators-modelling-outlooks/MFA-Guide.pdf
Google Scholar

Park, J. Y., & Chertow, M. R. (2014). Establishing and testing the "reuse potential" indicator for managing wastes as resources. *Journal of Environmental Management*, **137**, 45– 53. https://doi.org/10.1016/j.jenvman.2013.11.053
Crossref | PubMed | Web of Science® | Google Scholar

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001: 2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, **129**, 81– 92. https://doi.org/10.1016/j.resconrec.2017.10.019
Crossref | Web of Science® | Google Scholar

Pearce, D., & Turner, K. (1990). *Economics of natural resources and the environment*. Baltimore, MD: Johns Hopkins University Press.
Google Scholar

Ridoutt, B. G., & Pfister, S. (2010). Reducing humanity's water footprint. *Environmental Science & Technology*, **44**(16), 6019– 6021. https://doi.org/10.1021/es101907z
Crossref | CAS | PubMed | Web of Science® | Google Scholar

Ripple, W. J., Wolf, C., Newsome, T. M., Galetti, M., Alamgir, M., Crist, E., ... Laurance, W. F. (2017). World scientists' warning to humanity: A second notice. *BioScience*, **67**(12), 1026– 1028. https://doi.org/10.1093/biosci/bix125
Crossref | Web of Science® | Google Scholar

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2018). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, **207**, 542– 559. https://doi.org/10.1016/j.jclepro.2018.10.014
Crossref | Web of Science® | Google Scholar

Scheepens, A. E., Vogtlander, J. G., & Brezet, J. C. (2016). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. *Journal of Cleaner Production*, **114**, 257– 268. https://doi.org/10.1016/j.jclepro.2015.05.075
Crossref | Web of Science® | Google Scholar

Smol, M., Kulczycka, J., & Avdiushchenko, A. (2017). Circular economy indicators in relation to eco-innovation in European regions. *Clean Technologies and Environmental Policy*, **19**(3), 669– 678. https://doi.org/10.1007/s10098-016-1323-8
Crossref | Web of Science® | Google Scholar

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... Sörlin, S. (2015). Sustainability. planetary boundaries: Guiding human development on a changing planet. *Science*, **347**(6223). https://doi.org/10.1126/science.1259855
Crossref | PubMed | Web of Science® | Google Scholar

Steinmann, Z. N., Schipper, A. M., Hauck, M., & Huijbregts M. A. J. (2016). How many environmental impact indicators are needed in the evaluation of product life cycles? *Environmental Science & Technology*, **50**(7), 3913– 3919. https://doi.org/10.1021/acs.est.5b05179

Crossref | CAS | PubMed | Web of Science® | Google Scholar

Takiguchi, H., & Takemoto, K. (2008). Japanese 3R policies based on material flow analysis. *Journal of Industrial Ecology*, **12**(5–6), 792– 798. https://doi.org/10.1111/j.1530-9290.2008.00093.x
Wiley Online Library | Web of Science® | Google Scholar

Tecchio, P., McAlister, C., Mathieux, F., & Ardente, F. (2017). In search of standards to support circularity in product policies: A systematic approach. *Journal of Cleaner Production*, **168**, 1533.– 1546 https://doi.org/10.1016/j.jclepro.2017.05.198
Crossref | PubMed | Web of Science® | Google Scholar

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., … Wood, R. (2014). *The global resource footprint of nations: Carbon, water, land and materials embodied in trade and final consumption calculated with EXIOBASE 2.1*. Leiden/Delft/Vienna/Trondheim. Retrieved from http://exiobase.eu/index.php/publications/creea-booklet/72-creea-booklet-high-resolution/file
Google Scholar

Verones, F., Moran, D., Stadler, K., Kanemoto, K., & Wood, R. (2017). Resource footprints and their ecosystem consequences. *Scientific Reports*, **7**. https://doi.org/10.1038/srep40743
Crossref | PubMed | Web of Science® | Google Scholar

Vogtländer, J. G., Brezet, H. C., & Hendriks, C. F. (2001). The virtual eco-costs '99: A single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation. *The International Journal of Life Cycle Assessment*, **6**(3), 157– 166.
Crossref | Web of Science® | Google Scholar

Wijkman, A., & Rockström, J. (2012). *Bankrupting nature: Denying our planetary boundaries [a report to the Club of Rome]. Earthscan from Routledge*. London: Routledge.
Google Scholar

Zink, T., & Geyer, R. (2017). Circular economy rebound. *Journal of Industrial Ecology*, **12**(1), 59. https://doi.org/10.1111/jiec.12545
Google Scholar

Citing Literature

Roberta De Angelis, Circular economy: laying the foundations for conceptual and theoretical development in management studies, Management Decision, 10.1108/MD-05-2019-0587, **ahead-of-print**, ahead-of-print, (2020).
Crossref

Steve Harris, Michael Martin, Derek Diener, Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy., Sustainable Production and Consumption, 10.1016/j.spc.2020.09.018, (2020).
Crossref

Sir Yee Lee, Jiayao Hu, Ming Kim Lim, Maximising the circular economy and sustainability outcomes: An end-of-life tyre recycling outlets selection model, International Journal of Production Economics, 10.1016/j.ijpe.2020.107965, (107965), (2020).
Crossref

Willi Haas, Fridolin Krausmann, Dominik Wiedenhofer, Christian Lauk, Andreas Mayer, Spaceship earth's odyssey to a circular economy - a century long perspective, Resources, Conservation and Recycling, 10.1016/j.resconrec.2020.105076, **163**, (105076), (2020).
Crossref

Jaime Mesa, Arturo González-Quiroga, Heriberto Maury, Developing an indicator for material selection based on durability and environmental footprint: A Circular Economy perspective, Resources, Conservation and Recycling, 10.1016/j.resconrec.2020.104887, **160**, (104887), (2020).
Crossref

Alberto Bezama, Carlo Ingrao, Sinéad O'Keeffe, Daniela Thrän, Resources, Collaborators, and Neighbors: The Three-Pronged Challenge in the Implementation of Bioeconomy Regions, Sustainability, 10.3390/su11247235, **11**, 24, (7235), (2019).
Crossref