Linking Industrial Ecology and Ecological Economics

A Theoretical and Empirical Foundation for the Circular Economy

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Summary

The circular economy (CE) is a new model for the production and consumption of goods, which has attracted wide political attention as a strategy toward sustainability. However, the theoretical foundation of CE remains poorly structured and insufficiently explored. Recent studies have shown that the CE model draws on different schools of thought and that its origins are mainly rooted in fields such as industrial ecology (IE) and ecological economics (EE). In this article, we investigate the links between CE, IE, and EE and provide an overview of the similarities and differences between these fields. At the same time, we analyze to what extent the linkages between IE and EE can create a coherent body of knowledge for CE, and be used to identify further research opportunities. This paper shows that, until now, research on CE seems to be mainly rooted in the field of IE and based on concepts and tools that already exist in other fields, rather than inventing new ones. The reconciliation of IE and EE could provide a mechanism to extend beyond such a narrow focus, and increase knowledge of the theoretical and practical framework of CE to benefit sustainability.

Introduction

The circular economy (CE) refers to a model of production and consumption of goods that is fundamentally different from the linear economy model which has dominated modern society. The latter is based on a simple, linear process: extract, produce, consume, and trash, with insufficient attention to the pollution generated. Thanks to the regulation and technology, some loops have been implemented, but they are insufficient and represent an ineffective path to sustainability. Thus, this economic model does not take into account most of the environmental impacts that come with resource consumption and waste disposal, and results in excessive virgin resource extraction, pollution, and waste (Sauvé et al. 2016). Also, it ignores the fact that our planet has limits and there is a risk of irreversible and abrupt environmental change which could make Earth less habitable (Rockström et al. 2009).

In contrast, CE takes into account many of the impacts on the environment of resource consumption and waste. One of the main objectives of CE is to decouple environmental pressure and economic growth (Ghisellini et al. 2016). To this end, CE promotes the adoption of closed-loop production models

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in order to optimize the use of virgin resources, thus reducing pollution and waste while ensuring the proper functioning of ecosystems and human well-being (Murray et al. 2017).

Interestingly, the ideas that have recently attracted so much attention under the banner of CE have been around since at least the 1960s. Preston (2012) claims that the notion of a CE has its roots in industrial ecology (IE), a field first developed in the 1970s. More in-depth studies on the roots of CE (Ghisellini et al. 2016; Murray et al. 2017) reveal that the term itself was used for the first time in the literature in the 1980s by environmental economists Pearce and Turner (1989) when they explained the change of the traditional open-ended economic system to a circular economic system as a consequence of the laws of thermodynamics (Georgescu-Roegen 1971). According to Ghisellini and colleagues (2016), Murray and colleagues (2017), and (Greyson 2007) these ideas were built on the previous work of Boulding (1966), one of the forefathers of ecological economics (EE). Indeed, he put forward the idea that a circular economic system is a prerequisite for the sustainability of human life on Earth. Thus, these studies show that the CE model traces different schools of thought and that its origins seem to be mainly rooted in fields of IE and EE.

In this regard, the first aim of this paper is to investigate the links between IE, EE, and CE in order to grasp the similarities and differences between these fields. At the same time, we indicate the potential for broadening the theoretical and empirical knowledge base for CE and using CE to promote the broader ideas of IE/EE. Our final purpose is to understand to what extent the linkages between IE and EE can create a coherent body of knowledge for CE and be used to identify further research opportunities.

This study is structured as follows: The following section describes the research methods implemented to track the links between IE, EE, and CE. Then, we provide a brief theoretical overview of IE, EE, and CE, their principles, underlying concepts, and tools. This is followed by an analysis of similarities and differences between IE/EE, IE/CE, and EE/CE. The final two sections suggest some guidance regarding further research on CE, and highlight the key findings of the study.

Research Methods

This study is based on a literature review. In the first step, we tracked the connections between CE, IE, and EE in existing literature. A search for publications referring to all three keywords within the Scopus database ("circular economy," "industrial ecology," and "ecological economics") in their title, abstract, and keywords yielded only one publication (Loiseau et al. 2016) (results provided by the Scopus database search updated on 14 July 2017). When only two of our keywords were sought at a time, the number of publications increased significantly (see figure 1). We reviewed the identified publications—first based on their abstracts and then, when relevant, full-text versions—looking for information on linkages between the three different fields of study. We focused on the overlaps between CE, IE, and EE and the roots, concepts, principles, and tools they have in common.

In addition to the first search, we investigated the appearance of the different terms in the specific journals representing the different areas of study. In journals specific to IE (*Journal of Industrial Ecology* and *Progress in Industrial Ecology*), we combined the terms by boolean operators such as: (1) "circular economy" AND "ecological economics" and (2) "circular economy" OR "ecological economics," respectively, and 0 and 66 papers came up. Finally, we did the same with the journal that deals with EE, namely *Ecological Economics*, by using the following combinations: (3) "circular economy" AND "industrial ecology" and (4) "circular economy" OR "industrial ecology." While no paper came out with the formula (3), (4) led to 32 papers.

Interestingly, CE seems to have attracted more attention in the IE community than in EE. Regarding papers referring to CE, IE, and EE, only one was found with the keywords used, but by reading the abstracts of papers we found another, even more explicit, on the relationships between these fields (Ghisellini et al. 2016).

Our analysis is based on the identification of other research tracks for CE. On one hand, we study how IE and EE taken separately can form a theoretical basis for CE by showing the theories, concepts, and tools they have in common. On the other hand, we explain how IE and EE taken collectively can contribute to the discussions about the theoretical background of CE.

Theoretical Foundations of the Fields

Industrial Ecology

IE is an interdisciplinary field that differs from other areas of study in the sense that its scientific profile is based on a metaphor. Nature is employed as a model explicitly, or at least implicitly, phrased in terms of a natural ecosystem metaphor, and based on a proclaimed analogy between industrial systems and natural ecosystems (Isenmann 2008; Ehrenfeld 2004; Erkman 1997).

