Ecological Economics 231 (2025) 108545

Contents lists available at ScienceDirect

Ecological Economics

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

Towards an ecological metaphor for regenerative circular economies

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ARTICLE INFO

Keywords:
Biomimicry
Ecomimicry
Sustainability
Sustainable Development

ABSTRACT

An ecological metaphor can enable transitions towards regenerative circular economies. Yet, this potential remains latent because its conceptual development, which is a prerequisite for its practical operationalization, is in its incipient phase and largely vague. To strengthen its epistemological underpinning, we propose a forward-looking interdisciplinary research agenda which brings together theories, ontological positions, analytical approaches, and strategies of action from ecological economics, panarchy theory, socio-metabolic research, process ecology, environ network theory, the constructal law, nature-based solutions, complexity economics, doughnut economics, regenerative economics, and ergodicity economics. The agenda facilitates the concentration, consolidation, and acceleration of theoretical and methodological innovation for the generation and accumulation of a diverse yet coherent body of knowledge on the interpretation of the process of regeneration and for illuminating the ways in which regenerative circular economies may function.

1. Introduction

The circular economy (CE) encompasses visions of an economic model aiming to address (mainly but not only) environmental issues by reorganizing the patterns of production, distribution, and consumption (rather than reducing their levels per se) along the principles of circularity. The latter are not set in stone or follow a commonly agreed definition, but often cited examples of such principles include those highlighted by the *Ellen MacArthur Foundation* for transitioning to a CE at a global scale (Ellen Macarthur Foundation, 2013), those characterising circular business models for facilitating the CE transition (Geissdoerfer et al., 2022; Schulte, 2013), and those described in the waste hierarchy

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https://doi.org/10.1016/j.ecolecon.2025.108545
Received 22 September 2024; Received in revised form 15 January 2025; Accepted 1 February 2025
Available online 17 February 2025

framework to be followed as core CE strategies (Potting et al., 2017). Currently, no general theory exists yet which can explain all aspects of the dynamics underpinning a CE, including all dynamic feedback loops between economic activities and waste generation while addressing holistically not only all types of waste and their full cycles, but also any potentially emerging hindrances (Lu et al., 2024). Some have also argued that the dominant conceptualization of a CE in the academic discourse is that of an economic machine which runs on competitive circular business models where change is incremental and which follows (and potentially re-enforces) a logic similar to a linear economy (Fromberg et al., 2023a; Fromberg et al., 2023b). In our opinion, this continuation of the flawed machine metaphor misses the point and power of an organic, life-based system which is emergent, adaptive, and creative. An ecological metaphor of a CE which is more holistic in its approach, is still in its infancy and largely vague (Fromberg et al., 2023a, Fromberg et al., 2023b).

Here, we make the case for conceptualizing a CE from a regenerative perspective, one which draws inspiration from nature to operate within ecological boundaries. In line with recent calls for engaging in integrated multi-domain and multi-scale research on regenerative dynamics and practices (Fischer et al., 2024), we propose an interdisciplinary research agenda which brings together a diverse set of theories, ontological positions, analytical approaches, and strategies from ecological economics, panarchy theory, socio-metabolic research, process ecology, environ network theory, constructal law, nature-based solutions, complexity economics, doughnut economics, regenerative economics, and ergodicity economics.

In contrast to a review which documents literature systematically, this perspective paper has a speculative and philosophical character. The aim is to raise awareness among interested readers of the challenge making real progress towards regenerative CEs. The paper brings to the reader's attention the existence of a non-exhaustive set of diverse theories and approaches based on the interdisciplinary expertise and research interests of the authoring team, and which, if considered together, may be relevant for methodological and theoretical innovation in this field. Our ambition is that this conceptual cross-disciplinary synthesis will allow for further exploration of the various underlying theories and methods, contributing to the development of novel intellectual positions and, ultimately, help practitioners and policy makers to implement these and shape viable (i.e., regenerative) CEs. The choice of these particular precepts, concepts, and theories is based on our individual experiences investigating some of these topics. Our main assumption is that regeneration is a prerequisite fundamental building block for the conceptual development of an ecological metaphor.

We structure the paper as follows: First, we introduce the metabolic perspective on socio-economic systems and we explore the concept of regeneration within CEs. Then, we present the research agenda and its various elements along with some examples. We reflect on the implications of conceptualizing alternative economic visions which may even lead to contrasting outcomes (i.e., green-growth / degrowth debate) and we elaborate on the relationship between the concepts of regeneration and sustainability. We also touch upon the scale where interventions could be effective, and we highlight the increasing importance of pluralism in economic thinking for enabling future research towards obtaining a more comprehensive and functional description of regenerative CEs. Finally, we stress the importance of science and policy embracing indigenous wisdom, and of nurturing poly-rationality in decision-making processes. We don't claim that this will be the final word on a workable framework but rather hope this synthesis of disparate strands will spark further discussion and research.

2. Metabolic and nature-inspired perspectives on the economy

A regenerative economy may be defined by resorting to ecological metaphors. In other words, societies, including their economies can flourish and attain circularity principles by metabolising resources analogous to living organisms where anabolic processes build up complexity and catabolic processes decompose it (Makriyannis, 2022; Daly, 1968). The fundamental dynamics of an economy could thus draw inspiration from life forms and their ecological functions (i.e., bio-mimicry), as well as from the properties of natural ecosystems (i.e., eco-mimicry) where the process of regeneration is central (Benyus, 2013; Fath et al., 2019).

The metabolic perspective on societies has been around since the 1860s (Fischer-Kowalski, 2003) whereas a thermodynamic approach to understand and study economies started to emerge around the 1970s (Cleveland and Ruth, 1997). In this regard, economies were understood as *"dissipative structures"* dependent on a constant inflow of exergy (i.e., part of energy which is available as useful work), materials, and information, and where two types of economic growth were distinguished (Kneese, 1988). The first one was the growth of an (unrealistic) quasi-static economy producing more of everything while maintaining its *"equilibrium"* (i.e., where prices ensure that markets clear and both producers and consumers optimise their utility according to their preferences) while assuming abundance of natural resources (Kneese, 1988). The second was a dynamic and evolutionary one related to qualitative developments, technological innovations, and increased complexity for generating knowledge and decelerating global entropic increase (Kneese, 1988). The metabolic perspective favours the latter which is viewed as a more realistic interpretation of how economies function and progress. Along similar lines, the Ayres-Warr cycle was proposed to describe an endogenous growth mechanism as a set of feedback loops which accounts not only for capital and labour but also for cumulative exergy consumption where its authors argued that *"physical resources have been, and still remain, a major factor of production and driver of growth"* (Warr and Ayres, 2012). They also hypothesized that the increasing value of information and communication technologies will be driving economic growth in the future (Warr and Ayres, 2012).

Several other bio-inspired theories and approaches have emerged over the years. These include (among others) the theory of *autopoiesis* conceptualizing *"living systems as cognitive systems and living as a process of cognition"* (Maturana and Varela, 1972), *energy network science* emphasizing the importance for robust monetary circulation in both the supply and the demand side of an economy (Goerner, 2013), and the *metabolic scaling theory* seeking to identify universal network properties which transcend design in complex adaptive systems such as cities (West, 2018; Lu et al., 2024) and economies (Makriyannis, 2022).

The concept of regeneration has already been explored for its relation (or rather, distance) to the concepts of sustainability and restoration (Fischer et al., 2024; Reed, 2007). Similarly, the term *regenerative design* was distinguished from *regenerative development* to clarify that the former is a process which aims at comprehending the place-based context of an intervention whereas the latter is a process which enables the realization of strategies for the most effective transformational change fostering long-term self-organization and co-evolution of actors in harmony with their surrounding environment (Cross and Plaut, 2019; Mang and Reed, 2013). These two terms have been brought together into an integrated place-based approach known as *regenerative development and design* to align modern science with indigenous wisdom and enable the capacity of local communities to constantly evolve, adapt, and thrive in their environments as stewards (Gorissen et al., 2024). Along these lines, the term *regenerative practices* has been defined as "'*sets of hierarchically organized doings/sayings, tasks and projects' (ref. 29, p. 30)—and implies four key elements: (1) a practical understanding of how the regenerative dynamics of something work, as is emerging in different academic domains"* [...]; *"(2) rules or guiding principles for how to perform regenerative actions; (3) a teleo-affective structure clarifying what is and what is not desirable; and (4) a general understanding about what regeneration and regenerative practices are"* (Fischer et al., 2024). In the context of the previous definition, *regenerative dynamics "occur when desired outcomes, such as social well-being or soil health, regenerate in a system not only once, but over and over[12]"* and *"are partly self-perpetuating and* *endogenous but are shaped and constrained by contextual and interconnected conditions and require resources such as energy, labour or materials to be sustained"* (Fischer et al., 2024).

Over time, several frameworks have been developed to capture the concept of regeneration across different contexts and scales ranging from neighbourhoods (Sala Benites et al., 2022) to urban areas (Gejer and Gomes Da Silva, 2021), cities (Bunyan, 2015; Cornelius and Trueman, 2008; Girarder et al., 2010; Newton, 2013; Schurig and Turan, 2021; Thomson and Newman, 2020; Thomson and Newman, 2018), city-regions (Axinte et al., 2019), businesses (Hahn and Tampe, 2021; Konietzko et al., 2023; Ryan et al., 2023), economies (Klomp and Oosterwaal, 2021), and regenerative cultures (Wahl, 2016).

A recent literature review showed that, as a term, *"regeneration"* has had only a small, yet increasing, frequency of appearance in the numerous definitions of the CE (Kirchherr et al., 2023). Based on their findings, the authors of that study proposed a meta-definition for the CE as *"a regenerative economic system which necessitates a paradigm shift to replace the 'end of life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities"* (Kirchherr et al., 2023). Perhaps the most popular CE definition where regeneration has a prominent role is that of the *Ellen MacArthur Foundation* (Järvenpää et al., 2023) whereby the technical metabolism of an industrial system is "*orchestrated"* to mimic nature's biological metabolism *"by intention and design"* having *"processes themselves renew or regenerate the sources of energy and materials that they consume"* (Ellen MacArthur Foundation, 2019). Here, it is stressed that the redesign of products and services also plays a central role in understanding the workings of a regenerative CE. This is because the vast majority of existing products and services are still designed within a cradle-to-grave paradigm meaning that their individual components cannot enter the technical or natural cycle without losing quality or without damaging nature. Taking a *strong sustainability* perspective can help alleviate some of the losses that occur during trade-offs, but is not sufficient to guarantee no net loss of natural quality. As land stewards, we can only aspire to rebuild as much natural capital as we consume.

Yet, even among experts there seems to be no agreement on a clear definition of a regenerative economy which is still perceived by some to be synonymous to a CE even though they are two distinct concepts (REGEN:U project, 2023). According to the *Sustainable Development Solutions Network Switzerland*, a regenerative economy is "*a holistic, dynamic system that fosters renewal, restoration, preservation, and net positive impacts across ecological, economic, and social systems, necessitating transformational change within and across individuals, organizations, and societies"* (Unter et al., 2024). For the *Capital Institute*, a regenerative economy is demarcated from other visions of the nature and scope of an economy by stating explicitly its assumptions and its main goal which is to foster healthy socio-economic and socio-ecological relationships for well-being and prosperity rather than waiting for them to materialize from an exponential growth of gross domestic product (GDP) (Fullerton, 2015). Similarly, the *Research Alliance for Regenerative Economics* (RARE) defines a regenerative economy as *"a socio-economic system which aims to drive inclusive prosperity while addressing societal needs within planetary boundaries by continuously channelling money, information, and renewable natural resources into self-feeding, self-organizing, and adaptive learning internal circular processes which nourish its capacity to thrive for long periods of time"* (Fath et al., 2019).

3. Towards regenerative circular economies

Regardless of all efforts, the practical implementation of regeneration remains unclear, and opinions about its further development differ. Furthermore, being a malleable concept, its interpretation by policy makers may have profound implications for developing policies (Pugalis, 2016). An example from the UK where the concept of regeneration was introduced in urban planning policies with the intention to foster social inclusion, highlighted the shortfall that *"often the 'excluders' are not in view and the 'excluded' are not in focus"* (Furbey, 1999). Some have argued that regeneration should *"not be considered as a primary principle of a circular economy"* due to its conceptual vagueness and its seeming incompatibility with technical cycles, noting that most of its applications so far have been limited to agriculture (Morseletto, 2020). But for others, regeneration is relevant not only for the restoration and maintenance of biogeochemical, resource, and ecosystem cycles but also for stimulating the social cycles of care, wealth, knowledge, and political power in socio-economic systems (Calisto Friant et al., 2023). Regarding the adoption of regenerative business models by organizations, recent research highlighted the importance of early-stage development for forecasting environmental impacts and for minimizing or mitigating (or ideally avoiding) rebound effects (Das, 2024). It has also been stressed that the shift towards regenerative CEs is not about returning to some past romanticized era but about shifting policy focus towards the well-being for all life on Earth where all societal actors have the necessary conditions for capacity building and agency for place-based development within planetary boundaries (Benites and Osmond, 2021). In this sense, positive change is meant to be conceptualized and communicated with compelling yet pragmatic narratives which have the potential to bring actors together to overcome dichotomies (Hunt and de Laurentis, 2015) and co-create designs where *"sustainability is the consequence and not the concept of creation"* (Jain, 2021).

Evidently, conceptual clarity on the process of regeneration is a prerequisite for establishing solid theoretical foundations of an ecological metaphor of a CE. When considering the above points, there seems to be convergence in recognizing that the concept of regeneration goes beyond a mere description of renewability, and that it can be understood as a context-dependent co-evolutionary adaptation process between the system of interest with other systems and with their surrounding environment which emerges from self-organization, interconnectivity, and interdependence through feedback loops subject to multi-scale spatio-temporal dynamics. Even though the practical operationalization of regeneration remains unclear and may be challenging (Buckton et al., 2023), it is also an opportunity in that its concrete implementation in other fields or sectors besides agriculture, is non-trivial and requires a holistic, transdisciplinary approach to account for multiple dimensions of complexity simultaneously.

Various organizations, initiatives, and academics have been working with the concept of regeneration. A prominent example is the *International Ecological Engineering Society* calling for the global community to embrace nature-based design in circular problem-solving processes (International Ecological Engineering Society (IEES), 2022). Another example is the *BioFi project* which seeks to catalyse the emergence of bioregional financing facilities (analogous to mycelial networks or *"islands of coherence"* as per Ilya Prigogine) for facilitating place-based learning and coordinating decentralized efforts in restructuring, pooling, and redirecting capital flows towards regenerative projects and initiatives (Power and Seefeld, 2024). Particularly during the past decade, there has been an increasing research interest for following a bio-inspired (i.e., bio-mimetic or eco-mimetic) approach to study, design, and operate robust human-made systems in the context of a regenerative CE (Johnson and Webster, 2021) with examples ranging from supply chains (de Souza et al., 2019; Howard et al., 2019) to industrial systems (Chatterjee et al., 2021; Layton, 2014), power grids (Huang et al., 2023), farming systems (Fabien, 2016), buildings (Garcia-Holguera et al., 2016), cities (Galychyn et al., 2022), business ecosystems (Tate et al., 2019), trading networks (Kharrazi et al., 2017), economic networks (Iskrzyński et al., 2021), and sustainability transitions (Ceddia et al., 2022) among many others.

4. A research agenda

Clockwise, Fig. 1 brings together theories, ontological positions, analytical methods, and strategies to address the process of regeneration (either explicitly or implicitly) by assuming that it has a foundational role in the ecological metaphor of a CE. Then, a few questions are posed as potential future research directions.