This new approach to the industrial system seeks to transform industrial activities into cyclical processes, taking natural ecosystems as models. It considers the industrial system as an entity based on resources and services provided by the biosphere, of which it is a subsystem. Thus, it highlights principles for the design of industrial systems, such as the closure of material and energy loops, energy efficiency, and dematerialization. This requires implementing sustainable manufacturing strategies and changing the industrial design of products and processes.

For this, the industrial system can be described as a particular configuration of stocks and flows of matter, energy, and information. To study these flows, IE uses different tools or methods such as life cycle assessment (LCA) to evaluate the environmental impacts throughout a product's life cycle from the extraction of raw materials to the end of life. It also uses eco-design tools that help to take environmental impacts into account in

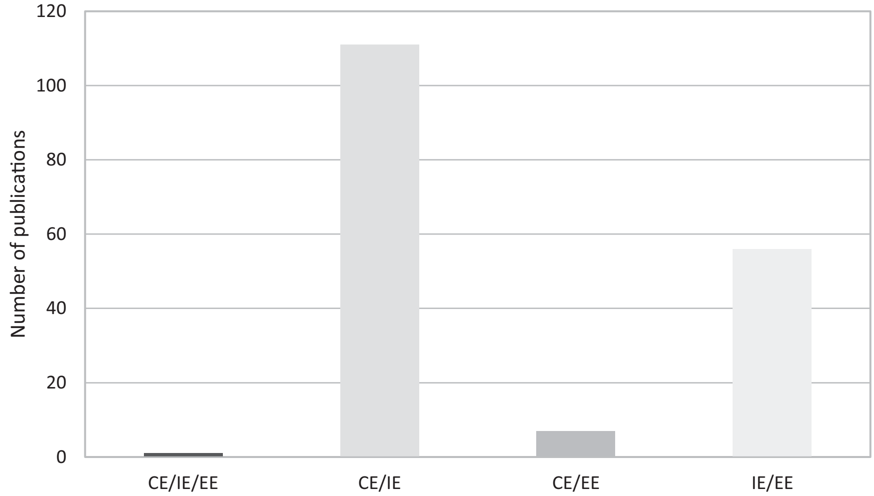

Figure 1 Number of publications referring to the keywords circular economy (CE), industrial ecology (IE), and ecological economics (EE) in the Scopus database (search updated on 14 July 2017).

product design and development. Other tools are used to study industrial, urban, and regional metabolisms, such as material and substance flow analysis. Some tools from disciplines other than engineering are used to understand the behavior of the relevant actors and organizations.

Ecological Economics

EE provides a general and comprehensive framework for studying economy–society–environment interactions, thus offering useful insights into any kind of sustainability or environmental policy (Daly and Farley 2011; Costanza 1991). EE has focused on pollution and waste prevention, and on adopting a precautionary approach to environmental problems. Among other things, ecological economists emphasized the need to shift from a throughput-based, open-ended economic system to a circular one. Such a circular economy model would respect the laws of thermodynamics, in particular reducing entropic degradation to some extent (Faber et al. 1996; Pearce and Turner 1989). Fitting our social and economic systems within the planetary boundaries (Steffen et al. 2015) requires a serious transformation of our production processes and rethinking of our needs, not simply the narrower reduction of environmental impacts per unit of production (or the so-called eco-efficiency), which has raised distrust and reluctance among ecological economists (Hukkinen 2001). In fact, efficiency of production has to be accompanied with *sufficiency* in consumption (using as little as possible in line with the concepts of sustainable and reasonable consumption) (Kronenberg 2007b), and broader ecosystem management considerations need to be part of economic planning. The latter include very diverse issues related to biodiversity conservation, preventing and adapting to climate change and other global opportunities, preservation of ecosystems' capacity to provide services to people, etc. All of the above theoretical considerations need to be complemented with practical recommendations regarding pathways that have to be followed to reach the desired new state, including uncertainties about future environmental development (Byström et al. 2000; Faber et al. 1996; Faucheux and Froger 1995). These issues are studied within EE, but also within related fields, such as sustainability transitions (Frantzeskaki et al. 2012; Meadowcroft 2011). In fact, EE is highly diverse and there are also other strands of EE which would not necessarily fit into the mainstream which we described, such as those building on institutional economics, Marxian economics, heterodox economics, etc.

Many tools have been proposed within EE, the overarching objectives of which were to ensure efficient use of resources and to reduce the generation of negative environmental impacts, ultimately making the social and economic systems fit the Earth's carrying capacity. Sometimes, this has been framed as decoupling environmental pressure from economic growth (Holm and Englund 2009; Huppes and Ishikawa 2009), although not all ecological economists would necessarily agree with such a framework because of its emphasis on growth (Jollands 2006; Hukkinen 2001). The focus has been on how people use and manage resources at all levels: from individual to global consumption patterns (Reisch and Røpke 2004), through the management of ecosystems and reducing the pressures that human activities exert on those ecosystems (Farber et al. 2006), to broad global governance schemes for economy–society–environment interactions (Spash 2002).

Circular Economy

Presently, CE is known worldwide as a model of production and consumption of goods promoting the adoption of closed-loop patterns in order to optimize the use of virgin resources, thus reducing pollution and waste while ensuring the proper functioning of ecosystems and encouraging human well-being. The ultimate goal of promoting CE is the decoupling of environmental pressure from economic growth (Ghisellini et al. 2016).