- **Ecological economics** is a transdisciplinary scientific field which goes beyond *"conventional"* economics, *"conventional"* ecology, environmental economics, and resource economics by taking a broader spatio-temporal view to study how economies and natural ecosystems affect each other (Costanza, 1991; Costanza, 1989). Here, the economy is considered from a *strong sustainability* perspective to be a social construct that is nested within the society, which in turn is embedded within (and dependent on) the natural environment (Pelenc et al., 2015; Sciubba, 2012). Moreover, economic growth and economic development are seen as two separate properties of an economy, an observation which was made already in the 1970s (Daly, 2015; Daly, 1972). In this regard, regeneration is addressed implicitly since a sustainable *"steady-state"* economy is viewed to be one which does *"not use natural resources faster than they are regenerated by the environment, produce wastes faster than the environment can absorb, detoxify, or dilute them, and does not diminish the ability of the ecosystems to generate life support services"* (Cleveland and Ruth, 1997). A recent simulation study which followed an ecological economics approach showed among others that technological change and circularity are necessary yet insufficient for achieving a steady-state economy (Mautinović et al., 2023).
- **Panarchy theory** can be used to explain the dynamic aspects of CE transitions since it was originally developed to demarcate the links between system dynamics and scale (Gunderson and Holling, 2002). Here, regeneration is captured in the adaptive cycle, which is the basic unit of analysis used to describe ecological succession in natural ecosystems through the stages of growth, conservation, collapse, and re-organization (Holling, 1986). For the system of interest, the challenge is to identify quantitative or qualitative methods which can characterize all its sub-systems and involved actors while addressing their dynamic progression through all four stages of the adaptive cycle simultaneously, across scales, and at varying rates (i.e., spatio-temporal nestedness of adaptive cycles) (Fath et al., 2015; Sundstrom and Allen, 2019). One promising method for analysing

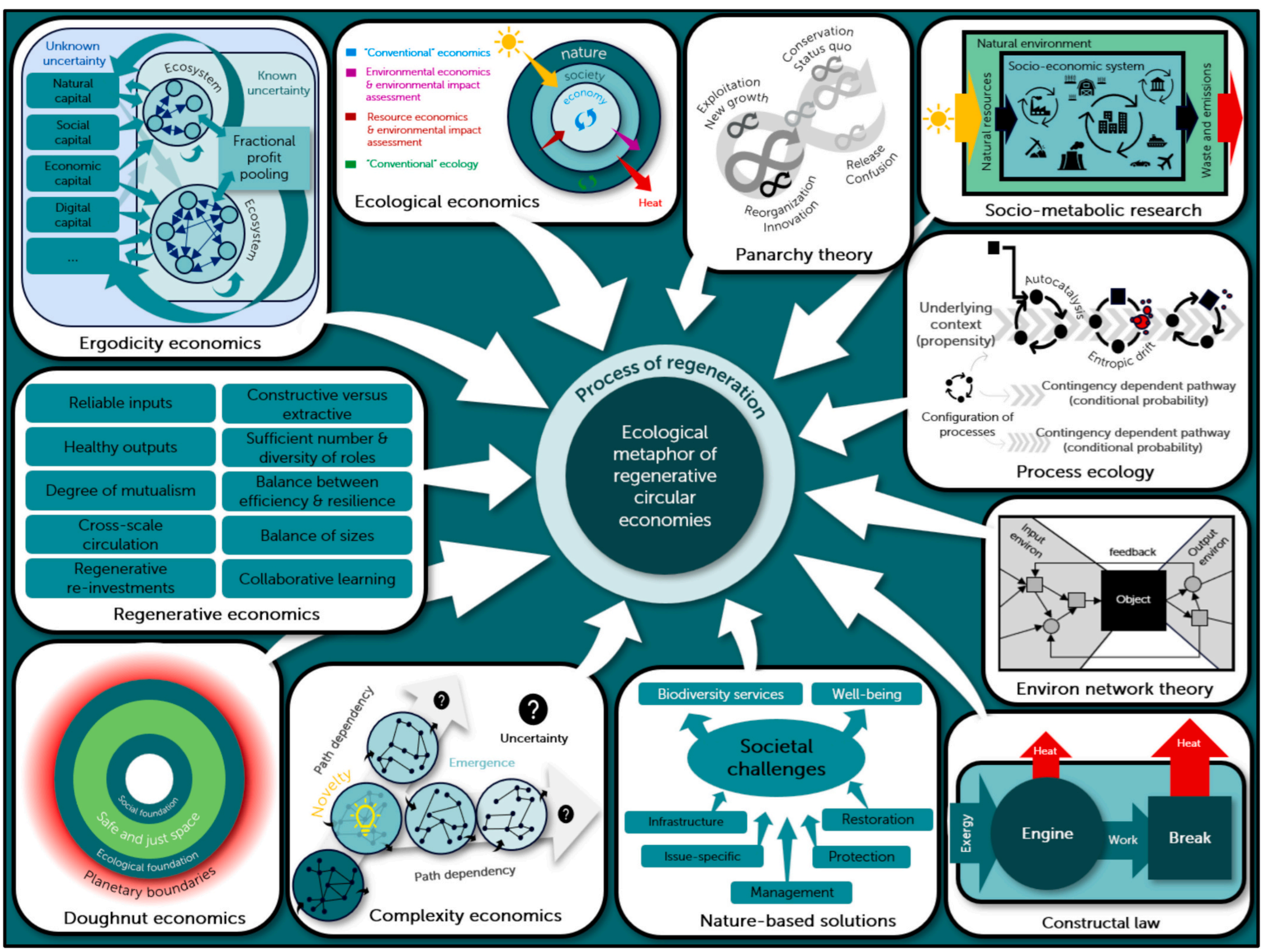

Fig. 1. A simplified illustration of a diverse set of interpretations on the process of regeneration for strengthening the ecological metaphor of regenerative circular economies. The perspectives considered include ecological economics (Costanza, 1991; Daly, 2015; Daly, 1972), panarchy theory (Fath et al., 2015; Gunderson and Holling, 2002; Sundstrom and Allen, 2019), socio-metabolic research (Haberl et al., 2019; Singh et al., 2022), process ecology (Ulanowicz, 2006; Ulanowicz, 2001), environ network theory (Fath, 2012; Fath et al., 2019; Patten et al., 1976), constructal law (Bejan and Lorente, 2011), nature-based solutions (Cohen-Shacham et al., 2016; Johnson et al., 2022; Sowińska-Świerkosz and García, 2022; Stefanakis et al., 2021), complexity economics (Arthur, 2021), doughnut economics (Raworth, 2017c), regenerative economics (Fath et al., 2019; Fullerton, 2015), and ergodicity economics (Bassi et al., 2015; Boyd and Reardon, 2023; Peters and Adamou, 2022; Peters and Gell-Mann, 2016; Taleb, 2017).

the evolutionary development of complex adaptive systems is QtAC (Castell and Schrenk, 2020; Schrenk et al., 2022), which has recently been used to study the socio-economic metabolism of islands (Hyde et al., 2024).

- As a grandparent to CE, **socio-metabolic research** is a systems approach which offers a solid foundation for the research agenda because it brings together natural sciences and social sciences in a rigorous way to measure, analyse, and model socio-economic systems in terms of their biophysical requirements and environmental pressures (Haberl et al., 2019) illuminating risks, inequalities, and capacities of societies to transform or collapse (Singh et al., 2022). Since its methodological focus is on understanding the fate of biophysical flows and stocks, socio-metabolic research is by default concerned with the process of regeneration.
- **Process ecology** is a theory which can be explored for its potential to study and expand our understanding of the underlying dynamics of socio-metabolic processes (Ulanowicz, 2009; Ulanowicz, 2001; Ulanowicz et al., 2009). Considering the increasingly prominent role that information networks may have for offering a unifying understanding of ecological systems (O'Connor et al., 2019), process ecology draws on concepts from information theory to describe the dynamics of natural ecosystems whereby competing yet complementary propensities of configurations of ecological processes are theorized to manifest as a dialectic between autocatalytic forces on the one hand and an entropic drift on the other (O'Connor et al., 2019; Ulanowicz, 2006; Ulanowicz, 2001). While the latter is wearing the system down, the former are assumed to bring structure through selective configurations of processes which enhance its ability to draw resources from the environment in a self-reenforcing, mutualistic way (i.e., centripetality), leading to the emergence of complexity over time (i.e., directionality) (Ulanowicz, 2006). Here, mutualism is theorized to be a fundamental property of natural ecosystems where competition arises only as a secondary phenomenon when two autocatalytic loops of processes compete over the same pool of resources (Ulanowicz, 2006). For the system of interest, the concepts of centripetality and directionality can be useful for capturing regeneration qualitatively by describing the various underlying contexts resulting from the degree of institutionalization, national and international regulations, technological development, socio-economic relationships, and other effects which may or may not lead to lock-ins [e.g., see (Ceddia et al., 2022)]. The quantitative method of process ecology is ascendency analysis which is a network-based method similar to ecological network analysis, and its applications to study socio-metabolic systems vary from the analysis of industrial systems (Carvalho and Serra, 2019) and cyber-physical systems (Chatterjee et al., 2024) to urban planning (Kiss and Kiss, 2018) and economic trade networks (Kharrazi et al., 2013; Kiss et al., 2024).
- **Environ network theory** can be used to study how socio-economic systems can maintain sustainable patterns and socio-metabolic processes as open, far-from equilibrium systems (Fath, 2012; Fath et al., 2019; Patten et al., 1976). Typically, the comprehensive conceptualization of a system involves the identification of its main interconnected objects, elements, components, or processes, and of their relations with the surrounding environment. The first step of system analysis involves drawing a system boundary separating the overall system from its surrounding environment. Such a reductionist approach is useful for managing complexity, but it implicitly assumes the existence of clear borders between the object of study from its surrounding environment when the relationships might be more fluid, multifaceted or of transcending nature. Here, the relationship of an object with its surrounding environment is made explicit where the input environ of an object represents all the inputs flowing into the object's internal environment from other objects in the system's external environment, and the output environ of the same object represents all generated outputs which flow towards other objects before exiting the system's boundary (Fath and Borrett, 2006). The advantage then is that objects become inseparable from each other, rather they are always connected through the input-output feedback loops of process couplings explaining how resource cycling emerges. There is still a permeable system boundary accounted for to maintain the validity of the second law of thermodynamics but at a scale which includes the necessary processes. Like process ecology, environ network theory also supports the emergence of mutualism in natural ecosystem as the manifestation of community-level relations and indirect flow effects (Fath, 2007). Also, both theories support a metabolic perspective by offering network-based methods with indicators for the comprehensive analysis of socio-economic and socio-ecological systems analogous to medical diagnostics of human health (de Jonge and Schückel, 2021).
- **The constructal law** has been proposed in 1996 to explain the generation and evolution of design in nature in terms of configurations, shapes, structures, patterns, and rhythms which reduce resistance, facilitating easier access to flows (Bejan and Lorente, 2011). The law states that *"for a finite-size system to persist in time (to live) its configuration must change such that it provides easier access to its currents"* (Bejan and Lorente, 2011). From this thermodynamic perspective, a system is conceptualized as an emerging flow architecture comprising on the one hand of a *"constructal engine"* evolving towards increasing power generation (or towards dissipating less energy) and on the other hand, of a *"break"* evolving towards more dissipation (Bejan and Lorente, 2011). This approach has been used to propose an explanation for the emerging non-uniform (i.e., hierarchical) distribution of wealth in an economy as it develops towards increased complexity (Bejan and Errera, 2017). The constructal law may help address the subtle intricacies of the process of regeneration in socio-economic and socio-ecological systems while being grounded on physics and thermodynamics.
- **Nature-based solutions** comprise a set of strategies whereby new types of infrastructure allow for the integration of biodiversity enhancement, ecosystem services provision, and circular flows of nutrients and resources in the design of the urban environment (Stefanakis et al., 2021). To facilitate common understanding, the following definition has been adopted by 193 Member States at the *United Nations Environment Assembly* in 2022: *"nature-based solutions are actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits"* (United Nations Environment Programme, 2022). Intervention types of nature-based solutions include, among others, habitat creation, regenerative grazing for food production, protection (e.g., from floods), restoration (e.g., for reintroducing native species) (Hafferty et al., 2025), and circular water management based on the principles of ecological engineering (Stefanakis, 2024; Stefanakis, 2023). However, it is important to note that not all types of *"green"* or *"blue"* interventions may be classified as nature-based solutions and eleven inclusion (or exclusion) criteria have been proposed for this purpose which are: *"(1) lack of functioning ecosystems; (2) random actions; (3) post-implementation goal(s); (4) negative/no impact on biodiversity; (5) same benefits as grey infrastructure alone; (6) unfair distribution of benefits; (7) 'copy-paste' implementation approach; (8) top-down model of governance; (9) static management approach; (10) financial expenses disproportionate to benefits; and (11) 'point scale' approach"* (Sowińska-Świerkosz and García, 2022). Substantial evidence already exists for the potential of nature-based solutions in terms of outcomes, scaling, and policy, but a lot of work remains to be done to address financing barriers, social aspects, and the role of the private sector among other issues (Johnson et al., 2022). Superficial participation, power inequalities, and *"democracy washing"* have also been identified as issues to be addressed by fostering conditions which

enable the generation of plural perspectives on matters of justice and well-being (Hafferty et al., 2025).

- In **complexity economics**, the economy emerges from the actions of its agents who act and react under uncertainty and constant change (Arthur, 2021). Since its approach aligns with multiple macroeconomic theories, it has been proposed to be considered more as a modelling framework rather than a separate school of economic thought (Roos, 2017). Even though the process of regeneration may not be addressed explicitly, it is captured indirectly through a living organism analogy where self-organization, novelty, and autonomy are assumed to emerge organically.
- **Doughnut economics** is an ontological normative position on the essence and purpose of an economy promoting the development of local thriving economies which place wellbeing as a core goal by considering not only the markets but also the households, the state, and the commons (Raworth, 2017a). Its usefulness in this research agenda rests on the fact that it builds on a diverse set of non-orthodox schools of economic thought (e.g., complexity economics, systems thinking, ecological economics etc.) and on that it considers simultaneously societal needs and planetary boundaries [for an explanation of the latter see (Muys, 2013; Richardson et al., 2023; Rockström et al., 2023)]. It also displays plasticity and adaptability in its working framework across contexts which renders it as a functional tool for engaging local actors in bottom-up initiatives (Raworth, 2017b). Part of the normative element relates to placing human wellbeing at the centre and nature at the periphery of the *"doughnut"* but as its author argued, this choice *"depends on the visual and symbolic interpretation different people / worldviews may choose to follow"* allowing for indigenous visions to also adopt it (Shareef, 2020). Such societal engagement ultimately intends to lead to self-organization for local capacity building with beneficial ripple effects across all levels and sectors of an economy, therefore making a direct link with the concept of regeneration. An example of research adopting this framework in its methodology suggested that current macroeconomic policy tools have been focusing excessively on monetary flows and economic growth offering limited *"understanding of the interconnections between environmental, social, and economic systems"* (Van Eynde et al., 2024).
- Being unrelated to neoclassical economics (Fath et al., 2019; Shannon et al., 2022), **regenerative economics** resembles more an ontological position and an eco-mimicry perspective rather than an established school of economic thought. Even though it is depicted as a separate category on Fig. 1, regenerative economics can be understood as an evolving amalgam of ideas, concepts, and principles from several of the aforementioned theories, approaches, and methods including process ecology, panarchy theory, environ network theory, energy network science, ecosystem ecology, and ecological economics among many others. Its contribution in this research agenda is invaluable as it comprises of ten principles as suggestive qualities describing a regenerative economy [see (Fath et al., 2019; Fullerton, 2015)]. Moreover, it offers quantitative methodologies and indicators which allow for benchmarking systemic properties of socio-economic systems against those of sustainable natural ecosystems. For example, network-based methods such as ecological network analysis (Fath and Scharler, 2018) and ascendency analysis (Ulanowicz, 2009) allow for a comprehensive and systematic study of the evolution of socio-economic and socio-ecological systems under varying or even contrasting developmental trajectories towards regenerative CEs. The application of network-based methods for studying socio-economic systems has already been proposed years ago for assessing among others socio-economic sustainability (Goerner et al., 2009; Huang and Ulanowicz, 2014; Lietaer, 2010; Lietaer et al., 2010; Ulanowicz et al., 2009) and the ecology and systemic risks of volatile global financial markets (May et al., 2008). The methodological toolkit may be extended with other quantitative methods such as emergy analysis (i.e., embodied solar energy) (Brown and Ulgiati, 2004) and exergy analysis (Sciubba, 2021) as well as with qualitative methods such as surveys, interviews, participatory research, and ethnographic studies among others [e.g., see (Das, 2024)]. Considering its emerging transdisciplinary nature, regenerative economics is likely to build more theoretical and methodological bridges with other scientific fields (also from the social sciences) and other alternative views of economic thought (such as complexity economics, ecological economics, bioregional economics etc.) which suggests that it may be constantly updating itself as new knowledge emerges.
- Recent research in **ergodicity economics** has shed light on the distinction between systems with what could be termed trivial dynamics, where the time dimension has a trivial role; and those with non-trivial dynamics, where the time dimension has a non-trivial role (Bassi et al., 2015; Boyd and Reardon, 2023; Peters and Adamou, 2022; Peters and Gell-Mann, 2016; Taleb, 2017). One illustrative example of the distinction: with trivial dynamics the system will, given long enough time, trend towards the average (ergodic); with non-trivial dynamics the system does not trend towards the average (non-ergodic). Mainstream economics implicitly assumes trivial dynamics, which is seldom true. Even simple compound growth (e.g. algal biomass in a pond, or a company's capital, growing at some rate) is non-trivial in the presence of any stochasticity (Boyd and Reardon, 2023; Peters and Adamou, 2022; Peters and Gell-Mann, 2016). Nature recognizes this, using strategies such as natural capital pooling that bias towards anti-fragility (Peters and Adamou, 2015). In this sense, economic actors may mimic natural ecosystems by adopting ergodic strategies such as fractional profit pooling for improved resilience and by engaging in practices for renewing all types of *"capital"* that they tap into besides the financial one [for example, the six types of capital defined by the *International Integrated Reporting Council* which include the financial, manufactured, intellectual, human, social and relationship, and natural capital (International Integrated Reporting Council, 2013)]. One key aspect of non-ergodic dynamics is that the typical (economic) outcome is worse than the average. Another crucial element is the distinction between (economic) risk and uncertainty in stochasticity. To pursue a regenerative CE design, or in other words, to distinguish between viable and non-viable green-growth, degrowth, or other kind of outcome, depends on including all relevant non-trivial aspects of the dynamics. Since nature has done this successfully for ~3.7 billion years, resulting in life thriving despite Earth's hostility to life already eliminating 99.9 % of all species, a regenerative CE would be well served by including ergodicity economics in the proposed research agenda (Boyd and Reardon, 2023).