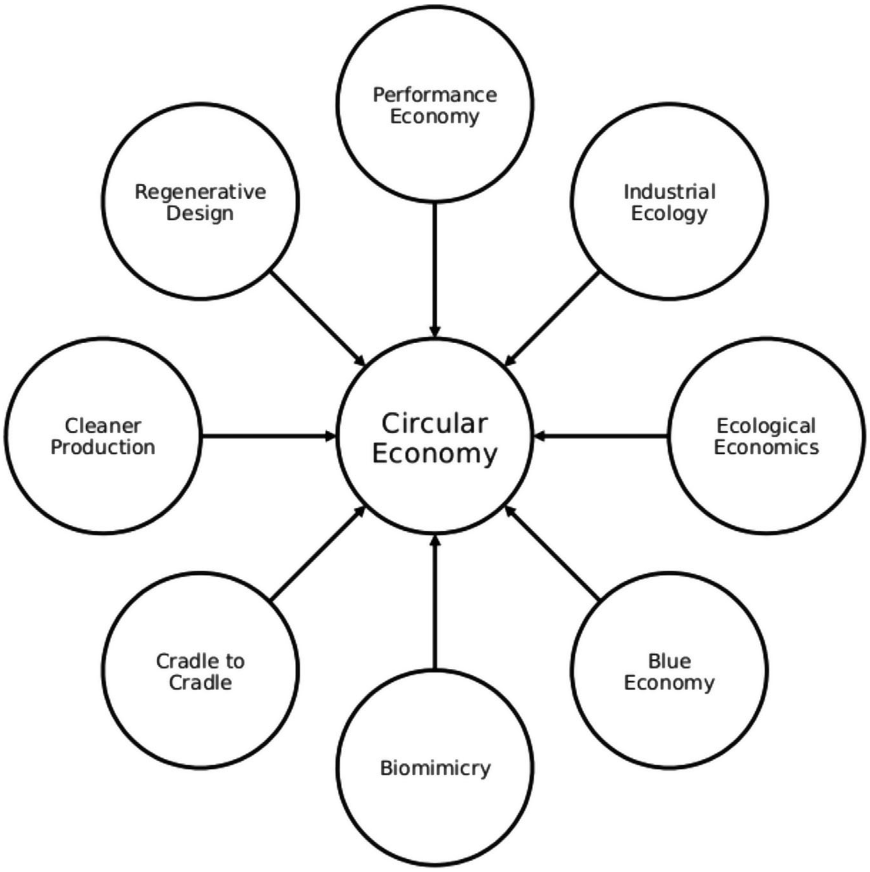

Figure 2 Key concepts closely related to the circular economy.

The implementation of CE strategies seems to follow different ways in different countries. For instance, some countries foster the development of CE at the micro level (company or consumer level), others at meso level (eco-industrial park), and still others at macro level (cities, province, and country). When it comes to specific CE implementation strategies, governments, companies, and international organizations seem to rely on concepts that already exist in other fields, rather than invent new ones.

China has been one of the first countries to include CE in its policy toward a more sustainable economic system (Su et al. 2013; Yuan et al. 2006), although similar initiatives have also been undertaken in Sweden and Germany (Murray et al. 2017). The Chinese policy includes many economic and management instruments, such as pollution levies, environmental taxes and eco-labeling, cleaner production, energy and water cascading, LCA, and also environmental management systems (ISO 14001) (Geng et al. 2009).

In Europe, CE has recently started to spread in business communities and governments. It is now promoted through the European Commission's (EC) Circular Economy Package with its own Action Plan (European Commission 2015) and a number of related documents. Other governments, international organizations, and companies operationalize their vision of CE as a sustainability strategy (CIRAIG 2015), referring to concepts such as cradle to cradle, performance economy, biomimicry, IE, EE, blue economy, cleaner production, and regenerative design (figure 2). The United Nations Environment Program (UNEP) has launched a program in China with a focus on implementing CE. The Ellen MacArthur Foundation commissioned McKinsey to produce three reports providing the business case for CE (Ellen MacArthur Foundation 2013, 2014, 2012).

Similarities and Differences between These Fields

Industrial Ecology and Ecological Economics

IE and EE were presented as modern representations of the biophysical economy by Cleveland (1999). Their conceptual relationships were highlighted or addressed in the community of IE, and specifically in the *Journal of Industrial Ecology*, where two articles made reference to relations between the fields (Andrews 2001; Koenig and Cantlon 1999). In *Progress in Industrial Ecology*, some articles also addressed the connection between these two fields (Allenby 2006; Kronenberg 2006; Korhonen and Strachan 2004). Similarly, in the EE community, several articles published in *Ecological Economics* have referred to existing overlaps between the two fields (Kronenberg and Winkler 2009; Korhonen and Snäkin 2005; Røpke 2005).

Table 1 Similarities and differences between industrial ecology (IE) and ecological economics (EE)

Similarities between IE and EE	The same purpose: maintaining socioeconomic activities within environmental limits Interdisciplinary character Systems approach The use of input-output analysis Sharing interest in physical flows rather than purely monetary quantities
Differences between IE and EE	IE is more selective while EE is more holistic IE sees the natural system as a model while EE as a stock of natural capital generating the flows of ecosystem services IE being slightly more practical and EE slightly more conceptual

Finally, these relationships were addressed in other fora (Kronenberg 2007a; Korhonen 2004; Duchin and Hertwich 2003).

The common features of IE and EE include their attachment to sustainable development and their interdisciplinary character. Although both fields refer to natural sciences, they mention other disciplines and approaches, such as engineering, systems ecology, and systems thinking (with EE paying more attention than IE to the social system [human behavior] and—especially—its economic subsystem). Ecology, seen as a system based on interdependencies, and evolutionary theory, forms important baseline foundations in both IE and EE. In IE, the natural system is seen as a model which can inspire the product design and manufacturing process to create an industrial ecosystem. EE considers the natural system as natural capital that is crucial for the existence of social and economic systems (natural capital as a stock and ecosystem services as flows). Both fields use input and output tables to study relationships between the natural and economic systems, which in IE are more often expressed in physical units. With regard to the use of the input-output framework, the work of R. U. Ayres provides one of the most representative links between IE and EE (Van den Bergh 2013).