5. Towards regenerative circular economies which green-grow or degrow?

Pertinent to transitions towards regenerative CEs, is the concept of growth which is inherent to the process of regeneration (for example, as one of the stages of the adaptive cycle). For some, growth in terms of GDP, circularity, and sustainability, is not only conceivable but desirable in a CE fostering sustainable development (Kirchherr, 2022). This orientation is aligned with the green-growth narrative which is dominant particularly (but not exclusively) in EU policy agendas (European Commission, 2023) and which, in a broad sense, has two main views. The conventional view on green-growth is driven by neoclassical economics and the idea that negative environmental externalities could eventually be internalized via market pricing mechanisms where the economy is guided to change gradually its valuation system towards environmental protection (Scrieciu et al., 2013). The expected outcome then would allow for economic (green) growth to occur but at a slower pace than the business-as-usual (where the markets are left to their *"own devices"*) due to a drag on the economy resulting from public policy measures targeting environmental issues (Scrieciu et al., 2013). The alternative view on green-growth draws inspiration mainly from post-Keynesian economics by theorizing that targeted policy interventions could boost economic growth at faster rates than *"brown"* economic growth (i.e., fossil-fuel dependent business-as-usual) due to so-called Keynesian multiplier effects and demand-driven growth dynamics that do not view economies as being in equilibrium and optimally allocating resources (Scrieciu et al., 2013). It is also assumed that the financial system and money supply are endogenous (i.e., where credit creation is done by commercial banks and where the supply of money is not entirely under the control of the central bank) and that investments (e.g., in low-carbon technologies) fostered by public policy measures, could spur innovation, leading to the creation of new markets with considerable potential for further economic growth (Scrieciu et al., 2013).

At the same time, there is increasing scepticism about the potential of green-growth addressing sustainability challenges. A recent survey among 764 scholars and policy researchers from various countries of origin and research disciplines showed that most of them stand for agrowth (i.e., economic growth agnosticism) (45 %) or degrowth (28 %) (King et al., 2023). In another recent research, it was shown that the significant decoupling of economic growth from greenhouse gas emissions achieved by some high-income countries is inadequate and too slow to meet the 1.5 °C target of the Paris agreement by 2050 in a fair way (i.e., proportionate to population) (Hickel and Vogel, 2023). In this regard, it has been argued that expecting the decarbonization of continuously growing economies to occur fast enough via speculative technologies is like proposing a downward marathon on an escalator which is accelerating upwards (Hickel and Kallis, 2020; Kallis, 2019). Moreover, economic forecasts related to the economic damage of climate change have received fierce criticism for their underlying assumptions i.e., "*that about 90% of GDP will be unaffected by climate change, because it happens indoors; using the relationship between temperature and GDP today as a proxy for the impact of global warming over time; and using surveys that diluted extreme warnings from scientists with optimistic expectations from economists"* (Keen, 2021). Some have also compared the global economy to a blind super-organism which constantly grows its demand for energy to satisfy its hunger for ever growing complexity, and where money and debt are *"social construct(s) with physical consequences"* defined as *"a claim on energy"* and *"a claim on future energy"*, respectively (Hagens, 2020). Others theorized that circuits of positive feedback loops for continuous autocatalytic economic growth may be responsible for degrading systemic sustainability, but they also argued that it may not necessarily be the size of an economy that matters but rather the way in which growth happens (Goerner et al., 2009). Along these lines, a bio-inspired approach has been proposed for increased systemic resilience emerging, among others, from the diversification of complementary currencies (Alves et al., 2022; Lietaer, 2016; Lietaer, 2010; Lietaer et al., 2010; Ulanowicz et al., 2009).

While agrowth (or growth agnosticism) calls for building economies which can thrive within just and safe planetary boundaries irrespective of what happens to GDP, degrowth proposes that the perpetuation of economic growth be abolished as a primary objective, and that global policy efforts should reduce the throughput of material and energy resources in a fair way, through locally contextualized democratic transformations focused on societal wellbeing (Hickel, 2021). Degrowth has been proposed to be analogous to a *"macro-economic diet for biophysically obese economies"* as the first and necessary step towards a post-growth steady-state economy which may still be experiencing fluctuations in its size thereafter but which *"should never overshoot biocapacity nor undershoot decent living standards"* (Parrique, 2023). The degrowth movement does not oppose technological innovation or the concept of CE (Marín-Beltrán et al., 2022) provided they are grounded on *strong sustainability* principles prioritizing social equity and planetary boundaries over market efficiency (Bauwens, 2021; Bimpizas-Pinis et al., 2021), and fosters the active involvement of all societal actors as stewards of a circular society (Jaeger-Erben et al., 2021).

Evidently, both green-growth and degrowth narratives differ fundamentally on how circular transitions should be linked with consumption reduction on the one hand, and with (economic) growth on the other hand, may it be via a *"waste as resource"* or via a *"sharing economy"* approach (Ortega Alvarado et al., 2021). However, both narratives acknowledge that the current economic system and the way its economic success is measured need to change [see debate (Raworth et al., 2022)]. Furthermore, proponents of both narratives seem to agree that total material throughput, particularly linked to *"harmful"* activities, should be reduced through pragmatic here-and-now actions through top-down policy and broad, bottom-up community engagement (Global Governance Institute, 2022). The fact that the current accounting does not distinguish the *"quality"* of the activity (i.e., money spent on destabilizing arms manufacturing or pollution clean-up or gambling, etc. versus money spent on preventative health care, education, community building, etc.) is one of its most egregious shortcomings, particularly when investors only look for highest returns.

Interestingly, a recent bibliometric analysis identified two main clusters in academic literature, one arguing that *"CE is a viable decoupling strategy"* for economic growth and the other highlighting *"the impossibility of a growing CE as a means to reach sustainability"*, the author concluded that the overall relationship between CE and economic growth to be inconclusive (Miller, 2023). It has also been argued that due to its neutrality, the CE concept may not actively address socio-ecological problems and thus it could be adopted in support of nearly any kind of socio-environmental policy, be it profit oriented (e.g., optimizing large value chains) or socially oriented (e.g., engaging citizens in repair cafes) (Savini, 2024).

Perhaps it is due to such conceptual plasticity that the CE may be expressed in a plurality of versions, co-existing alongside other visions of the economy. In a recent study it was proposed that nature-inspired visions of idealized circularity have made their first appearance even as early as the Greco-Roman times as efforts for bringing resources into social orders *"in collective harmony with nature and without waste"* (e.g., via innovations in engineering and architecture or social integration) (Greaves and Doezema, 2024). By adopting the actor-network theory the authors of that study argued that such normative visions were *"coproduced"* with political agendas throughout history generating novelties related to CE discourses which were powerful enough to shape the *"collective imaginations of right moral order in nature and culture"* (Greaves and Doezema, 2024). In another study, scenario analysis was used to envision and juxtapose four alternative futures of a CE (namely, *"planned circularity"*, *"bottom-up sufficiency"*, *"circular modernism"*, and *"peer-to-peer circularity"*) emerging from the levels of technological deployment (low or high) and of governance regimes (centralized or decentralized) while acknowledging that more visions may exist (Bauwens et al., 2020). Similarly, others proposed a typology of four main discourses of CE in literature (namely, *"reformist circular society"*, *"transformational circular society"*, *"technocentric circular economy"*, and *"fortress circular economy"*) by considering their approach towards social, economic, environmental and political considerations (holistic or segmented) and their stance towards technological innovation and ecological collapse (optimist or pessimist) (Calisto Friant et al., 2020). Evidently, whether transitions towards regenerative CEs will result in high or low green-growth, zero-growth, degrowth, or a steady-state economy is a topic which is likely to attract more interest in research and political agendas alike.

6. Regeneration as a precondition for sustainability to materialize

To assess the sustainability of any system one must first conceptualize the respective system. This step has massive implications for the outcomes of a sustainability assessment because *"assuming some structure for the world is philosophy – even metaphysics"* (Hyötyniemi, 2013). Even the most sophisticated and detailed model of a socio-economic system is but a reduced abstraction of reality accompanied by a set of assumptions which typically have a normative/ideological underpinning. For example, assuming that economic growth is by default desirable because it may bring collective benefits in the long run is a normative statement. System simplification and reductionism may be practical for analytical purposes but they also obscure the underlying complexity of the whole. One may find such wisdom in the ancient proverb of Lao Tzu (here slightly paraphrased): *"the socio-economic system which can be named is not the socio-economic system"* (Boyd and Reardon, 2023).

Whereas its implementation may be politically driven, *"sustainability"* itself is merely a concept used to simplify and reduce complexity and as such it is apolitical. Its conceptual abstraction is often visualized as a combination of three spheres: the environment, the society, and the economy. To the best of our knowledge, there exist two ways of combining these spheres to describe the concept of *"sustainability"* (Pelenc et al., 2015).

Weak sustainability assumes that these three spheres are independent from each other, there is the possibility of substitution between these elements where the lack of one can be replaced by surplus of the other, and when they somehow overlap reaching some kind of *"balance"* (i.e., they become weakly coupled) then the system is assumed to be sustainable. One may argue that, in general, the *weak sustainability* approach is in line with the field of (neoclassical-driven) environmental economics which seeks supposedly objective ways to *"internalize externalities"* by integrating diverse ecological and social aspects into markets and the circular flow of income, using monetary accounting methods and cost-benefit analyses i.e., *"what gets measured gets managed"* [for the origin of the quote see Houser (2022) and Martin (2023)]. A seemingly similar approach was introduced around the 1990s and became known in the corporate world as the *"Triple Bottom Line"* (TBL) which was closer conceptually to *strong sustainability* in that it originally called for the private sector to take responsibility for social and environmental impacts while protecting and preserving natural capital, instead of focusing solely on economic gains (Elkington, 2018). In 2018, however, there was a *"product recall"* whereby the inventor of TBL stated that it had *"failed to bury the single bottom line paradigm [i.e., hitting profit targets]"* and proposed to move towards a regenerative economy, *"a genetic code for tomorrow's capitalism, spurring the regeneration of our economies, societies, and biosphere"* (Elkington, 2018).

Strong sustainability assumes that these three spheres are nested in a specific order where the economy is considered to be a social construct embedded in the society which in turn is embedded in the natural environment (i.e., they are strongly coupled). This approach recognizes the existence of planetary boundaries and of limits to biophysical growth due to constraints in the ecological carrying capacity of natural ecosystems which maybe become irreversibly lost due to overexploitation (i.e., no amount of money or innovation will be able to restore them). Here, the trade-offs between ecosystem function and human well-being can be stated explicitly in anticipation that they may worsen in the future if business-as-usual continues, forcing the world into a *"sustainable retreat"* (Muys, 2013). This approach is often adopted by post-growth/degrowth proponents and is in line with the field of ecological economics recognizing that the allocation of price-tags is inadequate and inappropriate for capturing value (O'Neill, 2021). The latter is particularly relevant when considering that the plural perspectives on nature's values *"are expressed in and shaped by worldviews and knowledge systems, but also by power relations that underpin institutional structures in societies[79]"* (Pascual et al., 2023). Some have also proposed that demarcating CE as a separate concept from *strong sustainability* or degrowth may generate a false dichotomy hindering global efforts for sustainability (Schröder et al., 2019).

The explicit distinction between these two sustainability approaches highlights their potential implications when adopting either one of them to design policies or systems which intend to address the challenges of the poly-crisis. In other words, this starting point matters for how a socio-economic system will be conceptualized and analysed qualitatively or quantitatively.

In our view, the *strong sustainability* approach offers a more concrete link with the concept of regeneration, where the latter is a precondition for the former to manifest as an outcome through creativity and adaptability. Moreover, *strong sustainability* can be more realistically aligned with an eco-mimicry approach since it suggests that both the society and the economy depend on nature to exist.

In this regard, a regenerative CE aligns with Herman Daly's characteristics of a sustainable socio-economic system whereby (i) the sustainable rate of using renewable resources cannot be higher than their rate of regeneration; (ii) the sustainable rate of using non-renewable resources cannot be higher than the rate of a renewable resource being substituted; and (iii) the sustainable rate of emissions, waste, and pollutants cannot be higher than the rate at which they can be recycled, absorbed, or rendered harmless in their sinks (Daly, 2007).

7. At what scale to implement changes?

Selecting the level of analysis or of an intervention is crucial as it may affect substantially its outcome given that there may be *"interesting differences at one level that disappear in the summary at another level of analysis"* (Niquil et al., 2020). It has been argued that it is at the regional level where the implementation of circular strategies may be most effective, through the mobilization of tacit resources such as economic and technical expertise, as well as via cultural aspects and social dynamics (Chembessi et al., 2024). However, taking a regional perspective for dealing with socio-metabolic waste and resources while considering simultaneously the proximity principle of the CE, is challenging (Durand and Bahers, 2020).

The nestedness of scales has been proposed to be an important consideration for prioritizing accordingly the identification of leverage points for targeted interventions and scenario analysis with emergy analysis (i.e., a method which considers solar transformities to evaluate the total energy required for producing a specific product or service) being more suitable for assessing a socio-economic system at a national level and input-output analysis supporting regional coordination and identification of trade-offs (Yan et al., 2020). This nestedness of scales is consequence of, and how to make best use of it visible when, the non-trivial dynamics of complex dynamic ecosystems (e.g., of businesses, organizations, actors etc.) is fully included. Evidently, the transition to regenerative CEs is complicated, and it is conceivable that it will call for reconfiguring and managing more intensively the flow of resources, such as materials, energy, money, and information. It requires a paradigm shift in the rules of the economic game: policies, regulations, and practices should be thought in line with a debunking of the institutional and geographic distances separating consumption and productive apparatuses (Kampelmann and De Muynck, 2019).