The conceptual relationships between IE and EE are particularly evident. However, EE is more holistic, and almost everything that is related to the economy–society–environment interactions falls within its scope of interest. IE is more selective in the sense that it focuses primarily on industry and its products, and mainly studies the physical flows of energy and matter between industrial and natural systems. Within EE, these topics are discussed to a lesser extent, even though they obviously fall within its scope of interest (they are addressed rather in terms of market supply or consumption). Meanwhile, IE pays little attention to other aspects of the economy–society–environment interactions that can be addressed at the microeconomic level and that might help to conceptualize and operationalize the underlying IE metaphor (e.g., environmental externalities, proximity economics, industrial economics, biodiversity conservation, and the valuation of natural capital) (table 1).

Industrial Ecology and Circular Economy

Several studies converge on the idea that the theoretical and empirical foundations of CE are mainly based on the theory of IE (Ghisellini et al. 2016; Preston 2012; Ellen MacArthur Foundation 2012; Chiu and Yong 2004).

Similarly to IE, CE refers to the analogy comparing the industrial system to the natural system. It considers the industrial system as part of the larger ecosystem, and seeks to optimize the flow of matter and energy to limit the extraction of natural resources and environmental discharges, thus moving toward a closed loop of materials and energy flows (Geng and Doberstein 2008; Lifset and Graedel 2002; Frosch and Gallopoulos 1989).

In the same way, CE mainly focuses on the study of the flows of matter, energy, and information exchanged between the natural and industrial systems. IE focuses on the study of these flows between industrial systems and the natural system at the company level, between firms, and at a regional or higher level (table 2). A successful implementation of CE also requires efforts at three levels (Su et al. 2013; Zhu and Huang 2005; Chiu and Yong 2004):

- At the micro level, the product-oriented approach is linked to cleaner production, life cycle management, and eco-design, and involves actors such as suppliers, producers, consumers, and designers (Zhang et al. 2013; Geng et al. 2009);
- At the meso level, the eco-industrial and eco-agricultural park or system approach features the concept of industrial symbiosis (IS) as a waste trading system organized through clustered firms that trade by-products and share common services or infrastructures (Chertow 2000), although it can also imply other forms of interorganizational environmental management (Sinding 2000);
- At the macro level (city, regional, or national level), the service or functional economy emphasizes the utilization of services provided by products (Stahel 1994) and links to other forms of dematerialization and rematerialization (De Bruyn 2002). The concept of IS is extended to cities (urban symbiosis), based on the synergistic opportunities arising from the geographical proximity through the transfer of physical resources for environmental and economic benefit (Geng et al. 2009).

At each level, similar tools are used within CE and IE to study the flows of matter, energy, and information that cross the industrial and natural systems, reflecting different levels of industrial metabolism (Lifset 2014; Kytzia and Nathani 2004; Van Berkel et al. 1997).

Table 2 Similar tools used within circular economy and industrial ecology

Tools	*Purpose*	*Levels used*
Design for environment	Assists the designer to reduce human health and environmental impacts of a product, process, or service throughout their life cycles	Micro
Ecological footprints (water, carbon, material)	The ecological footprint measures human demand on nature, for instance the quantity of natural resources it takes to support people or an economy	Micro, meso, and macro
Life cycle assessment	Compares the relative environmental performance of alternative product systems to meet the same final use function	Micro
Material flow analysis (often with the use of input-output analysis)	Analyzing the pathways of matter related to resource and waste management problems (energy, carbon, and materials)	Meso and macro
Substance flow analysis	Analyzing the pathways of substances linked to environmental problems	Micro, meso, and macro

Ecological Economics and Circular Economy

Several authors have directly linked CE with concepts developed within ecological economics (and also, by extension, environmental economics) (Ghisellini et al. 2016; Loiseau et al. 2016). CE has mostly been built around the notion of efficient resource management, beginning even before resources are extracted from the environment (proper planning of economic activities) and continuing once they enter the economic system. These ideas have been present in EE since its inception, and already the earliest ecological economists highlighted that "goods which are 'consumed' really only render certain services" (Ayres and Kneese 1969, 284). This led to many ideas for sustainable consumption, such as product-service systems and the functional economy (Mont 2002), which focused on reuse, joint use of products, and other ways of increasing the intensity of the use of services that products provide, ultimately increasing the efficiency of resource use. Also, as "(r)esource exhaustion cannot mean physical disappearance of matter from the earth per se. It can mean, and is usually taken to mean, a change of form from desirable to undesirable" (Ayres 1993, 199). And this is meant to be reversed within the CE model.

On a broader level, CE has also acknowledged the systems approach of EE: the broad concepts of scale of economic activity versus the scale of the environment; and steady-state economics (Pin and Hutao 2007), which are meant to ensure that the economy does not outgrow the Earth's carrying capacity. Although this has most often been associated with the scarcity of natural resources and the fact that production systems permanently damage ecosystem productivity (Zhu and Wu 2007), CE goes beyond the simple resource productivity prescriptions, such as recycling waste, and encompasses adjusting industrial structures, developing new technologies, and reforming industrial policies (Yuan et al. 2006). Among such reforms, it is broadly agreed that CE should explicitly address complex issues covered by EE, such as the need to correct distorted prices (Andersen 2007).

Further Research Opportunities for Circular Economy

Beyond the Study of the Physical Flows of Energy and Matter

Studying the monetary dimension of the flows of energy and matter can improve our understanding of the effects of physical flows on the socioeconomic system. This is linked to the issue of environmental externalities, an area of focus within EE (Van den Bergh 2010; Howarth 1996), but which attracts relatively little attention within IE. This research opportunity has already been underlined by researchers in the IE community (Hond 2000; O'Rourke et al. 1996). They emphasized that decision makers, product developers, business leaders, public administrators, or consumers would be likely to take different decisions if they had information enabling them to assess the wider consequences of their decisions, or if they had to pay a price reflecting the monetary value of the externalities of the use of materials and energy. Obviously, even this view is narrow, compared to the broader and nonmonetary motivations behind individual behavior addressed within EE (Kenter et al. 2015; Snep et al. 2009; Martín-López et al. 2007).

Micro Foundation

Andrews (2001) argued that a micro foundation could help link the various aspects of IE research and practice. He indicated that it would open the possibility of studying phenomena at multiple levels and across levels. He drew his proposals from other disciplines, such as ecology and economics, which had already developed a micro foundation. He indicated that if industrial ecologists had paid more attention to microeconomic problems and tried to understand the decisions of economic entities and the factors influencing these decisions, they might

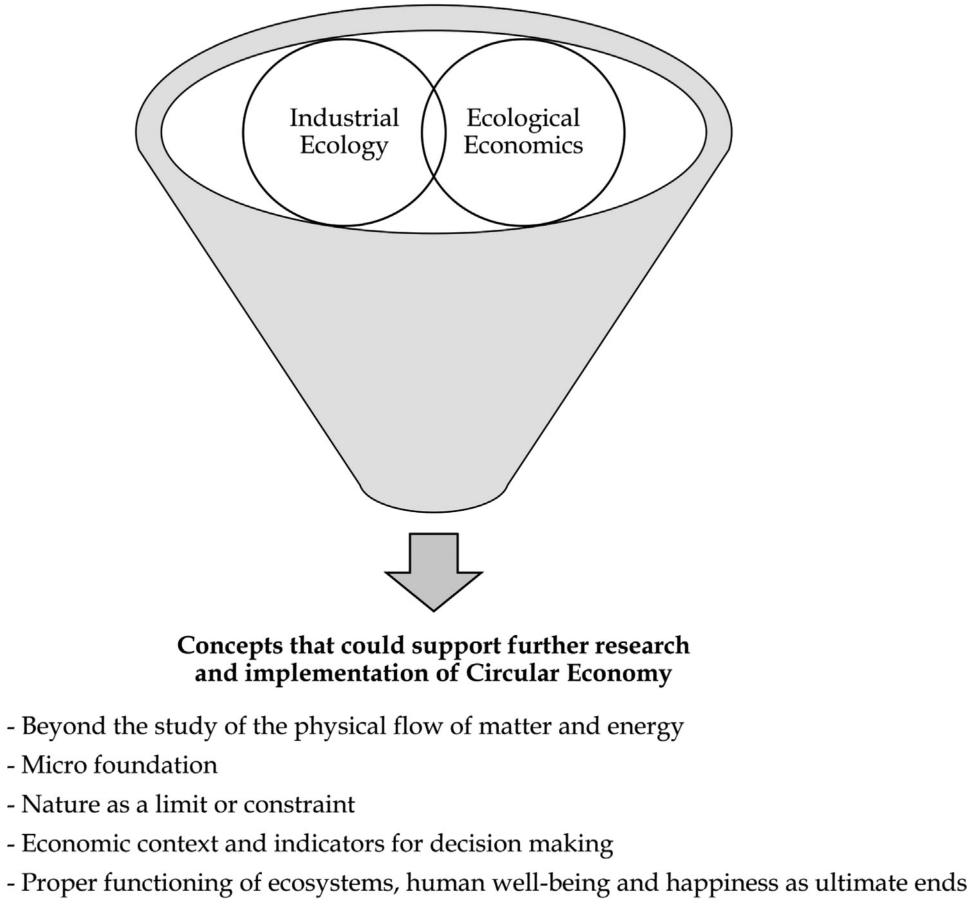

Figure 3 Concepts that circular economy derives from industrial ecology and ecological economics.

have suggested better ways to address those problems. It is also essential to take social and behavioral parameters into account in the study of interactions between natural systems and socioeconomic systems. These issues are rarely addressed in IE and seem to be crucial from the perspective of EE. Thus, bringing the two fields together would make the social dimension and the microeconomic level of CE more explicit, beyond the traditional product-oriented approach.

Nature as a Limit or Constraint

Many questions about the interactions between the natural system and the socioeconomic system addressed within EE have only received limited attention in the scope of IE, such as substitution of natural capital with human-made capital, biodiversity conservation, and valuation of nature. Interestingly, these issues have already been seen as of great importance for CE, according to the seminal report by the Ellen MacArthur Foundation. Among other things, the report stipulated that CE should enhance natural capital "by encouraging flows of nutrients within the system and creating the conditions for the regeneration of, for example, soil" (Ellen MacArthur Foundation 2012, 53). In theory, these issues are also important from the point of view of IE with its idea of nature as a model, although the notions of natural capital, biodiversity, and ecosystem services have largely escaped the conceptualization of an industrial ecosystem. Because EE focuses much more attention on these issues, the way in which they have been studied within EE could inform many discussions and practical recommendations within CE. Among these are new efforts to connect IE (especially through LCA) with ecosystem services, not to mention biodiversity (Bruel et al. 2016; Koellner et al. 2013). Furthermore, this is linked to the above-mentioned monetary and nonmonetary dimensions of the flows of matter and energy, and of the related externalities. The loss in value associated with biodiversity loss and the related loss of ecosystem services is often invisible and does not influence decision makers. It is difficult to provide information about pressure from industrial systems in corporate information systems. EE uses valuation techniques to reveal the value of nature and develops ways to overcome the current technical and ethical challenges to valuation, for example, by broadening the dominant monetary perspective on the value of nature by nonmonetary and deliberative approaches (Czembrowski et al. 2016; Kenter et al. 2015). One example of connecting these strands of research so far has been the analysis of the use of ecosystem services generated within the Catskill Mountains by New York City through the lens of inputs and outputs inherent in the analysis of urban metabolism (Kane and Erickson 2007).