Undoubtedly, further research is needed to understand how to assess socio-metabolic systems holistically and across different contexts and scales. Conducting ***in situ* and *ex situ* experiments** is a promising research avenue for example by deploying nature-based solutions across different contexts (e.g., cities) (Kisser et al., 2020). It is also becoming clear that a plurality of indicators which go beyond measuring GDP [such as the wellbeing, inclusion, and sustainability (WISE) metrics (Wellbeing Economic Alliance (WEAll), 2020)] will not be just useful but necessary for facilitating cross-comparison of CE studies and for informing future decision-making and policy development (Zhao et al., 2023). Towards this end, future research may also explore the use of mixed methods research designs (Schoonenboom and Johnson, 2017). **Quantitative methods** may include network-based methods [e.g., for analysing national and regional input-output tables (Mcnerney and Kryazhimskiy, 2009), for designing resilient industrial ecosystems (Layton, 2014), for assessing the circularity of products (Nazemi et al., 2024), and for community decision-making (Fulford and Paulukonis, 2024)], agent-based modelling [e.g., for simulating the viability of circular business models (Lange et al., 2021) and for studying the capacity of agents to switch trading partners and reorganize in the face of shocks (van Voorn et al., 2020)], and system dynamics modelling [e.g., for analysing CE transitions (Guzzo et al., 2021) and for offering explanations about the function of the financial system (Keen, 2024)]. Analyses may also focus on studying socio-metabolic systems in terms of material, energy, emergy/exergy, monetary, or information flows and stocks. For example, those could be modelled as circulating media delivering *"nutrients"* to interdependent *"organs"* (de Jonge and Schückel, 2021; Fath et al., 2019) or as diverse types of overlapping *"neural networks"* each one with specific structures and functions where money is analogous to (latent) *"charged impulses"* occurring at the micro level with the potential to induce socio-metabolic jolts at the macro level [e.g., see (Scott, 2024)]. **Qualitative methods** such as participatory workshops and semi-structured interviews can also help in addressing the multifaceted aspects of inclusion [i.e., economic, political, environmental, spatial, and social inclusion (Liang et al., 2021)] or exclusion [i.e., in terms of economic status, gender, age, disability, location, etc. (Anttiroiko and de Jong, 2020)]. By following a mixed-methods approach, the potential for obtaining insights from different angles will be enhanced, supporting a holistic systems-thinking perspective prior, during, and after the implementation of interventions. Here, it is noted that in multi-stakeholder multi-purpose projects which attempt to model complex socio-ecological systems, modellers need to also be aware of potential challenges arising in *"Chimaera models"* (i.e., complex models comprising of multiple diverse parts which integrate socio-economic with bio-physical processes and which may rely both on qualitative and quantitative data with the intention to address multiple goals simultaneously) (Edmonds et al., 2025).

Equally important for implementing changes effectively is the **translation and dissemination of the generated theoretical and methodological knowledge** across multiple channels to accelerate and facilitate its diffusion to different societal groups (i.e., the private sector, governmental authorities, the general public, etc.). Published examples include a call for business leaders to take action (BMW Foundation, RESPOND, Circle Economy, SYSTEMIQ, 2022), a guide for entrepreneurs, investors, accelerators, and policy makers for supporting the development of regenerative and distributive businesses (Sahan et al., 2022), and a guide on regenerative economics for secondary schools (Brandsberg-Engelmann et al., 2024).

8. What are the relationships, if any, with other alternative schools of economic thought?

Besides exploring the interrelations between the aforementioned theories, concepts, and approaches, it would also be interesting to look at potential relationships (if any) with other alternative schools of economic thought which have emerged over the past decades (Klomp and Oosterwaal, 2021) since those may also be of relevance in the context of bolstering an ecological metaphor of a CE theoretically and/or methodologically. For example, bioregional economics (James and Cato, 2014) studies the self-regulation of local economies within bioregions i.e., geographical regions that are defined by geological morphology, ecological systems, and common cultural values instead of national borders or political realities (One Earth, 2023), wellbeing economics focuses on the wellbeing of all life on Earth (Waddock, 2021), and feminist economics builds on the ethics of care and solidarity (Daibes, 2023; Lapniewska, 2018).

Alternative views on economics are often perceived by mainstream economists to be lacking strong foundations even though their focus is on challenging established knowledge by using different (i.e., *"heterodox"*) approaches to study and understand economies and by persisting in making their methodological choices explicit (Roos and Hoffart, 2021). Perhaps then future research could also focus on unfolding the contributions (if any) of such alternative views to developing further an ecological metaphor of a CE. Here, assuming *"narratives to be active drivers of economic activity"*, narrative economics (Roos and Reccius, 2021) can be of value for exploring the potential of improving epistemologically and ontologically our *"sense-making"* of various worldviews on green-growth, degrowth, post-growth, and the development of socio-economic and socio-ecological systems across different contexts.

To assess the validity of an economy-as-an-organism analogy between a base domain (i.e., an organism) and a target domain (i.e., an economy), eight criteria have been recently proposed (Makriyannis, 2022). In this sense, a solid analogy must exhibit: 1) properties of structure mapping, 2) high degree of mapping clarity, 3) high degree of base specificity, 4) high degree of systematicity, 5) applicability of universal laws to both domains, 6) potential to lead to candidate inferences or novel perspectives, 7) predictions or goal-relevant inferences, and 8) affirmation of established knowledge despite utilizing a different perspective (Makriyannis, 2022). The adoption of such criteria may help future research in circumventing the dual challenge of empirically testing qualitative abstractions of ecological metaphors and of coordinating methods in transdisciplinary research (Makriyannis, 2022).

9. What about indigenous wisdom?

Indigenous perspectives are essential for developing visions of place-based regenerative CEs. This becomes evident when considering that, throughout human history, indigenous societies have emerged in diverse cultural ways and under different ecological conditions yet sharing similarities in their relationship with the land, living as custodians by recognizing the importance of living processes and the regeneration of biophysical flows and stocks of their surrounding natural ecosystems (Wahl, 2016). The role of Indigenous Peoples and local communities in land management for biodiversity conservation is critical manifesting across 54 % of the world's remaining intact forests, and in places where their land overlaps with more than 40 % of Key Biodiversity Areas (i.e. *"sites that are critical for the survival of a unique variety of plant and animal species and are vital for the overall health of the Earth"*) and having high biodiversity intactness (Reytar et al., 2024). Therefore, the legal recognition of their traditional land rights by national and local governments is imperative for safeguarding territories and resources (Reytar et al., 2024).

Examples of future research may include: 1) fostering indigenous community-led visions for regenerative place-based development [such as the Māori interpretation of doughnut economics (Shareef, 2020)], 2) exploring the potential of localized low-tech designs for wellbeing and resilience inspired from the richness and diversity of indigenous wisdom (Calisto et al., 2023), 3) improving the access of indigenous communities to networking to strengthen their ability in protecting their territorial rights in a world which becomes progressively more oriented towards technology and digitalization (Barrena et al., 2024), and 4) the consideration of embedding indigenous knowledge in climate policies which is important not just for equity reasons but also for acknowledging their wisdom on nature and on adaptive strategies which they accumulated over centuries (Ram and Shahzar, 2024).