Economic Context and Indicators for Business and Policy Decision Making

The successful development of CE needs to bring economic considerations to IE for theoretical and practical reasons. Already in its name, CE refers to economics and this seems to have been done deliberately to attract more attention to this concept. Again, linking implications originating from IE and EE can provide a more comprehensive background for those interested in implementing CE at any level of decision making. For this purpose, IE can get closer to EE, and refer more broadly to costs, profits, allocation, market distortion, human behavior, and so on. These concepts may serve as relevant indicators to assess the monitoring of the implementation of CE, because they are broadly used and understood and often misinterpreted in mainstream economics (e.g., markets are assumed to work perfectly well, and human behavior is treated excessively simplistically, as if guided by selfish self-interest only). Good indicators are necessary to assess the strength of its development and provide guidance to decision makers in order to develop effective policy instruments.

Finally, to further the vision of recirculating resources, CE needs to depart more radically from its mainstream character. Although both IE and EE are highly relevant from the point of view of CE, the latter still fits into the dominant language of green growth and green economy. Meanwhile, as already argued by some authors (Ghisellini et al. 2016; Hobson and Lynch 2016), CE needs to be connected with an alternative vision of fitting the economy within the limited carrying capacity of the Earth, explicitly addressed in the context of *degrowth* (Jackson 2011). Degrowth needs to be seen as a planned and equitable transition to a state of lower production and consumption. In the case of CE, it can be associated with an economic pattern aimed at increased efficiency of production and consumption, by means of appropriate use, reuse, and exchange of resources, and doing more with less (Ghisellini et al. 2016). Endless growth is not feasible, and the politically popular *green growth* is an oxymoron. This issue has already been addressed in the IE community, especially in the special feature on visions of IE expressed during the Third International Conference on Eco-Efficiency (Schneider et al. 2011). However, it has been discussed far more frequently in the EE community (Martinez-Alier et al. 2010).

In fact, the current discussions on the economics of degrowth continue on from those on steady-state economics (Daly 1977), which have already been referred to by the proponents of CE (Ghisellini et al. 2016). On the grounds of EE, one needs to question the economic growth imperative and replace the mainstream focus on human welfare with a broader one on ultimate ends of human activity, such as well-being and especially happiness (Kallis et al. 2012; Jackson 2011).

Conclusions

This study gives an overview of the similarities and differences between CE, IE, and EE. Thanks to this investigation, we can better identify the roots, concepts, principles, and tools they have in common.

Clearly, research on CE has been and still is primarily rooted in the field of IE and therefore focused on the analysis of physical flows of energy and matter between industrial and natural systems. Moreover, CE seems to be mainly based on concepts and tools that already exist in other fields, rather than inventing new ones. Therefore, information provided to decision makers is still the same and it is only reframed in the context of a new concept.

The reconciliation of IE and EE could be a way to go beyond such a narrow focus and increase the knowledge of the theoretical and practical framework of CE by addressing new research directions (see figure 3) such as: (1) going beyond the physical study of material and energy flows to studying the socioeconomic consequences of these flows; (2) the establishment of a micro foundation to address the microeconomic aspects, but also the behavioral and social aspects of the natural system and socioeconomic system interactions; (3) the consideration of issues related to the Earth's carrying capacity; (4) taking economic considerations into account and building indicators for business and policy decision makers; and (5) setting the proper functioning of ecosystems alongside with human well-being and happiness as the ultimate objectives of socioeconomic activity. This reconciliation of IE and EE would be an interesting opportunity to bring new information into CE and better guide our socioeconomic system toward sustainability.

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References

Allenby, B. R. 2006. The ontologies of industrial ecology? *Progress in Industrial Ecology* 3(1–2): 28–40.

Andersen, M. S. 2007. An introductory note on the environmental economics of the circular economy. *Sustainability Science* 2(1): 133–140.

Andrews, C. J. 2001. Building a micro foundation for industrial ecology. *Journal of Industrial Ecology* 4(3): 35–51.

Ayres, R. U. 1993. Cowboys, cornucopians and long-run sustainability. *Ecological Economics* 8(3): 189–207.

Ayres, R. U. and A. V. Kneese. 1969. Production, consumption, and externalities. *American Economic Review* 59(3): 282–297.

Boulding, K. E. 1966. The economics of the coming spaceship earth. In *Environmental Quality in a Growing Economy: Essays from the Sixth RFF Forum*, edited by H. Jarrett. Baltimore, MD, USA: Johns Hopkins Press.

Bruel, A., N. Troussier, B. Guillaume, and N. Sirina. 2016. Considering ecosystem services in life cycle assessment to evaluate environmental externalities. *Procedia CIRP* 48: 382–387.

De Bruyn, S. M. 2002. Dematerialization and rematerialization as two recurring phenomena of industrial ecology. In *A handbook of* *industrial ecology*, edited by R. U. Ayres and L. W. Ayres, 209–222. Cheltenham, UK: Edward Elgar.

Byström, O., H. Andersson, and M. Gren. 2000. Economic criteria for using wetlands as nitrogen sinks under uncertainty. *Ecological Economics* 35(1): 35–45.

Chertow, M. R. 2000. Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment* 25(1): 313–337.

Chiu, A. S. and G. Yong. 2004. On the industrial ecology potential in Asian Developing Countries. *Journal of Cleaner Production* 12(8–10): 1037–1045.

CIRAIG (The International Reference Centre for the Life Cycle of Products, Processes and Services). 2015. *Circular economy: A critical literature review of concepts*. Montréal (QC), Canada: The International Reference Centre for the Life Cycle of Products, Processes and Services.

Cleveland, C. J. 1999. *Biophysical economics: From physiocracy to ecological economics and industrial ecology*. Cheltenham, UK: Edward Elgar.

Costanza, R. 1991. Ecological economics: A research agenda. *Structural Change and Economic Dynamics* 2(2): 335–357.

Czembrowski, P., J. Kronenberg, and M. Czepkiewicz. 2016. Integrating non-monetary and monetary valuation methods—SoftGIS and hedonic pricing. *Ecological Economics* 130: 166–175.

Daly, H. 1977. Steady-state economic: The economics of biophysical equilibrium and moral growth. San Francisco, CA, USA: W.H. Freeman.

Daly, H.E. and J. Farley. 2011. *Ecological economics: Principles and applications*. Washington, DC: Island.

Duchin, F. and E. Hertwich. 2003. Industrial ecology. In *Online encyclopaedia of ecological economics*. www.ecoeco.org/publica/encyc.htm. Accessed 26 February 2015.

Ehrenfeld, J. 2004. Industrial ecology: A new field or only a metaphor? *Journal of Cleaner Production* 12(8–10): 825–831.

Ellen MacArthur Foundation. 2012. Towards the circular economy: An economic and business rationale for an accelerated transition. www.ellenmacarthurfoundation.org/publications/towards-a-circular-economy-business-rationale-for-an-accelerated-transition. Accessed 6 May 2015.

Ellen MacArthur Foundation. 2013. Towards the circular economy: Opportunities for the consumer goods sector. www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-2-opportunities-for-the-consumer-goods-sector. Accessed 6 May 2015.

Ellen MacArthur Foundation. 2014. Towards the circular economy: Accelerating the scale-up across global supply chains. www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-3-accelerating-the-scale-up-across-global-supply-chains. Accessed 6 May 2015.

Erkman, S. 1997. Industrial ecology: An historical view. *Journal of Cleaner Production* 5(1–2): 1–10.

European Commission. 2015. Closing the loop—An EU action plan for the Circular Economy. *COM (2015)*. Brussels: European Commission.

Faber, M., R. Manstetten, and J. Proops. 1996. *Ecological economics: Concepts and methods*. Cheltenham, UK: Edward Elgar.

Farber, S., R. Costanza, D. L. Childers, J. Erickson, K. Gross, M. Grove, C. S. Hopkinson, J. Kahn, S. Pincetl, and A. Troy. 2006. Linking ecology and economics for ecosystem management. *Bioscience* 56(2): 121–133.

Faucheux, S. and G. Froger. 1995. Decision-making under environmental uncertainty. *Ecological Economics* 15(1): 29–42.

Frantzeskaki, N., D. Loorbach, and J. Meadowcroft. 2012. Governing societal transitions to sustainability. *International Journal of Sustainable Development* 15(1–2): 19–36.

Frosch, R. and N. Gallopoulos. 1989. Strategies for manufacturing. *Scientific American* 261(3): 144–152.

Geng, Y. and B. Doberstein. 2008. Developing the circular economy in China: Challenges and opportunities for achieving 'leapfrog development'. *The International Journal of Sustainable Development & World Ecology* 15(3): 231–239.

Geng, Y., Q. Zhu, B. Doberstein, and T. Fujita. 2009. Implementing China's circular economy concept at the regional level: A review of progress in Dalian, China. *Waste Management* 29(2): 996–1002.

Georgescu-Roegen, N. 1971. The entropy law and the economic process, 1971. Cambridge, MA, USA: Harvard University Press.

Ghisellini, P., C. Cialani, and S. Ulgiati. 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.

Greyson, J. 2007. An economic instrument for zero waste, economic growth and sustainability. *Journal of Cleaner Production* 15(13): 1382–1390.

Hobson, K. and N. Lynch. 2016. Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world. *Futures* 82: 15–25.

Holm, S.-O. and G. Englund. 2009. Increased ecoefficiency and gross rebound effect: Evidence from USA and six European countries 1960–2002. *Ecological Economics* 68(3): 879–887.

Hond den, F. 2000. Industrial ecology: A review. *Regional Environmental Change* 1(2): 60–69.

Howarth, R. B. 1996. Status effects and environmental externalities. *Ecological Economics* 16(1): 25–34.

Hukkinen, J. 2001. Eco-efficiency as abandonment of nature. *Ecological Economics* 38(3): 311–315.

Huppes, G. and M. Ishikawa. 2009. Eco-efficiency guiding micro-level actions towards sustainability: Ten basic steps for analysis. *Ecological Economics* 68(6): 1687–1700.

Isenmann, R. 2008. Setting the boundaries and highlighting the scientific profile of industrial ecology. *Information Technologies in Environmental Engineering* 1(1): 32–39.

Jackson, T. 2011. *Prosperity without growth: Economics for a finite planet*. London: Routledge.

Jollands, N. 2006. Concepts of efficiency in ecological economics: Sisyphus and the decision maker. *Ecological Economics* 56(3): 359–372.

Kallis, G., C. Kerschner, and J. Martinez-Alier. 2012. The economics of degrowth. *Ecological Economics* 84: 172–180.

Kane, M. and J. D. Erickson. 2007. Urban metabolism and payment for ecosystem services: History and policy analysis of the New York City water supply. *Advances in the Economics of Environmental Resources* 7: 307–328.

Kenter, J. O., L. O'Brien, N. Hockley, N. Ravenscroft, I. Fazey, K. N. Irvine, M. S. Reed, M. Christie, E. Brady, and R. Bryce. 2015. What are shared and social values of ecosystems? *Ecological Economics* 111: 86–99.

Koellner, T., L. Baan, T. Beck, M. Brandão, B. Civit, M. Margni, L. M. Canals, R. Saad, D. M. Souza, and R. Müller-Wenk. 2013. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. *The International Journal of Life Cycle Assessment* 18(6): 1188–1202.

Koenig, H. E. and J. E. Cantlon. 1999. Quantitative industrial ecology and ecological economics. *Journal of Industrial Ecology* 3(2): 63–83.

Korhonen, J. 2004. Industrial ecology in the strategic sustainable development model: Strategic applications of industrial ecology. *Journal of Cleaner Production* 12(8–10): 809–823.

Korhonen, J. and J. P. Snäkin. 2005. Analysing the evolution of industrial ecosystems: Concepts and application. *Ecological Economics* 52(2): 169–186.