10. Embracing poly-rationality

Wicked problems such as the debate about whether CEs need to *"green-grow"* or *"degrow"* to be sustainable, are characterized by uncertainty, complexity, and normative pluralism of contrasting and potentially incompatible worldviews where siloed economic sectors constitute additional barriers to decision-making. Yet, it is not frustration and conflict that will drive societies towards a sustainable future but collaboration and clarity (Fiscus and Fath, 2019). Progress will also be supported by reframing our perspective from dealing with *"problems"* in need of *"solutions"* towards addressing *"challenges"* with adaptive *"responses"* (Davies et al., 2024). In this sense, rethinking the design of local economic systems should not be seen as a technocratic task but rather as a social and political one (Boehnert, 2018). Therefore, questioning the incumbent approach of economic development is crucial for steering policies and CE strategies towards a *"re-grounded"* territorial *"terrestrial"* approach to address the *"growing impotence in proportion to the imminence of disasters"* and avoid the polarizing *"local versus global dichotomy"* (Latour, 2018). The focus would also need to shift towards fostering open knowledge and multi-level governance for improved management of resources for long-term socio-ecological sustenance (Barles, 2018; D'assenza-David, 2023; Latour, 2018). A transition to a regenerative CE can only be considered aligned with planetary boundaries and societal well-being when economic strategies and policy agendas adopt a holistic systems-thinking approach in terms of resource flows and stocks across scales, fully including any non-trivial dynamics, addressing biogeochemical cycles within territorial contexts.

Considering the above points, a poly-rationality approach will be invaluable given that none of the mainstream economic theories has been able to explain economic behaviour on its own (Chang, 2014) in part at least because none of them include the non-trivial aspects of time, and consequently, lacking ergodicity in the economy. Perhaps the way forward leads unavoidably to imperfect and suboptimal compromises, but the persistent systems which will result may be inherently robust precisely because of operating at the *"frontiers of poly-rationality"* (Hartmann, 2012). Interestingly, a recent simulation study on the ecosystem services and resilience of the Brazilian coastal city of Ubatuba which faces strong pressures from tourism, compared three distinct management approaches in terms of their worldview assumptions (i.e., individualistic, hierarchist, and egalitarian) and showed that a *"clumsy"* approach *"would locate resilience inside the 'solution space'"* suggesting that the pathway forward could be suboptimal but it would be one that is democratically negotiated, co-created, and legitimized between all active advocacy groups (Oliveira et al., 2024). Here, it is also important to note that *"perfection"* and *"optimality"* are themselves concepts within some system of human values, ideals, or priorities, and for this reason they should always be made explicit. The unveiling, articulation, and demarcation of a plethora of diverse logics could help to co-create systems where purpose for solving societal and environmental problems rather than for maximizing profit or utility, guides novel economic thinking and policy making (de Jong, 2021).

Yet, contributing to the further advancement of an ecological metaphor of a regenerative CE is neither easy nor trivial. Possible pitfalls in such exercise include vagueness in terminology (which could lead to time-consuming, diverging, and non-constructive debates), bias in featuring selective aspects of the incumbent phenomenon (while overshadowing or neglecting other relevant implications), and reification (i.e., the fallacy of accepting imaginary constructs as if they were real) (Olson et al., 2019). Another important consideration which originally has been proposed for nature-based solutions but which is applicable also for conceptualizing regenerative CEs is the way in which different stakeholders may approach nature (i.e., as an anthropogenic or non-anthropogenic concept), how they define nature (i.e., as *"wilderness"*, as a set of processes excluding humans, as a set of processes including humans, or as new *"artificial"* nature), how they value nature (i.e., from a utilitarian, relational or intrinsic perspective), and how they perceive the role of humans in nature (i.e., as protectors, as managers/stewards, as enhancers or as creators) (Lemes De Oliveira, 2025).

11. Conclusions

In an era where the increasing frequency and magnitude of climate change impacts, persistent inequalities, and wars can lead to fear, anger, frustration, societal paralysis, or even outright conflicts, increasing awareness on the availability of tools and positive visions for regenerative CEs, is vital. By assuming regeneration to be the foundation for sustainable socio-ecological and socio-economic systems we offer a speculative and forward-looking perspective on the way we envision progress towards regenerative CEs.

The interdisciplinary agenda proposed here does not claim to provide a complete description of the process of regeneration in the context of a CE or to cover all theories that address it. Rather, it is an attempt to bring forth some of its various interpretations as well as alternative ways which may facilitate the generation of research questions and hypotheses relevant for bolstering the theoretical underpinning and the methodological criterion for developing further the ecological metaphor of a CE. Such alternative approaches may be conflictual but still co-exist by offering a plurality of methods and action realms to contest or enrich established knowledge by generating new insights provided they are explicit in their ontological and epistemological foundations.

Ultimately, the aim of regenerative CEs is to enable local capacities for the development of socio-economic and socio-ecological systems which focus on the wellbeing of all life, and which can sustain their evolving complexity at sustainable rates within planetary boundaries. If stakeholders are willing to follow a bio-inspired approach for co-investing resources, time, and planning effort ahead while considering specific system characteristics and the underlying contexts, then small changes in governance, behavioural patterns, and technology improvement may contribute substantially to the development of regenerative CEs.

Author contribution

Filippos K. Zisopoulos conceived the idea of the research, synthesized the research agenda, compiled the document structure by coordinating and incorporating individual contributions of co-authors, and wrote the text as the main author. Prof. Brian D. Fath, Dr. Bruno Meirelles de Oliveira, Dr. Susana Toboso-Chavero, Hugo D'Assenza-David, Dr. Vitor Miranda de Souza, Dr. Hao Huang, Dr. Serban Scrieciu, Prof. Grant Clark, Dr. Dominik Noll, Prof. Simron Singh, Prof. Alexandros Stefanakis, Dr. Graham Boyd, Dr. Daan Schraven, and Prof. Martin de Jong contributed to paper development according to their specific areas of expertise by sharing knowledge and constructive criticism on the conceptual development of the research agenda, and by reading, reviewing, and editing the text. The order of authors is arbitrary since all of them contributed in different ways, at different parts, or across different times or versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Filippos K. Zisopoulos: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Brian D. Fath:** Writing – review & editing, Writing – original draft. **Bruno Meirelles de Oliveira:** Writing – review & editing, Writing – original draft. **Susana Toboso-Chavero:** Writing – review & editing, Writing – original draft. **Hugo D'Assenza-David:** Writing – review & editing, Writing – original draft. **Vitor Miranda de Souza:** Writing – review & editing, Writing – original draft. **Hao Huang:** Writing – review & editing, Writing – original draft. **Şerban Scrieciu:** Writing – review & editing, Writing – original draft. **O. Grant Clark:** Writing – review & editing, Writing – original draft. **Dominik Noll:** Writing – review & editing, Writing – original draft. **Simron Singh:** Writing – review & editing, Writing – original draft. **Alexandros Stefanakis:** Writing – review & editing, Writing – original draft. **Graham Boyd:** Writing – review & editing, Writing – original draft. **Daan Schraven:** Writing – review & editing, Writing – original draft. **Martin de Jong:** Writing – review & editing, Writing – original draft, Funding acquisition.

Declaration of competing interest

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

Acknowledgements

F.K.Z., M.d.J., and D.S. are grateful to the *Impact for Sustainability Fund*, a named fund at *Stichting Erasmus TrustFonds*, for funding (project number: 97090.2022.101.671/074/RB). The study falls within the Sino-Dutch project *"Towards Inclusive CE: Transnational Network for Wise-waste Cities (IWWCs)"* which is one of the projects of the *Erasmus Initiative Dynamics of Inclusive Prosperity*, and it is co-funded by the *Dutch Research Council* (NWO) and the *National Natural Science Foundation of China* (NSFC); NWO project number: 482.19.608; NSFC project number: 72061137071. H.H. acknowledges his support with a grant from the C3.ai Digital Transformation Institute, a grant from Princeton University's School of Engineering and Applied Science (SEAS), and a grant from Princeton Language and Intelligence (PLI). D.N. acknowledges funding under the research contract 2022.05039.CEECIND/CP1734/CT0001 (doi: 10.54499/2022.05039.CEECIND/CP1734/CT0001) through the Portuguese Foundation for Science and Technology (FCT) with MED (doi: 10.54499/UIDB/05183/2020) and CHANGE (doi: 10.54499/LA/P/0121/2020). The authors would like to acknowledge three anonymous reviewers for their constructive criticism.

Data availability

No data was used for the research described in the article.

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