Korhonen, J. and P. A. Strachan. 2004. Editorial: Towards progress in industrial ecology. *Progress in Industrial Ecology* 1(1–3): 1–23.

Kronenberg, J. 2006. Industrial ecology and ecological economics. *Progress in Industrial Ecology* 3(1–2): 95–113.

Kronenberg, J. 2007a. *Ecological economics and industrial ecology: A case study of the Integrated Product Policy of the European Union*. London: Routledge.

Kronenberg, J. 2007b. Making consumption "reasonable." *Journal of Cleaner Production* 15(6): 557–566.

Kronenberg, J. and R. Winkler. 2009. Wasted waste: An evolutionary perspective on industrial by-products. *Ecological Economics* 68(12): 3026–3033.

Kytzia, S. and C. Nathani. 2004. Bridging the gap to economic analysis: Economic tools for industrial ecology. *Progress in Industrial Ecology* 1(1–3): 143–164.

Lifset, R. 2014. Frontiers in footprinting. *Journal of Industrial Ecology* 18(1): 1–3.

Lifset, R. and T. E. Graedel. 2002. Industrial ecology: Goals and definitions. In *A handbook of industrial ecology*, edited by R. U. Ayres and L. W. Ayres, 3–15. Cheltenham, UK: Edward Elgar.

Loiseau, E., L. Saikku, R. Antikainen, N. Droste, B. Hansjürgens, K. Pitkänen, P. Leskinen, P. Kuikman, and M. Thomsen. 2016. Green economy and related concepts: An overview. *Journal of Cleaner Production* 139: 361–371.

Martín-López, B., C. Montes, and J. Benayas. 2007. The non-economic motives behind the willingness to pay for biodiversity conservation. *Biological Conservation* 139(1–2): 67–82.

Martinez-Alier, J., U. Pascual, F. D. Vivien, and E. Zaccai. 2010. Sustainable de-growth: Mapping the context, criticisms and future prospects of an emergent paradigm. *Ecological Economics* 69(9): 1741–1747.

Meadowcroft, J. 2011. Engaging with the politics of sustainability transitions. *Environmental Innovation and Societal Transitions* 1(1): 70–75.

Mont, O. K. 2002. Clarifying the concept of product-service system. *Journal of Cleaner Production* 10(3): 237–245.

Murray, A., K. Skene, and K. Haynes. 2017. The circular economy: An interdisciplinary exploration of the concept and application in a global context. *Journal of Business Ethics* 140(3): 369–380.

O'Rourke, D., L. Connelly, and C. Koshland. 1996. Industrial ecology: A critical review. *International Journal of Environment and Pollution* 6(2–3): 89–112.

Pearce, D. W. and R. K. Turner. 1989. *Economics of natural resources and the environment*. Baltimore, MD, USA: Johns Hopkins Press.

Pin, X. and Y. Hutao. 2007. Re-reading steady-state economy: Calm thinking on hot circular economy. *China Population, Resources and Environment* 17(3): 20–23.

Preston, F. 2012. A global redesign? Shaping the circular economy. London: Chatham House, Energy, Environment and Resource Governance (EERG), 1–20.

Reisch, L. A. and I. Røpke. 2004. *The ecological economics of consumption*. Cheltenham, UK: Edward Elgar.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, and H. J. Schellnhuber. 2009. A safe operating space for humanity. *Nature* 461(7263): 472–475.

Røpke, I. 2005. Trends in the development of ecological economics from the late 1980s to the early 2000s. *Ecological Economics* 55(2): 262–290.

Sauvé, S., S. Bernard, and P. Sloan. 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development* 17: 48–56.

Schneider, F., J. Martinez-Alier, and G. Kallis. 2011. Sustainable degrowth. *Journal of Industrial Ecology* 15(5): 654–656.

Sinding, K. 2000. Environmental management beyond the boundaries of the firm: Definitions and constraints. *Business Strategy and the Environment* 9(2): 79–91.

Snep, R., E. van Ierland, and P. Opdam. 2009. Enhancing biodiversity at business sites: What are the options, and which of these do stakeholders prefer? *Landscape and Urban Planning* 91(1): 26–35.

Spash, C. L. 2002. *Greenhouse economics: Value and ethics*. London: Routledge.

Stahel, W. 1994. The utilization-focused service economy: Resource efficiency and product-life extension. In *The greening of industrial ecosystems*, edited by B. R. Allenby and D. J. Richards, 178–190. Washington, DC: National Academy of Engineering.

Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, and C. A. de Wit. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223): 1259855.

Su, B., A. Heshmati, Y. Geng, and X. Yu. 2013. A review of the circular economy in China: Moving from rhetoric to implementation. *Journal of Cleaner Production* 42: 215–227.

Van Berkel, R., E. Willems, and M. Lafleur. 1997. Development of an industrial ecology toolbox for the introduction of industrial ecology in enterprises. *Journal of Cleaner Production* 5(1): 11–25.

Van den Bergh, J. 2010. Externality or sustainability economics? *Ecological Economics* 69(11): 2047–2052.

Van den Bergh, J. 2013. Robert Ayres, Ecological Economics and Industrial Ecology. *Environmental Innovation and Societal Transitions* 9: 1–7.

Yuan, Z., J. Bi, and Y. Moriguichi. 2006. The circular economy: A new development strategy in China. *Journal of Industrial Ecology* 10(1): 4–8.

Zhang, B., S. Yang, and J. Bi. 2013. Enterprises' willingness to adopt/develop cleaner production technologies: An empirical study in Changshu, China. *Journal of Cleaner Production* 40: 62–70.

Zhu, D. J. and X. F. Huang. 2005. Building up a model for circular economy based on object, main body, and policy. *Naikai Academic Journal* 4: 86–93.

Zhu, D. J. and Y. Wu. 2007. Plan C: China's development under the scarcity of natural capital. *Chinese Journal of Population, Resources and Environment* 5(3): 2–8.